Evaluation of temperature variances found within integral reefer containers during shipment of Japanese plums (*Prunus salicina* Lindl.) at dual and single temperature

BY

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Pectora roborant cultus recti

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

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SUMMARY

Evaluation of temperature variances found within integral reefer containers during shipment of Japanese plums (*Prunus salicina* Lindl.) at dual and single temperature

Stone fruit is susceptible to chilling injury and intermittent warming has been shown to alleviate chilling injury during cold storage. A dual temperature storage regime was developed in South Africa for plums based on the principles of intermittent warming. The regime consists of an initial period at -0.5°C, a variable duration warming period at 7.5°C, followed by -0.5°C. Refrigerated integral containers were designed to maintain product temperature and not to reduce product temperature, *per se*. Considering that dual temperature shipment requires significant refrigeration and effective distribution of cool air to remove sensible- and respiratory heat, the capacity of integral containers to ship plums successfully at dual temperature is questioned.

The objectives of this study were, firstly, to analyse pulp temperature data and possibly identify different temperature zones within containers shipping plums at dual temperature. Secondly, to understand the underlying processes differentiating the temperature zones and thirdly, to determine the effect of container performance on fruit quality.

Three processes were identified as important characteristics of pulp temperature data sets recorded during dual temperature shipping, namely cooling down, heating up and over heating in the container. The order of importance differed according to the cultivar shipped and the container's performance. Three temperature zones were identified in dual temperature containers, where the average pulp temperature, time to heat up and time to cool down for each temperature zone increased along the length, across the width from the left to the right and up the container system. The variable temperature conditions were possibly due to a variation in delivery air temperature, poor airflow and the effect of increased respiration and, therefore, production of vital heat by the fruit. The cooling down process was identified as the most important process discriminating the temperature zones.

With the exception of 'Fortune', variable temperature conditions found within integral containers shipping plums at dual temperature had a significant influence on the fruit firmness post-shipment, where deterioration levels increased from the front to the door end of the container due to an increase in pulp temperature. However, it was also shown that fruit firmness prior to shipment could have a determining effect on differences found. It could not be proven that variable temperature conditions resulted in significantly higher levels of internal defects within the integral container.

Temperature zones could not be identified within refrigerated integral containers shipping plums at single temperature, suggesting that the containers are able to maintain the temperature well throughout the container area.

A constant 2°C storage temperature could possibly replace the commercial dual temperature regime in the case of ‘Pioneer’ plums due to improved fruit firmness, similar colour development to the control and less sensible heat produced in the container resulting in a more stable container environment. However, unacceptably high levels of shrivel and internal browning were found.

OPSOMMING

Evaluasie van temperatuur variasie gevind in integrale houers gedurende verskeping van Japanese pruime (*Prunus salicina* Lindl.) teen dubbel- en enkeltemperatuur

Steenvrugte is vatbaar vir koueskade en dit is bewys dat periodieke verwarming gedurende koelopberging koueskade kan verlig. Die dubbeltemperatuur opbergingsregime is in Suid-Afrika ontwikkel vir pruime en is gebaseer op die beginsels van periodieke verwarming. Die regime bestaan uit ‘n inisiële periode by -0.5°C, ‘n variërende periode by 7.5°C, gevolg deur -0.5°C. Verkoelde integrale houers is ontwerp om produktemperature te handhaaf en nie soseer om produktemperatuur te verlaag nie. Die kapasiteit van integrale houers om pruime suksesvol teen dubbeltemperatuur te verskeep word dus bevraagteken, in ag geneem dat dubbeltemperatuurverskeping betekenisvolle verkoeling en effektiewe verspreiding van koue lug vereis om die waarneembare- en respiratoriese hitte te verwyder.

Die doelwitte van die studie was eerstens om die pulptemperatuurdata te analiseer en moontlik verskillende temperatuursones binne houers wat pruime teen dubbeltemperatuur verskeep te identifiseer. Tweedens, om die onderliggende prosesse wat die temperatuursones van mekaar onderskei te verstaan, en derdens om die effek van die houer se werkverrigting op vrugkwaliteit te bepaal.

Drie prosesse is geïdentifiseer as belangrike eienskappe van pulptemperatuur datastelle aangeteken gedurende dubbeltemperatuurverskeping, naamlik afkoeling, opwarming en oorverhitting wat binne die houer plaasvind. Die volgorde van belangrikheid het gevarieer afhangende van die kultivar verskeep en die houer se werkverrigting. Drie temperatuursones is geïdentifiseer binne integrale houers wat pruime teen dubbeltemperatuur verskeep, waar die gemiddelde pulptemperatuur, die opwarmingstyd en die afkoelingstyd vir elke temperatuursone in die lengte, oor die wydte van links na regs en van onder na bo in die houersisteem toegeneem het. Die variërende temperatuur toestande kan moontlik toegeskryf word aan ‘n variasie in leweringstemperatuur, swak lugvloei en die effek van toenemende respirasie, en dus die produksie van hitte vrygestel deur die vrugte. Die afkoelingsproses is geïdentifiseer as die belangrikste proses wat die temperatuursones van mekaar onderskei.

Behalwe in die geval van ‘Fortune, het variërende temperatuurtoestande in integrale houers wat pruime teen dubbeltemperatuur verskeep ‘n betekenisvolle invloed op die vrugfermheid na verskeping gehad, waar vrugveroudering toegeneem het van voor in die houer na die deur van die houer as gevolg van ‘n toename in pulptemperatuur. Daar is egter bewys dat

die vrugfermheid voor verskeping ook ‘n bepalende effek kon hê op die fermheidsverskille. Dit kon nie bewys word dat die variërende temperatuurtoestande betekenisvol hoër vlakke van interne defekte binne die integrale houer veroorsaak het nie.

Temperatuursones kon nie geïdentifiseer word binne verkoelde integrale houers wat pruime teen enkeltemperatuur verskeep het nie, wat dus impliseer dat die houers daartoe instaat is om temperatuur goed te onderhou binne die houer.

‘n Konstante 2°C opbergingstemperatuur kan moontlik die kommersiële dubbeltemperatuurregime vervang in die geval van ‘Pioneer’ pruime as gevolg van verbeterde vrugfermheid, soortgelyke kleurontwikkeling as die dubbeltemperatuurregime en minder hitte geproduseer binne die houer deur die pruime, wat ‘n meer stabiele houeromgewing veroorsaak. Onaanvaarbare hoë vlakke van verrimpeling en interne verbruining is egter gevind.

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CONTENTS

Page

Declaration i

Summary ii

Opsomming iv

Dedication vi

Acknowledgements vii

Literature Review 1
1. Temperature management in a refrigerated integral container 1
1.1 Containerized shipment 1
1.2. The refrigerated integral container 1
1.3. Temperature maintenance in a refrigerated integral container 2
    1.3.1. Pre-loading factors 2
    1.3.2. The mechanism of temperature maintenance 3
    1.3.3. Optimal airflow, air distribution and air circulation rate 3
    1.3.4. Fresh air ventilation and defrost cycles 5
1.4. Temperature variance within a refrigerated integral container 5
    1.4.1. Air temperature as influenced by position within the container 6
    1.4.2. Fruit pulp temperature as influenced by position within the container and pallet 7
1.5. Possible reasons for the development of temperature variances 9
    1.5.1. Optimization of pre-loading fruit handling procedures 9
    1.5.2. Variation in delivery air temperature 9
        1.5.2.1. Delivery of uniform air temperature at set point 9
        1.5.2.2. Positioning of the control temperature probe in the delivery air stream 10
        1.5.2.3. Fresh air ventilation, the influence of atmospheric conditions and differential coil frosting 11
    1.5.3. The heat of respiration and return air temperature 12
    1.5.4. Heat leakage into the container 12
    1.5.5. Poor airflow in the container and insufficient air-flow rate 13
1.6. Influence of container atmospheric conditions on fruit quality with special reference to South African plums shipped at dual temperature regimes 14
    1.6.1. Temperature 14
    1.6.2. Fresh air ventilation 16

1.6.3. Humidity 16
2. Stone fruit quality.. 17
2.1. Stone fruit post harvest.. 17
2.1.1. The influence of temperature on fruit ripening and fruit quality 17
2.1.2. The role of ethylene in fruit ripening.. 18
2.1.3. The importance of humidity management.. 19
2.2. Stone fruit internal quality disorders 20
2.2.1. Chilling injury.. 20
2.2.2. Gel breakdown 22
2.2.3. Internal browning.. 23
2.2.4. Over ripeness.. 23
2.3. Managing fruit quality 24
2.3.1. Intermittent warming.. 24
2.3.2. Dual temperature storage 25
3. Summary 25
4. References 26

Paper 1: Identification of temperature zones within integral reefer containers shipping Japanese plums (*Prunus salicina* Lindl.) at dual temperature and the effect of such zones on fruit quality 33

Paper 2: An evaluation of the temperature variances found within integral reefer containers shipping Japanese plums (*Prunus salicina* Lindl.) at single temperature and the effect thereof on fruit quality.......................... 100

Paper 3: Evaluation of electrolyte leakage and fruit quality of ‘Pioneer’ plums (*Prunus salicina* Lindl.) stored at various temperatures................................ 132

General discussion and conclusion... 154

LITERATURE REVIEW

1. Temperature management in a refrigerated integral container

1.1 Containerized shipment

Globally containerized shipment accounted for approximately 40 million metric tons of sea-borne cargo in 2002, representing 60% of all refrigerated seaborne trade (Anonymous, 2003), and accounting for 31% of the global cold food chain (Tso *et al*., 2006). It was further estimated that containerized shipment would grow to 70% in 2006 (Anonymous, 2003). The South African fruit export industry has to overcome two major obstacles, namely the distance to the overseas markets and the time it takes to complete such voyages. Both challenges require the development of technology to ensure that the horticultural product would arrive in a good condition. Since the deregulation of the South African fruit export industry in 1997, containerized fruit exports grew significantly (Anonymous, 2003). This was mainly due to the emerging of companies exporting proportionally smaller volumes for which containers were more suited. Containerized shipment presented other appealing advantages that furthermore resulted in the growth in containerized fruit exports. Containers minimized the risk of the product being damaged since it was handled fewer times. The risk of theft and food contamination was also reduced. Fruit with unique temperature requirements could also be accommodated in a containerized environment and traceability was simplified.

1.2. The refrigerated integral container

A refrigerated container essentially consists of three parts, namely an insulated box, a refrigeration system and an air circulation and distribution system (Irving, 1988).

The major difference between containerized shipment and conventional (break bulk) shipment, is that whereas the stowing decks operate as cold rooms and have the ability to pre-cool or re-cool the fruit units, the integral reefer containers (forty foot equivalent unit or FEU) were designed to operate independently and only maintain fruit temperature. The integral container was designed in such a way to reduce power consumption and that the refrigeration unit occupy as little space as possible, hence the limited capacity to refrigerate. Irving (1988) furthermore stated that although the refrigeration system of the container has sufficient capacity to cool cargo, the air-flow system was not designed to allow efficient cooling and should the container not be regarded as cooling devices, but devices that maintain the temperature of the cargo. Each container is able to maintain its own carriage temperature in the range of -30°C and +25°C depending on the type of goods (Tso *et al*., 2006; Yan-Qiao and Shi-Lang, 1996). Containerized shipment of especially integral containers, therefore, requires strict discipline in product handling- and pre-cooling protocols of fruit pallets prior to loading of such containers, due to the limited capacity to refrigerate.

1.3. Temperature maintenance in a refrigerated integral container

Good temperature control of a respiring product requires very good pre-cooling prior to container loading, the use of containers with good temperature control, high air circulation rate and good air distribution (Amos and Sharp, 1999). The quality of produce at outturn depends not only on good container performance, but also on good agricultural practises and the production of high quality produce (Irving, 1988).

1.3.1. Pre-loading factors

Proper pre-cooling of cargo to the required carriage temperature (<1°C for stone fruit) is crucial before loading of a container takes place (PPECB, 2006b), since reefer containers are built to maintain the temperature and not to lower it.

Fruit handling, pre-cooling and temperature storage procedures of pallets from harvest to stowage have been proven to be crucial in the case of fruit shipped in integral containers. In studies performed in Australia it was found that to achieve a maximum fruit temperature of +0.6°C it was necessary to ensure that the fruit was pre-cooled to below +2°C and preferably at carriage temperature, and that such conditions had to be maintained until loading of the ship (Scrine, 1982a). Irving (1988) also stated that fruit pallets should be under constant refrigeration and not stand outside the cold room for prolonged periods prior to stowage. Temperature recovery of warm loaded produce can take up to three weeks, depending on the container, position within the container and the ambient conditions, and this necessitates the pre-cooling of fruit units prior to stowage.

Pre-cooling of the reefer container should never take place. Once the doors of a pre-cooled container are opened, the ambient hot air will meet the internal cold air, resulting in a large amount of condensation on the interior surfaces. Water dripping from the roof of the container can result in weakening and staining of cartons as well as the occurrence of decay with excess moisture being present on fruit. Condensed water and heat entering the container during loading, combined with the heat generated by the respiring cargo, needs to be removed through the evaporator. As soon as the heat passes the evaporator, ice is formed and the machinery enters a defrost mode. Consequently, there will be less capacity available for cooling the cargo and might cause the refrigeration unit to switch off more regularly for defrosting (Irving, 1988).

1.3.2. The mechanism of temperature maintenance

The cooling and maintenance of temperature in an integral container is achieved through circulation of cold air with an evaporator fan over the refrigeration evaporator coils located in the front of the container wall and through the container, with an associated compressor and condenser (Scrine, 1982a; Irving, 1988).

Refrigerated reefer containers cool through bottom air delivery via a metal floor with channels (T-bar floor) through which the cold air is forced from the refrigeration unit along the length of the container. The higher the floor channels are, the more uniform the air distribution along the length of the container floor will be (Amos and Sharp, 1999). Amos and Sharp furthermore made a personal observation that shallow floor channels (<35 mm) do not seem to deliver adequate air to the door end of the container to ensure proper temperature control. The improvement of air distribution along the container floor by using a castellated section floor has proven to be unsuccessful (Scrine, 1982b). Wall battens assist in allowing air flow over the walls of the container and, therefore, in the removal of heat leaking into the container. Less air flows over smooth walled containers resulting in higher temperatures in produce closest to the walls of the container (Irving, 1988).

Warm air moves upwards from the cargo back towards the evaporator fan. Maintenance of temperature in an integral container is accomplished through the extraction of heat by the evaporator, aided by the fan that is responsible for the circulation of air through the cargo. The air is passed over the refrigerant in the evaporator coil and the heat transported by the refrigerant via the compressor to the condenser coil in the refrigeration unit. Air from the outside is forced over the condenser by the condenser fan and the heat is blown from the condenser into the ambient air (Irving, 1988).

1.3.3. Optimal airflow, air distribution and air circulation rate

Good temperature control, refrigeration capacity and air distribution are of vital importance to ensure product quality on arrival at the destination market. The refrigeration system of the container has sufficient capacity to cool cargo, but the air flow system was not designed to allow cooling to be done quickly. Containers should, therefore, not be regarded as cooling devices but rather devices that maintain the temperature of the cargo (Irving, 1988).

A good distribution of cool air throughout the container is important for rapid and efficient removal of the sensible- and respiratory heat and maintenance of the temperature differences within acceptable limits (Billing *et al*., 1995). Good air distribution over the walls and door of the container was shown to be important in removing heat leakage once loaded. Door battens are essential in ensuring adequate airflow over the end section of the cargo and, therefore, ensuring effective removal of heat leakage through the doors (Amos and Sharp, 1999).

The distribution of circulating air depends on the resistance of each path to the flow of air, and, therefore, also on the specific container design and stowage pattern (Irving, 1988). Air tends to circulate through zones that offer less resistance and a preferential pathway is created through void spaces (De Castro *et al.*, 2005). Covering the entire floor, from the front bulkhead to the end of the T-bar flow, with chilled cargo, therefore, forces the cool air to flow through both the cartons and the product, throughout the container. De Castro *et al*. (2005) furthermore stated that a back-mixing effect often occurs in the corners (known as the dead zone), decreasing the uniformity of the cooling process.

The PPECB (Perishable Products Export Control Board) of South Africa has increased the rate of air circulation in a container to 60 changes per hour when carrying fruit, compared to the standard minimum requirement of 30 to 40 changes per hour of the empty volume of the container when carried in an insulated hold (Scrine, 1982a). Amos and Sharp (1999), however, found that a high air circulation rate did not necessarily produce the best temperature control in studies performed to evaluate a range of 20’ container models for in-transit cold-disinfestation ability. Low air circulation rates could, however, also not succeed in achieving the required temperature uniformity in the container.

Airflow should not be restricted in the container. Large gaps of 70 mm and larger between the door and end of the T-bar floor may allow the overhanging of sagging cartons and, therefore, the restriction of airflow. Adequate space between the cargo and ceiling of the container is essential to ensure proper airflow. Cargo should, therefore, never be stowed above the red line found 2.4 m from the container floor along the length of the container. Inadequate space, and, therefore, a resistance to airflow, will result in a decrease in the total air-flow rate and affect the air distribution, ultimately resulting in an increase in fruit pulp temperature throughout the container (Irving, 1988).

The size and positioning of produce within a carton, the stacking arrangement of the cartons as well as the carton dimensions and total open area (TOA), influence the intensity and homogeneity of the air velocity profile throughout the packed produce (De Castro *et al.*, 2005). The ventilation openings on the carton must be designed in such a way that the holes are aligned to avoid the obstruction of air when the cartons are stacked on one another and side by side, since it plays a role in influencing the homogeneity of cooling. De Castro *et al*. (2005) also stated that the smaller the total open area on a carton, the higher the restriction to air circulation through the packed produce.

1.3.4. Fresh air ventilation and defrost cycles

Outside atmospheric air is introduced into the circulating airflow of an integral container through fresh air ventilation in an effort to prevent the build up of carbon dioxide and ethylene (Billing *et al*., 1998). According to the guidelines of the PPECB of South Africa, all integral containers shipping plums single and dual temperature should be ventilated at 15m^3 per hour (PPECB, 2006a).

Operating carriage temperatures at below freezing point is subject to frost deposition and progressive build up on the evaporator coil (Tso *et al*., 2006; Irving, 1988). The actual amount of frost deposited will depend on the moisture content of the air and the temperature of the evaporator coils. Defrost cycles are, therefore, essential for maximum cooling efficiency by ensuring that evaporators are kept free of excessive ice building up. Defrost cycles are programmed for set time periods. The air circulation fans are switched off during defrosting to ensure that the applied heat goes into the melting of the ice and not the heating up of the cargo (Irving, 1988).

Billing *et al*. (1998) found that too many defrost cycles may lead to the introduction of too much sensible heat in the container and too few defrost cycles may lead to delivery air temperature stability problems.

1.4. Temperature variance within a refrigerated integral container

The delivery air set point temperature, time between defrosting cycles and amount of atmospheric air introduced into the container are the dominating factors influencing temperature uniformity in the container (Billing *et al*., 1998). Irving and Sheperd (1982) stated that the total rate of air circulation determines, in part, the uniformity in temperature within a container, and that ideally the air should be distributed in such a way that the quantity of air flowing in each section should be proportional to the amount of heat to be removed to attain such temperature uniformity (Irving, 1988). Amos and Sharp (1999) concluded that a low rate of heat leakage, good air delivery to the walls and door end of the container, good temperature control, stability and uniformity across the container and high air circulation rate, to prevent excessive temperature increase in the circulating air stream, were required to meet the strict temperature requirements of the cold-disinfestation protocol for citrus fruit. Tanner and Amos (2003a) also concluded in studies performed on 40’ refrigerated containers, that in an effort to minimise deterioration of perishables in a container, a shipping refrigeration system had to be able to maintain the delivery air temperature at set point, minimise the variation throughout the whole container, have sufficient capacity to remove heat produced by the produce, heat introduced through fresh air ventilation and heat moving through the walls of the container, and finally to maintain stable temperatures over time.

Oosthuyse (1997) defined efficient air cooling as air- and pulp temperatures measured at any point within the container at a specific time, being fairly similar. Inefficient air cooling was identified through marked differences between the air- and pulp temperatures.

According to Irving (1988) single produce temperature in a container does not exist. This was illustrated through an estimation of the number of cartons in each 0.5°C interval for two containers with varying air flow and air distribution performance, shipped at an ambient temperature of 35°C. The high performing container resulted in only a smaller spread in temperatures measured.

1.4.1. Air temperature as influenced by position within the container

Temperature uniformity within a container is important, especially with chilling sensitive crops or crops that require temperatures to remain above freezing point (Harvey, 1981). Severe injury can occur in the coldest positions within the container if large variances occur or if a chilling sensitive crop is transported at unfavourable temperatures for prolonged periods. Heap (1989) stated that “however good a container and however well cooled, packed and stowed the cargo may be, there is of necessity a temperature gradient within the container dependent on outside conditions, thus an awareness of what a normal and reasonable temperature distribution is, is needed.” Many studies have been undertaken on 20’ refrigerated container shipments and less so on 40’ refrigerated container shipments.

According to Irving (1988) the direction of air flow determines where the hottest and coldest positions in the container will be. The cartons in the top layers of a pallet will be the warmest in the case of bottom air delivery and in the case of top air delivery, the bottom layers will be the warmest.

Amos and Sharp (1999) evaluated eight different 20' foot refrigerated container models and found the following. Depending on the air distribution through the floor channels, the temperature was either the highest nearest to the walls or in the centre of the container. In some cases the temperature was higher at only one side of the container. Changes in temperature were evident as outside atmospheric conditions changed and fresh air vents were opened.

Tanner and Amos (2003a) showed that the temperature range within a 40' container carrying kiwifruit with a set point temperature of -0.5°C was between 5°C and 6°C during steady state and that the maximum temperature recorded was always closest to the door-end of the container, remaining between 4°C and 4.5°C. An assessment of temperature frequency distributions for all measurements within the container showed that in-pallet temperatures were approximately only 30% of the voyage time within the recommended range. Irving (1988) found a temperature spread of between 1°C and 5°C in integral containers shipping pears. Oosthuyse (1997) measured the highest air- and pulp temperatures at the door end and in the top layers of the pallets in containers shipping mangoes. A marked difference in air- and pulp temperatures was found indicating not only poor airflow at the door end of the container, but also inefficient air cooling.

In studies performed on dual temperature shipment of plums in a 40' integral container by Punt and Huysamer (2005), it was found that a prolonged re-cooling phase of three to ten days was associated with the period following the intermittent warming period, depending on position within the container and pallet. On average throughout the voyage the air temperatures increased from the cooling unit to the door end of the container, and from the bottom to the top of the pallet, with the highest temperatures (11°C to 12°C) found in the top layers within the pallet during the intermittent warming period at 7.5°C. Air temperature measured at the bottom of the pallet closest to the cooling unit and in the middle of the container, was the closest to the set point temperature.

1.4.2. Fruit pulp temperature as influenced by position within the container and pallet

The fruit pulp temperature is dependant on the delivery air temperature, the localised airflow past the specific fruit pallet, the heat produced by the product due to respiration and the packaging material's thermal characteristics (Billing *et al*., 1993; Billing *et al*., 1995). Fruit temperature is always higher than the surrounding air temperature and it has been found that fruit temperature generally increases across the width of the container, along the length of the container and up the height of the container system (Tanner and Amos, 2003a). Harvey *et al*. (1983) determined that the pulp temperature of kiwi fruit shipped in a container was similar at ¼ length and ¾ length of the container.

Billing *et al*. (1993 and 1995) showed that the fruit pulp temperature measured near the bottom of a pallet shipped in a refrigerated deck was always influenced by the delivery air temperature, irrespective of the amount of localised airflow past the pallet. It was also found that the fruit pulp temperature at the bottom of the pallet increased with increasing distance from the fan. It was suggested that the delivery air temperature also significantly increased with distance from the fan.

Fruit temperature gradients exist within a pallet of fruit and the amount of localised primary volumetric flow delivered within a refrigerated cargo hold has a significant effect on the temperature gradient (Billing *et al*., 1995). It was also shown that the localised airflow had a significant effect on the time required for temperature recovery in the centre and upper part of the pallet. Lower airflow rates resulted in longer recovery times for the middle and upper trays within the pallet than the lower pallet trays. The upper trays also cooled faster than the middle pallet trays where higher air speeds occurred over the top of the pallet. Billing *et al*. (1993) showed that the fruit pulp temperature near the top and middle of the pallet were on average not more than 0.5°C warmer than near the bottom of the pallet irrespective of the location within a deck of a refrigerated vessel. Temperature gradients of up to 2°C were, however, also found. Restricted airflow past pallets, due to tightness of stow, resulted in elevated fruit temperatures in the middle and top positions within a pallet.

In an assessment of a temperature contour plot drawn up of a 40' integral container, Tanner and Amos (2003b) highlighted the higher pulp temperatures found at the door end of the container in the bottom, middle and top carton layers of pallets of kiwifruit shipped at a set point temperature of -0.5°C. Since the warmest fruit were always found at the door end of the container, it was suggested that this fruit should always be utilised first upon arrival in the market place.

In studies performed with dual temperature shipment on plums, Punt and Huysamer (2005) found that the pulp temperatures increased slowest during the step up phase from -0.5°C to 7.5°C, and the step down phase from 7.5°C to -0.5°C, in the middle layers of the pallet closest to the door end of the container. The most rapid cooling rate was found in the bottom and middle layers of the pallet closest to the cooling unit. It took between two to three days for the fruit pulp temperature to reach 7.5°C, eventually peaking at 9.5°C to 11°C in all pallets. The highest peak pulp temperatures were measured in the middle and top layers of the pallet. Fruit pulp temperatures took three to 11 days to reach -1°C after the step down phase during dual temperature shipment, again determined by the position within the container (Punt, 2002).

1.5. Possible reasons for the development of temperature variances

1.5.1. Optimization of pre-loading fruit handling procedures

Tanner and Amos (2003a) stated that there is an opportunity for the implementation of pre-loading fruit handling procedures, container design and operation improvements in an effort to minimize the temperatures variances found in a 40’ integral container.

Pre-cooling of pallets and limiting exposure to ambient conditions during loading are crucial in optimising pre-loading fruit handling procedures (Tanner and Amos, 2003a). The assessment of fruit pulp temperatures in the core of the pallet prior to loading was also identified as a means to ensure that cargo is loaded at carriage temperature.

1.5.2. Variation in delivery air temperature

Within an ideal container the delivery air temperature would be uniform across the width of the container, constantly at set point temperature, not be influenced by outside atmospheric conditions or the air ventilation (Amos and Sharp, 1999). Billing *et al.* (1993), however, concluded that satisfactory delivery air temperature did not guarantee that fruit pulp temperatures were maintained within the prescribed temperature range.

1.5.2.1.Delivery of uniform air temperature at set point

According to the standards set by PPECB in South Africa, the delivery air temperature (DAT) should be within 0.5°C of the set point temperature (PPECB, 2006a). Most shipping companies claim that their containers can control the supply air temperature within 0.3°C of the set point temperature. Billing *et al.* (1998), however, found that this only occurred under optimal conditions when the refrigeration controller was programmed correctly and no excessive building up of ice occurred on the evaporator. During steady state and outside atmospheric conditions of 16°C, the DAT delivered to the left hand side of the container (as viewed from the door end) were more stable, less cyclic and approximately 1°C colder than the DAT on the right hand side of the container. The DAT was 0.4°C colder than the -0.5°C set point temperature. In studies performed by Amos and Sharp (1999), all containers evaluated showed non-uniform air velocity and DAT in the floor channels across the width of the container. Tanner and Amos (2003a) performed trials in 40' containers and measured DAT as low as -5°C for short periods and -2.5° for longer periods at a set point temperature of -0.5°C. It was, therefore, very likely that the fruit, especially in the bottom layers of the pallets, would be exposed to freezing conditions. The average DAT was recorded to be close to set-point temperature.

Tanner and Amos (2003a) suggested the design of a container delivery air system that will reduce or eliminate the spatial variability in DAT across the width of the container. Designing of air refreshing ducting that will reduce or even eliminate the differential frosting occurring on the evaporator coil was suggested as a means to reduce the variability in DAT across the width of the container.

1.5.2.2. Positioning of the control temperature probe in the delivery air stream

In studies performed by Tanner and Amos (2003a), the control temperature probe was located at the centre of the coil width, running the width of the 40' container. Decreased airflow and, therefore, higher DAT on the right hand side of the container (as a result of differential coil frosting that occurred during the shipment period over the equator, resulting in increased airflow resistance), resulted in the delivery of colder air on the left hand side of the container in an attempt by the refrigeration unit to gain control. The average set point temperature was, therefore, adhered to, but the delivery air temperature varied by more than 4°C.

Billing *et al*. (1993) recommended that temperature probes should be evenly installed throughout the delivery air plenum to enable the measurement of the average DAT as well as the variation of DAT across the deck of a refrigerated vessel to ensure optimum and even control of DAT throughout the voyage. It was further recommended that DAT should remain at set point throughout the voyage to ensure optimal temperature maintenance.

1.5.2.3. Fresh air ventilation, the influence of atmospheric conditions and differential coil frosting

Control of the amount of sensible- and latent heat introduced through the fresh air ventilation port is important in an effort to ensure an even temperature profile throughout the container.

According to Billing *et al*. (1998), no significant difference in temperature profile could be found between a regular atmosphere container having a fresh air ventilation port open at 15% and a controlled atmosphere container where the ventilation port was shut. Performance, however, changed as the outside atmospheric temperature increased. The DAT across the container's width differed by up to 2°C when the outside atmospheric temperature increased to 30°C. The DAT on the left hand side of the container decreased to 1°C colder than the set point temperature of -0.5°C. Temperature stability problems occurred where the DAT differed more than 2°C across the width of the container together with an erratic DAT cycle.

Amos and Sharp (1999) showed that air ventilation, the rate of ventilation and outside atmospheric conditions had a significant influence on the DAT in the trials performed in evaluating the performance of a range of 20' refrigerated containers. Tanner and Amos (2003a) had similar results in trials performed in 40' refrigerated containers shipped at -0.5°C set point temperature. A significant, temporary variation in DAT, spatially and across the width of the container, was found in the time period corresponding to the shipment period over the equator. A contour plot was drawn up for this period and air temperatures (within the carton) were as low as -2.9°C on the left hand side of the container (as viewed from the door end of the container). The variation was ascribed to reduced airflow (due to increased resistance) on the right hand side of the evaporator due to differential coil frosting, since the fresh air vent (now providing air with an increased moisture load) was also positioned on the right hand side of the container. Irving (1988) similarly found in trials performed on integral containers containing pears that the temperature spread in the container markedly increased as the outside ambient temperatures increased. This was more prevalent in containers with a lower air-flow rate or poor air distribution.

Tanner and Amos (2003b) suggested that the defrost frequency should be set according to the refrigeration system's requirements in the most extreme ambient conditions, in an effort to lower the variability in DAT.

1.5.3. The heat of respiration and return air temperature

Refrigerated air circulates in the cargo space of the container and absorbs the heat leaking through the walls of the container and the heat produced by the produce. Consequently the air temperature leaving the cargo is higher than the DAT (Irving, 1988).

Scrine (1982a) stated that the maximum fruit temperatures are usually above the return air temperatures (RAT) of a container and exemplary temperature control is important due to the range of air temperatures found in the container. Oosthuyse (1997) showed that the RAT accurately estimated the pulp and pallet air temperatures when fruit respiration was not elevated, but underestimated when the fruit pulp temperatures indicated an elevation in fruit respiration. An elevation in fruit respiration and, therefore, increased production of heat, also accentuated the effect of poor airflow and temperature management in the container. A difference of 1°C was calculated between the DAT and the RAT of a container of pears shipped at -0.5°C (Scrine, 1982a).

Billing *et al.* (1993) found that the RAT within cargo decks was generally higher than the DAT. A temperature difference of up to 0.6°C occurred at the return air grills across the width of the deck within the refrigerated vessel. It was established that this difference was not due to the differences found in DAT.

The amount of heat produced through the respiration of produce depends on the fruit commodity. According to Irving (1988) less than 50% of the air should flow over the walls of the container, with the rest of the air redirected to flow through the cargo for produce with high heats of respiration like avocados. The redirection of airflow can be achieved through the use of dunnage bags. In the case of fruit commodities with lower heats of respiration like apples, approximately 50% of the air should flow over the walls of the container to control the heat leakage into the container. The percentage of air flowing over the walls of the container should also increase up to 70% as the temperature difference between the inside and the outside of the container increases.

1.5.4. Heat leakage into the container

The highest proportion of heat leakage occurs at the front wall of the integral container where a number of pipes and cables penetrate the container. The most heat leakage occurs at the door end of a porthole container (Scrine, 1982b). Scrine (1982b) concluded that container heat leakage was a significant factor in increasing the temperature and reducing the relative humidity within porthole and integral containers shipping meat.

Integral containers are placed either in a non-refrigerated cellular or vehicle hold or on the deck of the vessel where the ambient temperatures can reach 30°C to 40°C. The high temperature ambient environment greatly increases the amount of heat leakage, especially in the case of the integral containers with higher heat leakage values than porthole containers (Irving, 1988).

The proportion of heat generated by the produce and heat leaking through the container walls, determine how the circulating air should be distributed within the container. The porthole containers and integral containers are shipped in different environments and the two containers ideally require different air distribution patterns (Irving, 1988). Air distribution through the floor channels close to the walls, over the walls and door of the container was shown to be important in removing heat leakage and, therefore, enabling the required temperature control to ensure adherence to the Japanese citrus cold-disinfestation protocol in 20’ containers (Amos and Sharp, 1999). Air distribution predominantly through the centre floor channels ensures rapid cooling of warm loaded stow.

Tanner and Amos (2003b) highlighted the high temperatures found at the door end of a 40’ container with a contour plot. It was stated that a possible reason for the higher temperatures found, was heat infiltration through the doors due to poorly maintained seals.

1.5.5. Poor airflow in the container and insufficient air-flow rate

Containers with bottom air delivery require cargo to present a uniform resistance along the container length with no short circuits (Scrine, 1982b). Certain pallets and cartons are, however, incompatible with the container dimensions and length which leads to a by pass at the door end of the container. Large gaps left between the end of the pallet rows and the door, result in poor airflow at the door of the container due to air easily short circuiting past the pallets nearest to the doors (Tanner and Amos, 2003b).

Tanner and Amos (2003b) furthermore stated that the large distance from the fan at the front of the container to the door end of the container, result in lower airflow at the door-end of the container due to short circuiting of air from the refrigeration end of the container along the length of the container. A lower volume of cold air is, therefore, delivered to the door-end of the container resulting in higher air temperatures. Punt and Huysamer (2005) similarly concluded that even though the DAT was within the required tolerances during trials performed on dual temperature shipment of plums, inadequate airflow through palletized, climacteric plums with high metabolic rates, led to an excessive increased in pulp temperature.

Tanner and Amos (2003b) recommended the use of inflated dunnage bags or void plugs at the door end of the container to improve the uniformity of vertical airflow through the pallets. It has also been shown that the stowage of cargo almost to the container doors (Scrine, 1982b) or the use of battens in the door gap, ensured that more air flowed to the door end of the container and as a result the fruit pulp temperature was reduced (Irving, 1988). The use of a graded, perforated floor has shown encouraging results where a known quantity of air is ducted to the door end of the container and the remaining cold air uniformly distributed over the length of the container (Scrine, 1982b).

In the initial design of the clip-on refrigeration units and the integral containers, an air-flow rate of 60 changes per hour was specified. Many integral containers do, however, not meet the specification and have an air-flow rate of only 40 changes per hour. An average rise in temperature, due to heat leakage and the heat of respiration, of 2.4°C occurs in these containers compared to a rise of 1.6°C in containers meeting the specification. New containers are also available with an air-flow rate of 90 changes per hour. A temperature rise of only 1.1°C or less is estimated for these containers (Irving, 1988).

1.6. Influence of container atmospheric conditions on fruit quality with special reference to South African plums shipped at dual temperature regimes

The effect of temperature, atmospheric composition and humidity levels on biological processes within fruit and vegetables should be thoroughly understood by those designing and operating containers (Harvey, 1981). The voyage time constitutes a large portion of the total post harvest life and it is, therefore, of vital importance that the container environment should be optimal to ensure an adequate marketing period. The biological requirements of the commodities shipped must, therefore, be the primary factor in designing a container that will provide the specific commodity with an optimum transit environment.

1.6.1. Temperature

Maintenance of optimum temperature is the most important factor in limiting losses and ensuring the delivering of a quality product (Harvey, 1981). Higher than required optimal shipping temperatures lead to an increase in respiration rate of fruit and chilling or freezing injury can occur at sub-optimal temperatures, both leading to a deterioration in quality (Tanner and Amos, 2003a).

The dual temperature shipping regime, similar to intermittent warming, was developed in South Africa and has been proven to limit the occurrence of chilling related internal disorders like internal browning in Japanese plums (*Prunus salicina*). The dual temperature shipping regime consists of an initial period at -0.5°C, a variable intermittent warming period at 7.5°C, followed by -0.5°C for the remainder of the voyage period (Punt and Huysamer, 2005). Numerous dual temperature regimes exist and the cultivar and maturity of the fruit determine which dual shipping regime is chosen. Chilling injury in stone fruit occurs at temperatures between 2.2°C and 7.6°C, according to Crisosto *et al*. (1999). This range in temperatures is often referred to as the ‘killing zone’ and leads to severe internal defects like gel breakdown. Fruit exposed to such temperatures for prolonged periods should, therefore, be at the highest risk to develop chilling injury associated internal defects. Punt and Huysamer (2005), however, found no internal defects in fruit shipped at dual temperature.

Kiwifruit quality (fruit firmness) was measured prior to and after shipment (at a set point temperature of -0.5°C) in a 40’ container by Tanner and Amos (2003b). A more variable fruit firmness distribution was recorded after shipping, and ascribed to the differential rate of change in firmness with position in the container. Exposure to variable temperature regimes at different positions, therefore, resulted in variable fruit firmness levels. Pallet position, temperature and loss of firmness were linked through an accumulated degree-day model and a fruit firmness contour plot could, therefore, be drawn to predict fruit firmness throughout the container. The softest fruit were found in the warmest areas in the container, namely at the door end of the container, on the right hand side of the container and in the top layers of the pallets.

Scrine (1982b) performed trials on meat shipped in porthole and integral containers and found significantly more weight loss in carcasses stowed near the periphery of the container than in those within the bulk. The difference was also significant in relation to distance from the air inlet. It was concluded that the container heat leakage was a significant factor in increasing the temperature and reducing the relative humidity.

1.6.2. Fresh air ventilation

Exclusion of ethylene from the transit environment may lengthen the life of the product and prevent certain physiological disorders. Ethylene levels can be controlled in a container environment by ensuring that produce with a very high ethylene production rate is not shipped together with a commodity producing less ethylene, by making use of ethylene scrubbers such as potassium permanganate to remove ethylene from the container atmosphere and by using air-exchange systems to prevent the accumulation of ethylene and CO_2 within the container (Harvey, 1981).

According to the guidelines of the PPECB of South Africa, plums shipped at dual temperature in integral containers should be ventilated at 15m^3 per hour (PPECB, 2006a). This regulation was implemented due to the subsequent increase in the production of ethylene upon the onset of the intermittent warming period and the rise in respiration levels it causes.

1.6.3. Humidity

Packaging material of most standard plum shipments is not moisture-retentive and it is, therefore, important that the shipping container must be able to maintain an adequate level of relative humidity as prescribed.

Punt and Huysamer (2005) showed in studies performed on dual temperature shipment of plums in 40’ integral containers that a change in DAT causes a dramatic fluctuation in relative humidity and that the required humidity levels are seldom achieved. According to Mitchell (1986b), slow cooling of fruit exaggerates water loss due to the large vapour pressure deficit continuing for prolonged periods. An increase in temperature leads to an increase in the capacity of the air to hold moisture in the vapour phase and, therefore, leads to a drop in relative humidity if the specific humidity does not substantially increase (Scrine, 1982b). According to Kader (2002) the relative humidity should be at least 85% to 95% for fruits. Punt (2002), however, found relative humidity levels of 72% to 92%. The increase in DAT to 7.5°C resulted in a sudden drop in relative humidity which took three days to stabilize. The lowest relative humidity levels were found at the door end of the 40’ container.

The refrigeration unit must be designed to maintain high relative humidity levels. The evaporator coils for systems not designed for horticultural produce operate at a temperature of about 6°C lower than the desired air temperature. This results in an excessive amount of moisture condensing on the coils, leading to an decrease in relative humidity levels to as low as 70% to 80%. Coils with a large surface area and refrigeration controls that maintain the highest possible coil temperature, achieve the same refrigeration capacity as smaller coils but can operate at a higher temperature. The amount of moisture removed from the air is, therefore, reduced. The refrigeration coils should be large enough to operate at 3°C colder than the room temperature to limit moisture loss (Thompson, 2002). Kader (2002), however, stated that relative humidity can be controlled through maintaining the refrigeration coils within approximately 1°C of the air temperature.

2. Stone fruit quality

2.1. Stone fruit post harvest

Optimum conditions (temperature, relative humidity, CO_2, O_2 and ethylene levels) are imperative for the maintenance of fruit quality.

2.1.1. The influence of temperature on fruit ripening and fruit quality

Temperature is the single most important factor influencing the deterioration rate of fruit commodities (Kader, 2002). Quality deteriorates at high temperatures due to increased respiration and ethylene production, and there is a risk of freezing or chilling injury at sub-optimal temperatures. According to Thompson (2002) the temperature in a storage facility should be kept within 1°C of the optimum storage temperature.

The effect of temperature on deterioration rate is indicated by the Q_{10} value. For every increase of 10°C above the optimum temperature, the rate of deterioration increases by two- to three-fold (Kader, 2002).

$$Q_{10} = \frac{\text{Rate of deterioration at temperature } (T + 10°C)}{\text{Rate of deterioration at } T}$$

Temperature fluctuations influence the respiration rate. Respiration is a catabolic process associated with ripening and senescence where carbohydrates, proteins and fats are oxidized (O_2 is used in the process) to produce simple end products, energy, carbon dioxide, water vapour and vital heat (Kader, 2002). An increased respiration rate, therefore, also results in a decrease in O_2 levels and an increase in CO_2 levels within a specific environment, resulting in an acceleration of the deterioration rate (Kader, 2002).

The ethylene production rate increases with an increase in temperature (Kader, 2002). Auto-inhibition of ethylene production is seen in immature climacteric fruit and non-climacteric fruit exposed to exogenous ethylene. In contrast, ethylene is auto-stimulatory in mature climacteric fruit exposed to exogenous ethylene (Lelièvre *et al*., 1997). An increase in temperature, therefore, results in an increase in ethylene production, with the increased ethylene levels being auto-stimulatory to mature climacteric fruit.

2.1.2. The role of ethylene in fruit ripening

Ethylene (C_2H_4) is a natural product of plant metabolism and regulates many aspects of growth, development, senescence and plant organ abscission (Kader, 2002). The amino acid methionine is converted to S-adenosylmethionine (SAM), which is the precursor of 1-aminocyclopropane-1-carboxylic acid (ACC), being the immediate precursor of ethylene (C_2H_4). Two important enzymes are responsible for the conversions, namely ACC synthase, converting SAM into ACC, and ACC oxidase, converting ACC into ethylene (Lelièvre *et al*., 1997). Both these enzymes are influence by genetic factors and environmental conditions (Kader, 2002).

Fruit are divided into two broad groups, namely climacteric and non-climacteric types, depending on whether or not a peak in respiration and ethylene production during ripening is observed. A large increase in respiration and ethylene production rates is associated with climacteric fruit after harvest (Holcroft *et al.*, 2002). Climacteric fruit are, therefore, consequently harvested when mature, but not ripe, and have the ability to ripen after harvest. The respiratory peak is ascribed to the increase in endogenous ethylene but can, however; also occur before or after the ethylene peak (Lelièvre *et al*., 1997). The sharp increase in climacteric ethylene production is considered to control the initiation of changes in aroma, colour, flavour, texture and other biochemical and physiological processes (Lelièvre *et al*., 1997). In contrast, the ripening of non-climacteric fruit is considered to be an ethylene-independent process where the triggering and regulation of the ripening process as a whole do not require ethylene (Lelièvre *et al*., 1997). No increase in respiration and ethylene production is observed after harvest (Holcroft *et al*., 2002). Little is known about the regulatory mechanisms regarding biochemical changes during ripening of non-climacteric fruit. Endogenous ethylene is, however, implicated in some aspects of ripening of non-climacteric fruit at a certain stage of fruit development (Lelièvre *et al*., 1997).

Climacteric fruit can further be divided into climacteric and suppressed climacteric types (Holcroft *et al*., 2002). This classification is primarily based on ethylene production, where suppressed climacteric cultivars show considerably less and delayed ethylene production after harvest. ‘Pioneer’ and ‘Sapphire’ plum cultivars were classified as climacteric cultivars, and ‘Songold’ and ‘Angeleno’ as suppressed climacteric cultivars, due to considerably higher ethylene production rates observed in the former (Kruger, 2002). Kruger (2002) also measured higher respiration rates on climacteric plums, compared to suppressed climacteric plums, with the difference being even greater at higher temperatures. Heat generated by climacteric fruit (vital heat), as opposed to suppressed climacteric fruit, will be greater due to higher respiration rates and fruit ripening more rapidly (Holcroft *et al*, 2002). The chance of temperatures rising rapidly during shipment is, therefore, much greater in the case of climacteric fruit.

Storage at low temperature was a prerequisite for ‘Songold’ plums to soften at 15°C (Kruger, 2002; Taylor *et al*., 1993a), through inducing an increase in ethylene production (Kruger, 2002). Suppressed climacteric plums, therefore, require low temperatures to develop a ‘competency to produce ethylene’ (Holcroft *et al*., 2002). Application of low levels of ethylene to ‘Angeleno’ plum has proven successful to ensure normal ripening (Holcroft *et al*., 2002).

2.1.3. The importance of humidity management

The relative humidity should be kept at 85% to 95% for fruit commodities in long term cold-storage (Kader, 2002). Levels below this range will result in unacceptable degrees of moisture loss (Thompson, 2002). At a given relative humidity, water loss will increase with an increase in temperature (Kader, 2002).

Fruit shrivel is the result of the cumulative effects of water loss and visual shrivel usually appears when water loss has reached 4% to 5% in stone fruits (Mitchell, 1986a). Mitchell (1986a) furthermore stated that plums lose water more slowly than other stone fruits. Water loss occurs when there is a lower vapour concentration outside the fruit than inside the fruit and the rate of water vapour movement is dependant on the difference in vapour pressure. The cuticle forms a major barrier to the movement of water and solutes and is a non-cellular, nonliving, lipoidal membrane (Storey and Price, 1999). Major differences in the crystalline form of the epicuticular wax on the bloom and non-bloom side of d’Agen plums were observed by Storey and Price (1999). The plum epicuticular wax consists of an underlying amorphous wax layer adjacent to the cuticle and is kept together with crystalline granules of wax protruding from the surface. It was found that the number and size of the granules were small and the underlying amorphous wax layer predominated on the non-bloom side of the fruit. It was concluded that the microclimate of the fruit (temperature, light and humidity) may modify the composition and crystalline structure of epicuticular waxes.

Water loss and, therefore, shrivel can be minimized through cooling fruit as soon as possible after harvest, storage at low temperatures between -0.5°C and 0°C and relative humidity of 95%, and adjusting the air velocity to the lowest level needed to maintain the cold-storage temperature (Mitchell, 1986b). According to Kader (2002) relative humidity can be controlled through regulating the air movement and ventilation, as well as through maintaining the refrigeration coils within approximately 1°C of the air temperature.

2.2. Stone fruit internal quality disorders

2.2.1. Chilling injury

Chilling injury (CI) is genetically influenced and triggered by a combination of storage temperature and storage period (Crisosto *et al*., 1999; Lurie *et al*., 2005), and is associated with a decrease in respiration and polygalacturonase activity (PG), as well as lower levels of water soluble pectins in peaches and nectarines (Lill, 1985) and increased membrane permeability (Murata, 1990; Wang, 1982). Chilling injury manifests in stone fruit as a lack of juiciness (mealiness or woolliness), flesh browning (internal browning), black pit cavity, flesh translucency (gel breakdown), red pigment accumulation (bleeding), failure to ripen and a loss of flavour after prolonged storage and ripening at room temperature (Crisosto *et al*., 1999). These symptoms develop mainly during ripening after cold-storage at 0°C to 1°C for approximately two weeks (Fernàndez-Trujillo *et al*., 1998b).

The development of CI symptoms (mealiness and flesh browning) in peach, nectarine and plum is delayed and the intensity of the flesh browning lower when the fruit is stored at 0°C than when stored at higher temperatures (Crisosto *et al.*, 1999; Luchsinger and Walsh, 1998; Mitchell, 1986b). Crisosto *et al*. (1999), Eksteen (1982) and Mitchell (1986b) stated that CI in stone fruit occurs at temperatures between 0°C and 10°C, with the most severe injury occurring between 2.2°C and 7.6°C (Lurie and Crisosto, 2005). This temperature range is often referred to as the ‘killing zone’.

Chilling increases membrane permeability, possibly due to physical phase transition of membranes from a flexible liquid-crystalline to a solid-gel structure at a critical temperature resulting in the development of membrane cracks (Wang, 1982). Murata (1990) stated in his review, that membrane permeability demonstrated an increased rate of solute leakage as a result of chilling stress. The loss of membrane integrity enhances the leakage of cell fluids and solutes out of the cells into the cell wall area where binding with pectins takes place, resulting in the occurrence of woolliness in peaches and nectarines (Furmanski *et al*., 1979; Von Mollendorff *et al*., 1992). Healthy cell membranes have the ability to regenerate if exposed to chilling temperatures for only short periods before actual injury occurs, resulting in a decrease of electrolyte leakage (Lyons *et al*., 1979; Taylor, 1993; Taylor *et al.*, 1993a). Prolonged exposure of 'Songold' plums to chilling temperatures, however, led to irreversible degeneration of membranes, and a loss of regulatory ability (Taylor, 1993; Taylor *et al.*, 1993a). Membrane permeability, of climacteric fruit especially, also shows an increasing trend during ripening and senescence (Murata, 1990).

Two enzymes, namely pectin methyl esterase (PE) and polygalacturonase (PG), play an important role in fruit softening due to the breakdown of pectin polysaccharides, resulting in an increase in soluble pectin polysaccharide (Wang *et al*., 2003). When peaches suffer from CI, the activity of PE, a prerequisite for optimal PG activity, is sustained and pectinate is accumulated (Artés *et al*., 1996). The activity of PG is, however, irreversibly inhibited during prolonged storage at low temperature and pectinate cannot be hydrolyzed. The accumulated pectinate can then bind to Ca^{2+} and produce a jell-like state (Wang *et al*., 2003). The calcium-pectate gel may then bind water and produce the apparent dryness associated with mealiness in peaches and nectarines (Dawson *et al*., 1995).

In work performed by Gigardi *et al*. (2005) it was found that conventional cold storage, 1-methycyclopropene (1-MCP), ethylene, intermittent warming and controlled atmosphere (CA) storage all modified the activities of pectin methyl esterase (PE), endo-polygalacturonase (endo-PG) and exo-polygalacturonase (exo-PG). Wooliness, a CI disorder in peaches and nectarines, was reduced through the induction of endo-PG and exo-PG activity and the repression of PE activity. The ethylene and intermittent warming treatments resulted in induced PG activity, but had no effect on PE activity. CA storage resulted in a decrease in activity of all three enzymes, and fruit firmness was better preserved and woolliness decreased. The cold-storage and 1-MCP treatments resulted in an inhibition of PG activity, but had little effect on PE activity. Immature stone fruit have a higher susceptibility to develop CI symptoms compared to mature fruit (Mitchell, 1986a; Eksteen, 1982; Fernandez-Trujillo *et al*., 1998b). Both Dong *et al*. (2001) and Zhou *et al*. (2001) have shown that a minimum level of ethylene is required to prevent woolliness in nectarines and peaches. According to Harvey (1981) certain fruits may be treated with ethylene prior to shipment to limit the occurrence of CI.

Wang *et al*. (2003) found a total loss of PG activity after a critical storage period and CI symptoms were irreversible. Chilling injury manifestation can be divided in two stages, the primary and secondary event. The primary event is initiated when the specific commodity is stored below the critical temperature, leading to metabolic dysfunction and internal damage in the cells (Hakim *et al*., 1997). The accumulative harmful effects are reversible when fruit is transferred to temperatures above the critical temperature for normal fruit ripening (Artés *et al*., 1996). The second event is a consequence of the primary event and leads to cell death and visible symptoms (Hakim *et al.*, 1997). According to Artés *et al*. (1996) changes in the metabolism of the pectin substances will be provoked during the second stage if storage at low temperature continues, resulting in the development of woolliness in peaches. Transfer of the fruit to higher temperatures at this stage will only exacerbate the injury.

2.2.2. Gel breakdown

Gel breakdown (GB) is the consequence of abnormal physiological processes (Taylor *et al*., 1993a) where plums with a normal external appearance develop a gelatinous breakdown of the inner mesocarp surrounding the stone, while the outer mesocarp still has a healthy appearance (Taylor, 1996). In severe cases the gelatinous breakdown spreads outwards, changing from a translucent to a brown discolouration, associated with a loss of juiciness.

The major physiological factors implicated in the development of GB, are the integrity of the cell membrane and the capacity of pectic substances in the cell wall to bind cell fluids (Taylor, 1996). As the permeability of the cell membrane increases, the cell fluids leak into the cell wall area where binding with the pectins occurs. Gel breakdown is, therefore, associated with a loss of juiciness and is restricted to the inner mesocarp surrounding the stone, possibly due to the ripening pattern within ‘Songold’ plums (Taylor *et al*., 1993b).

During ultra-structural studies performed on ’Songold’ plum by Taylor (1993), it became apparent that GB was associated with empty spaces in the cell walls, thickening of the cell walls and misshapen cells. This suggested that, similar to woolliness in nectarines, the disorder was caused by the formation of gel complexes in intercellular spaces.

Higher levels of GB were found during cold-storage in more mature ‘Songold’ plums due to earlier loss of membrane integrity (Taylor *et al*., 1994b). The decline in the occurrence of over ripeness in ‘Songold’ plums upon prolonged low temperature storage and subsequent ripening was substituted with an increase in GB and internal browning (Taylor *et al*., 1993a). Gel breakdown was already evident in fruit harvested at an advanced maturity (Taylor *et al*., 1994a), indicating that gel breakdown cannot be classified as a true cold-storage chilling disorder (Taylor, 1996). The development of GB is, therefore, probably associated with physiological changes during ripening and senescence and occurs in over-mature fruit and also more-mature fruit harvested at the upper end of the optimum picking window.

Measurement of electrolyte leakage enables the evaluation of membrane permeability (Lurie *et al*., 1987). An increase in total percentage electrolytes measured, was contributed to increased membrane permeability and fruit ripening and a significant decline observed in the last days of storage due to the bonding of electrolytes with pectins (Taylor *et al*., 1993b).

Gel breakdown develops more rapidly in ‘Songold’ plums stored at dual temperature compared to -0.5°C single temperature stored fruit. The gel breakdown levels were, however, significantly higher in the single temperature stored fruit compared to the dual temperature stored fruit during ripening at 10°C (Taylor *et al*., 1994a). More than 60% GB was found in plums stored at both regimes, indicating that neither could be used effectively to prevent the disorder (Taylor, 1996).

2.2.3. Internal browning

Internal browning (IBR) is classified as a CI disorder (Crisosto *et al*., 1999; Lurie *et al*., 2005), where plums with a normal external appearance, develop a brown discolouration of the mesocarp tissue, changing from light to dark brown with increased severity, and is associated with a loss of juiciness (Taylor, 1996).

Internal browning may be related to tissue deterioration or senescence (Lurie *et al*., 2005), leading to rupturing of cell membranes and an increase in membrane permeability (Taylor *et al*., 1993a). Browning of the mesocarp occurs due to the oxidation of phenolic compounds, catalysed by the enzyme polyphenol oxidase, when the previously compartmentalized enzyme has unrestricted access to the phenols (Taylor *et al*., 1993a). More recent research has shown that browning of the mesocarp occurs in immature fruit, probably due to higher polyphenol concentrations (Taylor, 1996).

2.2.4. Over ripeness

Over ripeness is a natural process occurring due to fruit ripening and senescence and can be defined as a disorder where the plums are abnormally soft with an excessive amount of free juice. In severe cases the mesocarp tissue becomes translucent below the sub-epidermal region, while the inner mesocarp tissue remains normal in appearance. Over ripeness can furthermore be identified by cutting the fruit in half along the equatorial axis, where twisting the two halves will result in the skin and sub-epidermal layers of the mesocarp separating from the inner mesocarp, which remains attached to the stone (Taylor, 1996).

2.3. Managing fruit quality

2.3.1. Intermittent warming

Intermittent warming (IW) involves cold-storage of fruit and a set number of interruptions of the chilling exposure, by placing the fruit at a higher temperature (20°C to 24°C), for a set amount of time (Lurie *et al*., 2005).

IW has been shown to alleviate and/or delay chilling injury during cold-storage on a number of fruit commodities, namely cucumber (Cabrera and Saltveit, 1990), tomato (Hakim *et al*., 1997; Artés *et al.*, 1998), grapefruit (Hatton and Cubbedge, 1980), pomegranate (Artés *et al*., 2000), zucchini squash (Kramer and Wang, 1989) and peaches and nectarines (Anderson, 1979; Artés *et al*., 1996; Dawson *et al*., 1995; Gigardi *et al*., 2005; Fernàndex-Tujillo and Artés, 1997 and 1998; Lill, 1985; Wang *et al*., 2003). IW has also been proven to be successful on cranberries, lemons, okra, potatoes and sweet peppers (Wang, 1991). In studies performed on peaches by Fernàndez-Trujillo and Artés (1998a), IW proved to result in a reduction in symptoms of chilling injury (woolliness, gel breakdown and scald) by promoting a gradual increase in nectarine fruit ripening during the critical period of CI development and, therefore, an acclimatization to subsequent periods of chilling (Fernàndez-Trujillo and Artés, 1997). Anderson (1979) found similar results and also noted a trend in IW maintaining acidity levels. Lill (1985) found that IW was effective on peaches at temperatures as low as 12°C, but that the length of the warming period has to be longer compared to when the temperature was 20°C. Too frequent IW resulted in induced softness and rot in peaches and too infrequent (every 21 days) IW resulted in irreversible chilling injury (Wang *et al*., 2003).

Both Artés *et al*. (1996) and Wang *et al.* (2003) showed that IW effectively increased the activity of PG (polygalacturonase), resulting in a decrease in activity of PE (pectin methyl esterase) and effectively stopping the chilling injury. The warming period may have effectively sustained the normal physiological function of the fruit’s enzymatic system and thereby maintained good fruit quality.

According to Dawson *et al*. (1995) mealiness (chilling disorder) in nectarines is a physiological disorder involving the cell walls and that IW resulted in significant softening during storage, alleviating the development of mealiness by the promotion of cell wall changes associated with normal ripening.

2.3.2. Dual temperature storage

The dual temperature storage regime is based on the principles of intermittent warming previously discussed, to alleviate CI related defects found in plums.

Browning of the mesocarp, referred to as internal breakdown by Dodd (1984), seriously affected the quality of ‘Songold’ plums. Hartmann *et al*. (1988) showed that the disorder could be prevented by harvesting at the correct maturity and shipping the fruit at a dual temperature storage regime (Boyes and De Villiers, 1949). The dual temperature storage regime was commercially applied since 1988 (Taylor, 1993). Gel breakdown, however, became evident after the IBR was no longer present and over ripeness also presented quality problems (Gant, 1992). Gel breakdown was already evident in fruit harvested at an advanced maturity (Taylor *et al*., 1994a), indicating that GB cannot be classified as a true cold-storage chilling disorder (Taylor, 1996).

3. Summary

The shipment of deciduous fruit in refrigerated reefer containers has proven to be advantageous, resulting in a significant growth in containerized shipment since deregulation of the South African Fruit Industry in 1997. The refrigerated 40’ integral reefer container was, however, designed to maintain temperature and not to pre-cool or re-cool the cargo, and does it, therefore, necessitate very good pre-cooling protocols.

The achievement of a stable and uniform temperature profile throughout the whole container is influenced by a number of factors. It has been proven that poor pre-cooling protocols, outside atmospheric conditions, a spatial variation in DAT, insufficient removal of heat produced and introduced into the container environment, and an inefficient air flow and -distribution towards the door end of the container result in a temperature gradient throughout the container. It is, therefore, important to understand what a reasonable temperature distribution is. Ideally, the cold air should be distributed in such a way that the quantity of air flowing in each section should be proportional to the amount of heat to be removed to attain temperature uniformity.

Optimal shipping conditions are imperative for the maintenance of fruit quality. Temperature is the single most important factor influencing the deterioration rate of fruit commodities. The auto-stimulatory nature of ethylene in climacteric fruit necessitates the maintenance of optimal atmospheric conditions and temperature. Relative humidity should be maintained at levels between 85% and 95% to limit the occurrence of defects like shrivel and decay.

Stone fruit is susceptible to CI, being genetically influenced and triggered by a combination of storage temperature and storage time. The harmful effect of CI is reversible when fruit is transferred to temperatures above the critical temperature for normal fruit ripening. Prolonged storage at temperatures below the critical temperature leads to irreversible injury. Intermittent warming has been shown to alleviate and/or delay CI during cold-storage on a number of fruit commodities and was the dual temperature storage regime developed for plums based on the principles of IW to alleviate the CI related defects found in plums.

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Identification of temperature zones within integral reefer containers shipping Japanese plums (*Prunus salicina Lindl.*) at dual temperature and the effect of such zones on fruit quality

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Abstract

'Sapphire', 'Fortune' and 'Laetitia' (*Prunus salicina* Lindl.) plums were harvested at an optimum maturity. Only A-size (50-55 mm) and AA-size (55-60 mm) fruit were used and colour sorting was performed only on the 'Sapphire' fruit. A digital temperature logger, namely the 'Thermocron® iButton®' with a temperature range of -5°C to +26°C, was used to log the air- and pulp temperature data at three different heights within the fruit pallet, in all 20 pallets shipped within each integral container. The trials were packed, loaded and shipped at a PD5 dual temperature regime (2 days at -0.5°C, followed by 5 days at 7.5°C and the remainder of the voyage at -0.5°C) from Cape Town, South Africa to Antwerp, Belgium. Average fruit firmness and total soluble solids were measured prior to shipment and average fruit firmness, on the day of arrival, and the occurrence of internal defects, after a shelf life period of seven days, were evaluated post-shipment. Three processes were identified as important characteristics of pulp temperature data sets recorded during commercial dual temperature storage, namely the cooling down process, the heating up process and the role of over heating in the container. The order of importance differed according to the plum cultivar shipped and the container's performance. Three temperature zones were identified in integral containers shipping plums at dual temperature, where the average pulp temperature, time to heat up and time to cool down for each temperature zone increased along the length, across the width from the left to the right and up the container system. The variable temperature conditions were possibly due to a variation in delivery air temperature, poor airflow and the effect of increased respiration and, therefore, production of vital heat by the respective plum cultivars. The cooling down process was identified as the most important process discriminating the temperature zones. Fruit size had a significant influence on average fruit firmness and total soluble solids prior to shipment. Variable temperature conditions found within the ‘Sapphire’ and ‘Laetitia’ containers had a significant influence on the fruit firmness post-shipment, where deterioration levels increased from the front to the door end of the container due to an increase in pulp temperature. However, it was also shown that fruit firmness prior to shipment could have a determining effect on differences found. Temperature variances found within the ‘Fortune’ container had no significant influence on the fruit firmness post-shipment, confirming that ‘Fortune’ could possibly be classified as a true suppressed climacteric plum cultivar. It could not be proven that variable temperature conditions resulted in significantly higher levels of internal defects within the integral container.

Keywords: Integral reefer container; dual temperature; temperature variance; temperature zones; multivariate analysis; *Prunus salicina;* plum quality

1. Introduction

The South African fruit export industry has to overcome two major obstacles, namely the distance to the overseas markets and the time it takes to complete such voyages. Both challenges require the development of technology to ensure that the horticultural products arrive in a good condition. Since the deregulation of the South African fruit export industry in 1997, containerized fruit exports grew substantially from 28.7 million metric tons by an annual average of 2.2 million metric tons (Anonymous, 2003). Containerized shipment presents appealing advantages that contributed to the growth. Containers minimize the risk of the product being damaged, since it is handled fewer times, the risk of theft and food contamination is reduced, traceability is simplified and fruit with unique temperature requirements can be accommodated in a containerized environment.

Between seven and eight million cartons of plums are exported annually from South Africa (Anonymous, 2006). Browning of the mesocarp, referred to as internal breakdown by Dodd (1984), seriously affects the quality of plums exported from South Africa. Stone fruit is susceptible to chilling injury (CI), being genetically influenced and triggered by a combination of storage temperature and storage time (Crisosto *et al*., 1999; Lurie and Crisosto, 2005). The harmful effect of chilling temperatures is reversible when fruit is transferred to temperatures above the critical minimum threshold in time (Artés et al., 1996). However, prolonged storage at temperatures below the critical temperature leads to irreversible injury (Hakim *et al*, 1997). Intermittent warming (IW) has been shown to alleviate and/or delay CI during cold storage on a number of fruit commodities and a dual temperature storage regime was developed in South Africa for plums based on the principles of IW to alleviate the CI related defects (Hartmann *et al*., 1988; Taylor, 1993). The dual temperature shipping regime consists of an initial period at -0.5°C, a variable intermittent warming period at 7.5°C, followed by -0.5°C for the remainder of the voyage (PPECB, 2006a; Punt and Huysamer, 2005). Numerous dual temperature regimes exist and the cultivar and maturity of the fruit determine which regime is chosen (PPECB, 2006a).

Integral reefer containers (forty foot equivalent unit or FEU) were designed to operate independently and only maintain fruit temperature. The integral container was, therefore, designed in such a way to reduce power consumption and the refrigeration unit to occupy as little space as possible, hence the limited capacity to refrigerate. Irving (1988) furthermore stated that the air-flow system of an integral container was not designed to allow efficient cooling, which further accentuated the fact that the integral container should not be regarded as a cooling device. Taking into consideration that dual temperature shipment requires refrigeration and effective distribution of cool air to remove the sensible- and respiratory heat throughout the container, the capacity of integral containers to ship plums successfully at dual temperature is questioned.

Fruit pulp temperature in a container is dependant on the delivery air temperature, the localised airflow past the specific fruit pallet, the heat produced by the product due to respiration and the packaging material's thermal characteristics (Billing *et al*., 1993; Billing *et al*., 1995). Fruit temperature is always higher than the surrounding air temperature and it has been found that average fruit temperature generally increases across the width of the container, along the length of the container and up the height of the container system in single temperature and dual temperature shipments (Punt and Huysamer, 2005; Tanner and Amos, 2003a).

Numerous factors have been identified as influencing the temperature variance found within an integral container, namely pre-loading fruit handling procedures, variation in delivery air temperature, the heat of respiration, heat leakage into the container, poor airflow distribution in the container or insufficient air-flow rate.

Proper pre-cooling of cargo to the required carriage temperature (<1°C for stone fruit) is crucial before loading of a container takes place (PPECB, 2006b). Air ventilation, the rate of ventilation and outside atmospheric conditions can result in a variation in delivery air temperature across the width of the container contributing to the development of temperature variances within the container (Amos and Sharp, 1999; Tanner and Amos, 2003a).

Plum fruit is classified as climacteric fruit, showing a peak in respiration and ethylene production during ripening, releasing vital heat to the storage environment (Holcroft *et al*, 2002). Kruger (2002) measured higher respiration rates in climacteric plums, compared to suppressed climacteric plums, which suggests that the vital heat produced by climacteric plums will also be greater. The chance of temperatures rising rapidly during shipment is, therefore, much greater in the case of climacteric fruit.

Integral containers are placed either in a non-refrigerated cellular or vehicle hold or on the deck of the vessel where the ambient temperatures can reach 30°C to 40°C. The high ambient temperature environment greatly increases the amount of heat leakage (Irving, 1988). The large distance from the fan at the front of the container to the door end of the container, results in lower airflow at the door end of the container due to short circuiting of air along the length of the container (Tanner and Amos, 2003a). A lower volume of cold air is, therefore, delivered to the door end of the container resulting in higher average air temperatures. For this reason, the PPECB (Perishable Products Export Control Board) of South Africa has increased the required rate of air circulation in a container to 60 changes per hour when carrying fruit, compared to the standard minimum requirement of 30 to 40 changes per hour of the empty volume of the container when carried in an insulated hold (Scrine, 1982).

The objectives of this study were, firstly, to generate and analyse pulp temperature data and possibly identify different temperature zones within integral containers shipping plums at dual temperature, where a number of positions within a specific zone experience similar temperature conditions. Secondly, to understand the underlying processes that differentiate the temperature zones and thirdly, to determine the effect of the container's performance and, therefore, the existence of temperature zones on fruit quality.

2. Materials and methods

2.1. Plant material

'Sapphire', 'Fortune' and 'Laetitia' (*Prunus salicina Lindl.*) were sourced from a commercial stone fruit farm in the Wellington, Western Cape region in South Africa. Trial fruit were harvested and packed during the second (peak) commercial harvesting week in the case of each cultivar. Only A-size (50-55 mm) and AA-size (55-60 mm) plums were used in the trials.

The harvested plums were hydro-cooled for approximately twenty minutes with the water temperature set at 3°C to enable cooling of the fruit pulp temperature to approximately 15°C, whereupon the bins were moved to a holding room with a set-point temperature of 15°C.

Packing took place in a temperature controlled pack house with the air temperature set at 20°C within the packing area and 15°C within the palletization area. The wrapping of the pallets (packed fruit units) with perforated plastic wrapping, instead of using straps and corner pieces, is commercially preferred and widely used to stabilize the pallet. All pallets used for trial purposes were, therefore, also wrapped. After packing and palletization, the fruit pallets were forced-air cooled for 8 hours or until the fruit pulp temperature in the centre of the pallet reached -0.5°C, whereupon the pallets were moved to the holding room with a set-point temperature of -0.5°C. The pallets were cold stored in the holding room until loading of the respective integral containers took place.

'Sapphire' plum

'Sapphire' plums were harvested at an optimum maturity and packed according to export standards on 9 December 2004 (week 50). The average maturity at harvest of the A-size and AA-size plums for both 'Sapphire' container trials was 8.1 kg and 7.6 kg fruit firmness (all firmness measurements (kg) were obtained using an 11.2 mm penetrometer) and 12.9°Brix and 13.2°Brix total soluble solids (TSS), respectively (Table 1). Colour sorting was performed on the 'Sapphire' plums in categories 'red' or 'green', to limit the occurrence of mixed fruit colour within a carton and pallet. The average fruit firmness of the 'green' fruit in both 'Sapphire' container trials was 7.7 kg and of the 'red' fruit 7.9 kg, and the average TSS for the 'green' fruit was 12.6°Brix and 13.2°Brix for the 'red' fruit (Table 1).

'Fortune' plum

'Fortune' plums were harvested at an optimum maturity and packed according to export standards on 4 January 2005 (week 1). The average maturity at harvest of the A-size and AA-size plums was 7.9 kg and 7.3 kg fruit firmness and 13.3°Brix and 13.8°Brix TSS, respectively (Table 1). No colour sorting was performed on 'Fortune' plums since the red colour was fully developed at harvest.

‘Laetitia’ plum

‘Laetitia’ plums were harvested at optimum maturity and packed according to export standards on 17 January 2005 (week 3). The average maturity at harvest of the A-size and AA-size plums was 7.5 kg and 7.8 kg fruit firmness and 13.3°Brix and 13.0°Brix TSS, respectively (Table 1). No colour sorting was performed on ‘Laetitia’ plums since the red colour was fully developed at harvest.

2.2. Treatments

Randomized packing and palletizing

The plums were sorted onto packing tables according to fruit size with an AWETA high speed (four lane) packing machine, with a number of tables packing a specific fruit size simultaneously. The packers randomly selected fruit from the table in front of them and packed it into either the 104 mm X 300 mm X 400 mm double layer carton (for the A-size fruit) or the 76 mm X 400 mm X 600 mm single layer carton (for the AA-size fruit). Once a carton was filled, it was placed on the rotating track running through the packing area to the palletizing area located in a separate room. Several pallets, each containing a different packing type as determined by the fruit size, were constructed simultaneously by a team of palletizers. Several pallets of the same packing type were also constructed simultaneously depending on the volume of fruit coming through the pack house and the fruit size distribution. Each person would randomly select a carton from the rotating track and place it on any of the corresponding pallets being constructed. Ten pallets containing only A-size fruit and ten pallets containing only AA-size fruit were randomly constructed for each integral container.

Packing material

A-size plums were packed into a 104 mm X 300 mm X 400 mm double layer carton. The first layer of plums was packed onto a pulp tray, placed at the bottom of the carton, and covered with an interleaf paper sheet to absorb any excess moisture. Another pulp tray with a second layer of fruit was placed on top of the first layer. The top layer was protected from additional moisture loss, due to exposure to fast moving cold air, with a perforated plastic shrivel sheet (perforation holes 1cm in diameter) and a corrugated paper sheet on top. Each carton contained approximately 60 fruit. AA-size plums were packed into 76 mm X 400 mm X 600 mm single layer cartons. The plums were packed onto a plastic ‘Ilip’ tray containing holes at the bottom of the fruit cups. The fruit was protected from additional moisture loss with a perforated plastic shrivel sheet (perforation holes 1cm in diameter). Each carton contained approximately 52 fruit.

Temperature recording

A digital temperature logger, namely the 'Thermocron® iButton®' (DS1921Z-F5) (Dallas Semiconductor, iButton Product Group, Dallas, Texas) with a temperature range of -5°C to +26°C, was used to log temperature data. The iButton® is a computer chip enclosed in a 16 mm diameter stainless-steel, waterproof case which enabled the measurement of both pulp- and the air temperatures.

The iButtons® were placed in 60 positions throughout each integral container. Air- and pulp temperatures were measured on three layers within each of the 20 pallets shipped within each integral container. The iButtons® were placed on the 4th, 10th and 16th layer of a pallet containing A-size plums (104 mm X 300 mm X 400 mm cartons) and on the 4th, 12th and 22nd layer of a pallet containing AA-size plums (76 mm X 400 mm X 600 mm; Figure 1). Hence, air- and pulp temperatures were measured at a similar height in the bottom-, middle- and top section of each of the twenty pallets. Temperature was logged throughout the palletizing process, forced-air cooling, cold storage, loading of the containers, dual temperature shipment, transport to the inspection point, and until the doors of the containers were opened for unloading and logger retrieval.

Only one air temperature logger was placed in the centre of each assigned pallet layer by taping the logger to the fruit tray in the carton (Figures 2 and 3). The logger was always placed in the upper fruit layer, in between the fruit and slightly off centre towards the top right hand corner of the carton so that the logger was placed in the centre of the specific pallet layer. The pulp temperature of three fruit per layer was measured by pushing the iButton® into a slit in the fruit made with a knife and taping closed the opening. The pulp temperature loggers were placed in one fruit in the centre of the pallet layer, next to the air temperature logger and in two fruit on the opposite outside perimeters of the pallet layer (Figures 2 and 3).

Loading plan

Each reefer container can transport 20 pallets with dimensions 1 m X 1.2 m. Eleven pallets were loaded on the left hand side of the container by loading the pallets along the 1.0 m-width of the pallet and nine pallets were loaded on the right hand side of the container by loading the pallets along the 1.2 m-length of the pallet. The container was loaded in such a pattern and void plugs were used at the door end of the container to prevent the formation of 'chimneys' or open areas on the container floor through which air can short circuit and cause poor airflow within the container (De Castro *et al*., 2005; Irving, 1988). Ten pallets containing A-size fruit and ten pallets containing AA-size fruit were assigned to positions within the container in such a manner that the effect of the carton dimensions and characteristics would not influence the airflow pattern within the container; i.e., the A/AA pallets were evenly distributed (Figure 4A). This loading plan was consistent for all containers loaded. Two identical containers were loaded in the 'Sapphire' trial and only one container each in the case of the 'Fortune' and 'Laetitia' trials. Colour sorting was performed during the packing of the 'Sapphire' trial. The 'red' and 'green' pallets were randomly positioned through pallet positions one to 20. The positioning of the A-size and AA-size pallets was, however, consistent with the loading plans of all the other cultivars (Figures 4A and 4B).

'Sapphire' logistics

The 'Sapphire' trial was packed on 9 December 2004 (week 50). After packing, inspection of the fruit by PPECB (Perishable Products Export Control Board) and palletization, the pallets were forced-air cooled and moved to a holding room with a set-point temperature of -0.5°C. The fruit was cold-stored for one day until the morning of 11 December 2004, whereupon the pallets were loaded into the two integral containers, according to the pre-determined loading plan (Figure 4B), once the core pulp temperature for each pallet had been verified to be less than 1°C as specified by the PPECB (PECB, 2006b). Two similar integral containers, namely 'Sapphire' container number 1, with serial number MWCU6724349, and 'Sapphire' container number 2, with serial number MWCU6716699, were loaded and transported without generator power to the terminal in Cape Town, South Africa and plugged into plug points for refrigeration to continue over the next five days. The 'Safmarine Mgeni' (voyage A683) vessel departed on 16 December 2004 and arrived in Antwerp as port of delivery after 21 days on 5 January 2005. The estimated time of arrival had been 2 January 2005, but the vessel was delayed by three days. Both containers were shipped at a PD5 dual temperature shipment regime. The set-point temperature of the container was, therefore, adjusted after two days on the 19th of December 2004 from -0.5°C to 7.5°C, and again adjusted after five days on the 24th of December 2004 to -0.5°C for the remainder of the voyage (PPECB, 2006a).

'Fortune' logistics

The 'Fortune' trial was packed on 3 January 2005 (week 1). After packing, inspection of the fruit by PPECB and palletization, the pallets were forced-air cooled and moved to a holding room with a set-point temperature of -0.5°C. The fruit was cold-stored for five days until the morning of 9 January 2005, whereupon the pallets were loaded into the integral container, according to the pre-determined loading plan (Figure 4A), once the core pulp temperature for each pallet had been verified to be less than 1°C as specified by the

PPECB (PPECB, 2006b). The ‘Fortune’ container, with serial number MWCU6736993, was loaded and transported without generator power to the terminal in Cape Town, South Africa and plugged into a plug point for refrigeration to continue over the next three days. The ‘City of Cape Town’ (voyage A684) vessel departed on 12 January 2005 and arrived in Antwerp as port of delivery after 19 days on 30 January 2005. The estimated time of arrival had been 28 January 2005, but the vessel was delayed by two days. The integral container was shipped at a PD5 dual temperature shipment regime. The set-point temperature of the integral container was, therefore, adjusted after two days on the 14th of January 2005 from -0.5°C to 7.5°C, and again adjusted after five days on the 19th of January 2005 to -0.5°C for the remainder of the voyage (PPECB, 2006a).

‘Laetitia’ logistics

The ‘Laetitia’ trial was packed on 17 January 2005 (week 3). After packing, inspection of the fruit by PPECB and palletization, the pallets were forced-air cooled and moved to a holding room with a set-point temperature of -0.5°C. The fruit was cold-stored for three days until the morning of 21 January 2005, whereupon the pallets were loaded into the container, according to the pre-determined loading plan (Figure 4A), once the core pulp temperature for each pallet had been verified to be less than 1°C as specified by the PPECB (PPECB, 2006b). The ‘Laetitia’ container, with serial number MWCU6724138, was loaded and transported without generator power to the terminal in Cape Town, South Africa and plugged into a plug point for refrigeration to continue over the next six days. The ‘Safmarine Agulhas’ (voyage A693) vessel departed seven days late on the 27th of January 2005 and arrived in Antwerp as port of delivery after 18 days on 13 February 2005. The actual time of arrival was, therefore, also seven days late. The integral container was booked at a PD5 dual temperature shipment regime. However, the set-point temperature of the container was adjusted from -0.5°C to 7.5°C only after five days, instead of after two days, on the 1st of February 2005 and again adjusted after five days from 7.5°C to -0.5°C on the 6th of February 2005 for the remainder of the voyage (PPECB, 2006a).

2.3. Analyses

Fruit quality variables and pulp- and air temperature were evaluated. The fruit quality variables were evaluated prior to shipment on the day of harvest, and after the commercial shipping period had been completed. The occurrence of internal defects was evaluated after shelf life, seven days after the consignment arrived in the destination market, except in the case of the ‘Fortune’ trial. Pulp- and air temperature were measured from packing until the integral containers arrived in the destination markets and were unloaded.

Pre-shipment analysis

One carton was randomly selected from every pallet shipped in each trial. The fruit firmness and TSS were measured for 52 fruit in each sampled carton. Fruit firmness was measured with an electronic penetrometer fitted with an 11.2 mm tip (FTA - Fruit Texture Analyser) on both cheeks of each of the 52 fruit measured prior to shipment. Total soluble solids was determined by extracted juice from each fruit by cutting off one randomly chosen cheek and squeezing the juice out onto the calibrated, digital refractometer (Atago, PAL-1). The presence of internal defects was evaluated pre-shipment.

Post-shipment analysis

Upon arrival of the integral containers at the point of inspection, the pallets were unloaded and broken down layer by layer to retrieve the 'iButtons®' and perform the sampling procedure for the post-shipment quality analysis. Eight fruit were randomly sampled from each of the three cartons containing the 'iButtons®', in each of the assigned pallet layers. Twenty-four fruit were, therefore, sampled per layer and pooled for post-shipment- and shelf life quality analysis. Twelve of the 24 fruit were selected for shelf life analysis and the fruit firmness was evaluated on the remaining 12 sampled. A hand-held penetrometer was used for post–shipment measurement of fruit firmness, due to the lack of available equipment at the inspection site. TSS was not evaluated after shipment.

Shelf life analysis

The occurrence of internal defects was evaluated seven days after arrival in the destination market, except in the case of the 'Fortune' trial. Twelve of the 24 fruit sampled upon arrival were held under ambient conditions for seven days and the occurrence of internal defects, namely gel breakdown, internal browning, aerated flesh and over ripeness was evaluated. The occurrence of internal defects was expressed as a percentage of the total number of fruit evaluated, even though the defects were classified. The shelf life evaluation was performed by Marine Management Surveys Ltd.

Temperature recording

The 'Thermocron® iButton®' logged pulp- and air temperature data every 30 minutes from packing until arrival in the destination market.

2.4. Data analyses

Temperature data

Approximately 1700 temperature measurements were logged for each of the 60 positions within each integral container. Due to the magnitude of the data set, it was necessary to firstly compress and then simplify the data through using multivariate analysis (Johnson, 1998). Both variable directed techniques, where relationships among the response variables are explored (factor analysis), and individual-directed techniques, where relationships between the experimental units are analysed (cluster analysis and discriminant analysis), were used (Johnson, 1998).

Data analysis concentrated on the fruit pulp temperature data logged from loading to unloading of the container since it was important to ultimately understand the effect of the container's performance on fruit quality. A set of 40 variables was created from the pulp temperature data, where each variable described a number of hours within a certain temperature range for each of the 60 positions (Table 2). Each data set was, hereby, compressed to only 2400 values. According to Johnson (1998), the importance and usefulness of multivariate methods increase as the number of variables being measured and the number of experimental units evaluated increase, with the ultimate objective to simplify or summarize large amounts of data.

Fruit quality data

An analysis of variance and an analysis of covariance were performed on the quality variables to determine to what extent the different pulp temperature zones identified, influenced the occurrence of internal defects.

Data analysis

Data were analysed in seven steps using multivariate exploratory techniques (factor-, cluster- and discriminant analysis), the one-way analysis of variance procedure and the analysis of covariance procedure in the Statistica program (Statistica Release 7), as follows. Mean separation was conducted using the Bonferroni test at the 5% level.

Step one: Factor analysis

Factor analysis is a variable-directed analysis technique used to study potential relationships among the response variables measured (Johnson, 1998). The variables are partitioned into subsets containing highly correlated variables, with low correlations between variables in different subsets. It can, therefore, be assumed that when a relationship exists among the response variables, the variables are actually measuring a common underlying characteristic, factor or entity (Johnson, 1998; Cudeck, 2000). The goal of factor analysis is, therefore, to determine the number of fundamental influences (factors) underlying a domain of variables and to quantify the extent to which each variable is associated with the factor, in an effort to study the nature of each fundamental influence (Cudeck, 2000).

Forty variables were created to enable data analysis of the pulp temperature data through multivariate exploratory techniques. The created variables represented hours within a certain temperature range (Table 2). The temperature ranges created described either the different phases of dual temperature shipment or temperature ranges that might influence fruit quality. Since dual temperature storage is a dynamic temperature process, it was expected that there would be a number of fundamental influences determining the pulp temperature zoning of an integral container. The sensitivity of each variable to the overall temperature change process was determined by drawing frequency plots and understanding the course of the heating up and cooling down processes, and by comparing the duration of the respective temperature intervals for variables making up the heating up and cooling down phases, to the total number of hours measured at the specific temperature interval over the full storage period (data not presented). A number of variables were also created to evaluate over heating taking place in the container and variables were, therefore, also described in terms of their contribution to over heating, where applicable.

The factors were extracted through an orthogonal rotating technique, namely variance maximizing (varimax) rotating with the objective to maximize the variance of consecutive extracted factors, while minimizing the variance surrounding each newly created factor. The consecutive factors are independent of each other and uncorrelated since each consecutive factor is defined to maximize the variability not captured by the preceding factor (Cudeck, 2000). As consecutive factors are extracted, they account for less and less variability. The variance each factor extracts is represented by the eigenvalues.

According to Cudeck (2000) there is no definite answer as to how many factors need to be extracted. The model needs to account for data to an acceptable degree, where more factors describe the information better. On the other hand the solution needs to be interpretable, where fewer factors are often more easily interpretable. Two techniques can be used to identify how many factors should be extracted, namely the Kaiser criterion (1960) where only factors with eigenvalues greater than one are retained, or the Scree test of Catell (1966) where eigenvalues are plotted and the position where the decreasing eigenvalues seem to level off, is identified. The Scree test of Catell was used in our statistical analysis procedures to determine the number of factors to be extracted.

Once the number of factors to be extracted was determined, the correlation between the variables and the factors, namely the factor loadings, was examined. The factor loadings were varimax rotated to ensure that a 'simple structure' was evident, where certain loadings were higher than others for each variable-factor combination. It was, therefore, clear which variables defined the nature of each factor or fundamental influence.

A hierarchical joining tree diagram was created for each set of pulp temperature variables by using Ward's method as the amalgamation linkage rule and 1-Pearson *r* as the distance measure. Ward's method uses an analysis of variance approach to evaluate the distances between the groups (Ward, 1963) with the objective to unify groups in such a way that the variation inside the groups is limited, resulting in groups that are as homogenous as possible (Händle and Simar, 2003). This method is useful in verifying the results obtained through factor analysis.

Upon grouping the variables and verifying the results, it was clear that the grouped variables clearly defined certain pulp temperature phases. One variable was chosen per factor group that defined the identified pulp temperature phases the most accurately. These variables were used for the cluster analysis procedure where the 60 positions within each container were assigned into zones.

Step two: Cluster analysis (K-means clustering)

K-means clustering was used as an exploratory data analysis tool to enable the classification of similar experimental units, in this case the 60 positions within each integral container, into uniquely defined subgroups, clusters or pulp temperature zones (Johnson, 1998). The sorting of the units was done in such a way that the degree of association between the units within the same cluster group was maximised and between cluster groups, minimized. It is not known beforehand how many clusters there are in the data when performing K-means clustering. Normally useful structures are searched for in the data without an expectation of what might be found.

Pulp temperature phases playing an important role in determining the container's performance, were identified through the factor analysis procedure. Numerous variables representing the identified pulp temperature phases were chosen for each container and used as criteria to perform the cluster analysis procedure. Since the number of clusters in the data is not known prior to performing the cluster analysis, zoning structures were searched for in the data by specifying that an increasing number of clusters or zones had to be formed. It was clear when the clusters disintegrated and no longer represented meaningful zones in the container. Once the number of clusters to be specified was identified and the cluster analysis performed, the variable means for each cluster and the F-value for each variable were examined to assess how distinct the clusters were and how well the respective variables chosen discriminated between the clusters.

The 60 positions within each integral container were, therefore, individually assigned to a specific cluster or pulp temperature zone, where a pulp temperature zone is defined as an area in the integral container experiencing similar pulp temperature conditions.

Step three: Discriminant analysis (forward stepwise and canonical analysis)

Discriminant analysis was used to determine, in order of importance, which created variables were the best discriminators of the distinct pulp temperature zones (Johnson, 1998). The cluster analysis performed on the pulp temperature data enabled the classification of the 60 positions in each integral container and the formation of two or more groups, which is a prerequisite for discriminant analysis (Brown and Wicker, 2000; Händle and Simar, 2003).

A forward stepwise procedure was used as the variable selection procedure. Variables with the largest statistically significant F-value were selected stepwise and entered into the model (Johnson, 1998). The respective partial Wilks's lambda values indicate the unique contribution of each respective variable to the discrimination between groups. A lambda value equal to 0.0 denotes perfect discriminatory power, therefore, the lower the value, the greater the discriminatory power of the respective variable (Brown and Wicker, 2000). It should be noted that a highly significant discriminant variable is not necessarily a good discriminator and that the best discriminant variable should be identified by evaluating the partial Wilks's lambda values (Johnson, 1998).

A canonical discriminant analysis was performed on each set of pulp temperature data using only the discriminant variables selected with stepwise discriminant analysis. A scatter plot of the canonical scores for each discriminant function showed how well the cluster groups could be distinguished, where variables that discriminate well, result in populations not overlapping (Johnson, 1998).

The 60 positions within each container were, therefore, classified into distinct pulp temperature zones prior to performing discriminant analysis. The cluster analysis was based on variables chosen through factor analysis, where highly correlated variables were grouped. Through stepwise discriminant analysis the variables which discriminated the most between the temperature zones were identified in order of importance. Canonical discriminant analysis showed how well the selected variables distinguished between the cluster groups or temperature zones.

Step four: One-way analysis of variance (pulp temperature data analysis)

A one-way analysis of variance was performed on the pulp temperature data for the variables which best discriminated between the distinct pulp temperature zones, as identified through stepwise discriminant analysis.

Step five: Pulp- and air temperature data

The average pulp temperature at the end of the first day the container was loaded, the average pulp temperature recorded upon arrival at the destination point and the peak pulp temperature were evaluated per cluster group for each container trial. The average air temperature for each container trial was plotted with the average pulp temperature for each cluster group over the dual temperature cycle.

Step six: One-way analysis of variance (quality data analysis)

A one-way analysis of variance was performed on the fruit quality data for the variables ‘fruit firmness before’, ‘fruit firmness after’ and ‘percentage internal defects’ according to the distinct pulp temperature zones identified through cluster analysis. The effect of fruit size and fruit colour on fruit firmness and TSS prior to shipment was also evaluated.

Step seven: Analysis of covariance (quality data analysis)

An analysis of covariance was performed on only ‘Sapphire’ containers 1 and 2 fruit quality data for the variable ‘fruit firmness after’, with ‘fruit firmness before’ as the covariate, according to the distinct pulp temperature zones identified through cluster analysis.

3. Results and discussion

3.1. Results

Step one: Factor analysis

The Scree test of Catell assisted in determining the number of fundamental influences (or factors) to be extracted. The eigenvalues levelled off after three factors were extracted (Tables 3 and 4). It was important to study the cumulative percentage of total variance at this extraction point, since the model needed to account for data to an acceptable degree. The three factors extracted accounted for 84.8% ('Sapphire' container 1), 88.0% ('Sapphire' container 2), 83.8% ('Fortune') and 82.2% ('Laetitia') of the total variance.

The varimax normalized factor loadings for each variable-factor combination explain the degree of association (Tables 5 and 6). Certain variables were highly associated with a specific factor (loadings marked) and, therefore, defined the factor. Upon examining the results it was evident that each extracted factor represented a specific pulp temperature phase or condition within the container studied. The chosen variables clearly described the heating up- and cooling down phases, or periods of supra-optimal temperatures during shipping (Tables 5 and 6). The first extracted factor always accounts for the greatest amount of variance found and, therefore, represents the most important process taking place in the container, and so forth. The order of importance of the phases could, therefore be determined.

'Sapphire' Container 1

Factors 1, 2 and 3 extracted from the 'Sapphire' container 1 pulp temperature data accounted for 60%, 16% and 8%, respectively, of the total variance (Table 3). Each factor proved to be highly associated with certain variables, indicated in bold in Table 5. The variables defining factor 1 generally represented the heating up process taking place during the second phase of the dual temperature cycle, when the set point temperature was adjusted from -0.5°C to 7.5°C (Tables 2 and 5). Factor 2 exclusively represented over heating taking place in the container (Tables 2 and 5) and factor 3 generally the cooling down process taking place during the third phase of the dual temperature cycle when the set point temperature was reset to -0.5°C (Tables 2 and 5).

'Sapphire' Container 2

Factors 1, 2 and 3 extracted from the 'Sapphire' container 2 pulp temperature data accounted for 65%, 13% and 10%, respectively, of the total variance (Table 3). Each factor again proved to be highly associated with certain variables, indicated in bold in Table 5. The variables defining factor 1 generally represented the cooling down process taking place during the third phase of the dual temperature cycle (Tables 2 and 5).

Factor 2, as in the case of ‘Sapphire’ container 1, represented over heating taking place in the container (Tables 2 and 5) and factor 3, accounting for the least variance, generally represented the heating up process taking place during the second phase of the dual temperature cycle (Tables 2 and 5).

‘Fortune’

Factors 1, 2 and 3 extracted from the ‘Fortune’ pulp temperature data accounted for 61%, 14% and 9%, respectively, of the total variance (Table 4). Each factor proved to be highly associated with certain variables, indicated in bold in Table 6. The variables defining factor 1 generally represented the heating up process, as found for ‘Sapphire’ container 1 (Tables 2 and 6). Factor 2 generally represented the cooling down process and factor 3, accounting for the least variance, generally for over heating taking place in the container (Tables 2 and 6).

‘Laetitia’

Factors 1, 2 and 3 extracted from the ‘Laetitia’ pulp temperature data accounted for 53%, 20% and 9%, respectively, of the total variance (Table 4). Each factor proved to be highly associated with certain variables, indicated in bold in Table 6. The variables defining factor 1 generally represented the cooling down process, as found for ‘Sapphire’ container 2 (Tables 2 and 6). Factor 2 generally represented the heating up process (Tables 2 and 6). Factor 3, accounting for the least variance, exclusively represented over heating taking place in the container, as found for ‘Fortune’ (Tables 2 and 6).

A hierarchical joining tree diagram was computed for each set of variables. It was possible to verify the grouping of the variables obtained through factor analysis and similarly identify the underlying fundamental influences (data not presented).

Three underlying fundamental influences were, therefore, identified per set of pulp temperature data. The variables that best represented the temperature phases or conditions, were chosen to perform the cluster analysis, where the 60 positions within each container were individually classified or assigned into distinct pulp temperature zones.

Step two: Cluster analysis (K-means clustering)

Variables HU (≤ 7.5°C), representing the heating up process, CD (> 0.5°C), representing the cooling down process, and > 8°C FR, representing over heating taking place in the container, were chosen as criteria to perform the cluster analysis on all four sets of pulp temperature data (Tables 2, 5 and 6). Upon searching for structure in the data it was evident that the clusters or temperature zones no longer represented meaningful areas or zones when it was specified that more than three clusters had to be formed (data not shown). It was, therefore, clear that three pulp temperature zones exist within an integral container shipping plum fruit using a dual temperature storage regime (Figures 5 and 6).

'Sapphire' Container 1

Upon examining the variable means for each cluster group and the F-value for each variable, it was clear that cluster 3 represented the warmest area within 'Sapphire' container 1. Positions assigned to this temperature zone took significantly longer to heat up (although not different to cluster 2) and cool down again, and proved to be at temperatures higher than 8°C for significantly the longest period of time (Table 7 and Figure 7). These positions were predominantly found towards the door end, at higher levels within the pallet and on the right hand side of the container (Figure 5A). Positions assigned to cluster 1 proved to represent the coolest area within the integral container (Table 7 and Figure 7) and were found towards the front of the container, closer to the floor and predominantly on the left hand side of the container (Figure 5A). Positions assigned to cluster 2 represented the intermediate pulp temperature zone (Table 7 and Figure 7) and were positioned in the transition zone between cluster 1 and 3.

'Sapphire' Container 2

Positions assigned to cluster 3 proved to take significantly the longest period of time to heat up (although not different to cluster 2) and cool down again during the dual temperature cycle (Table 7 and Figure 8). There was no significant difference in the number of hours at temperatures higher than 8°C between the cluster groups. Positions assigned to cluster 3 were found towards the door end of the container and at higher levels within the pallet (Figure 5B). Positions assigned to cluster 1 proved to represent the coolest area within the container (Table 7) and were found towards the front of the container (Figure 5B). Cluster 2 was less clearly defined in 'Sapphire' container 2, compared to 'Sapphire' container 1 (Figures 5A and 5B).

'Fortune'

Variables HU (≤ 7.5°C) and CD (>0.5°C) played a significant role in discriminating between the cluster groupings in the 'Fortune' container (Table 8). Positions assigned to cluster 3 represented the warmest positions within the container, and took significantly longer to heat up (although not different to cluster 2) and cool down again (Table 8 and

Figure 9). However, only four positions within the ‘Fortune’ container were assigned to cluster 3 (Figure 6A). These positions were located at the door end of the container and towards the top half of the pallet (Figure 6A). A large proportion of positions assigned to the highest temperature zone at the door end of the container in the ‘Sapphire’ containers (Figures 5A and 5B) represent a larger intermediate temperature zone (cluster group 2; Figure 6A). Positions assigned to cluster group 1 were located towards the front of the container (Figure 6A) and took significantly the shortest period of time to heat up and cool down (Figure 9). There was no significant difference between the cluster groups in the number of hours at temperatures higher than 8°C (Table 8).

‘Laetitia’

Variables HU (≤ 7.5°C), CD (>0.5°C) and >8°C FR all played a significant role in discriminating between the cluster groupings in the ‘Laetitia’ container (Table 8). Positions assigned to cluster 3 represented the warmest temperature zone within the container and took significantly longer to heat up, cool down again and proved to spend significantly the longest period of time at temperatures higher than 8°C (although not different to cluster 2; Table 8 and Figure 10). Positions assigned to cluster 1 represented the significantly coolest area within the container (Table 8 and Figure 10). The low temperature zone made up by cluster 1 was proportionately smaller than the intermediate- and high temperature zones found towards the back of the container (Figure 6B). A clear transition zone was evident in the location of each cluster position. The average number of hours spent to heat up and cool down again, and hours spent at temperatures higher than 8°C, increased from the front of the container towards the door end of the container and from the bottom towards the top-end of the pallet (Figure 6B).

Step three: Discriminant analysis

A number of discriminant variables, as described in Table 2, were selected for each set of pulp temperature data by performing a stepwise discriminant analysis procedure (Tables 9, 10, 11 and 12). The respective partial Wilks’s lambda values indicate that variable CD (>0.5°C) discriminated significantly the most between the cluster groups in ‘Sapphire’ containers 1 and 2 (Tables 9 and 10) and the ‘Laetitia’ container (Table 12), since variable CD (>0.5°C) had the smallest partial Wilks’s lambda value (Table 12). Variables FR (1°C - 2°C) and CD (2°C - 1°C) discriminated the most between cluster groups in the ‘Fortune’ container (Table 11).

The scatter plot of the canonical scores for each discriminant function, or canonical root, were examined to evaluated how well the cluster groups could be distinguished using only the selected discriminant variables. In all the container trials canonical root one, having the greatest discriminatory power, discriminated cluster 3 from groups 1 and 2 (Figure 11, 12, 13 and 14). It is clear that the selected variables were successful in discriminating between the cluster groups since almost no overlapping occurred between groups in the scatter plots.

Step four: One-way analysis of variance (pulp temperature data analysis)

'Sapphire' Container 1

Seven variables were selected as the best discriminators of the three cluster groups in 'Sapphire' container 1 (Table 9). All the variable means differed significantly between the cluster groups, except in the case of variable FR (7°C - 8°C) (Table 13). Cluster 3, situated near the door end of the container (Figure 5A), took significantly the longest period of time to cool down (Pr>F: $p<0.0001$), spent significantly the longest time at temperatures 1°C off the prescribed set point (Pr>F: $p<0.0001$) and spent significantly the longest time at temperatures higher than 0.5°C during the first and third phase of the dual temperature cycle when the set point temperature was -0.5°C (Pr>F: $p<0.0001$). Cluster 3 took significantly longer for the pulp temperature to rise from 5°C to 6°C during the heating up phase, or second phase, of the dual temperature cycle, in comparison to cluster 1 (Table 13). The number of hours it took for the pulp temperature to lower from 1°C to 0°C was significantly the lowest in cluster 3 (Pr>F: $p=0.0029$). Cluster 3 also spent significantly the longest period of time at temperatures between 1°C and 2°C (Pr>F: $p<0.0001$).

'Sapphire' Container 2

Cluster 3, situated near the door end of the container (Figure 5B), took significantly the longest period of time to cool down (Pr>F: $p<0.0001$), spent significantly the longest time at temperatures 1°C off the prescribed set point (Pr>F: $p<0.0001$) and spent significantly the longest time at temperatures higher than 0.5°C during the first and third phase of the dual temperature cycle when the set point temperature was -0.5°C (Pr>F: $p<0.0001$). Cluster 1 situated near the front of the container spent significantly the shortest period of time at the above temperature ranges (Table 14). Cluster 3 took significantly the longest time to lower the temperature to 7°C during the cooling down phase, or third phase, of the dual temperature cycle (Pr>F: $p<0.0001$).

'Fortune'

All variable means differed significantly between cluster groups (Table 15). Cluster 3, situated near the door end of the container (Figure 6A), spent significantly the longest period of time between temperatures 1°C and 2°C (Pr>F: p<0.0001) and took significantly the longest time to cool down from 2°C to 1°C (Pr>F: p<0.0001).

'Laetitia'

All the selected discriminant variable means differed significantly between cluster groups (Table 16). Cluster 3, situated near the door end of the container (Figure 6B), took significantly the longest period of time to cool down (Pr>F: p<0.0001), spent significantly the longest time at temperatures 1°C off the prescribed set point (Pr>F: p<0.0001) and spent significantly the longest time at temperatures higher than 0.5°C during the first and third phase of the dual temperature cycle when the set point temperature was -0.5°C (Pr>F: p<0.0001). These results are similar to the 'Sapphire' container 1 and 2 results (Tables 13 and 14). The initial cooling down period from 7°C to 5°C was the shortest in cluster 1, situated near the front of the container (Table 16 and Figure 6B). Cluster 3 spent the shortest period of time between temperatures 1°C and 0°C during the cooling down phase (Pr>F: p<0.0001).

Step five: Pulp- and air temperature data

The average container air temperature was compared with the average pulp temperature for each cluster group (Figures 7, 8, 9 and 10). It was found that the daily mean air temperature for each container was very similar to the daily mean pulp temperature for the cluster group representing the intermediate temperature zone (cluster 2) in each container. Generally the average pulp temperature was the lowest in cluster 1 and 2, situated towards the front of each container, within the first day after the container was loaded, with cluster 3 already showing a marked increase in pulp temperature. The average peak pulp temperature generally increased along the length of the container, where cluster 1, situated at the front of the container, reached the lowest peak average pulp temperature and cluster 3, situated at the door end of the container, the highest average peak pulp temperature. The average pulp temperature measured in each cluster group at the end of the voyage period similarly increased along the length of the container where cluster 3, situated near the door end of the container, showed the highest average pulp temperature on arrival.

Step six: One-way analysis of variance (fruit quality data analysis)

Fruit size significantly influenced the average fruit firmness and TSS in the case of all four plum trials prior to shipment (Table 1). The average fruit firmness was significantly lower, and TSS significantly higher for AA-size fruit, except in the case of the ‘Laetitia’ trial. Colour sorting resulted in a significant difference in average fruit firmness and TSS for ‘green’ and ‘red’ fruit measured in ‘Sapphire’ container 1, but not in ‘Sapphire’ container 2 (Table 1).

Average fruit firmness and TSS measured prior to shipment were compared over pulp temperature cluster groups determined through factor analysis and cluster analysis. There were significant differences between cluster groups in average fruit firmness and TSS prior to shipment for the ‘Sapphire’ container 1 and container 2 trials (Table 1). Differences in fruit firmness over cluster groups post-shipment could, therefore, not only be attributed to temperature conditions during shipment. No significant differences in average fruit firmness and TSS could be found over cluster groups prior to shipment in the case of ‘Fortune’ and ‘Laetitia’ (Table 1). No internal defects were observed in any of the fruit prior to shipment (results not shown).

Average fruit firmness measured post-shipment differed significantly over cluster groups in the ‘Sapphire’ container 1 and container 2 trials (Table 17). ‘Sapphire’ container 1, cluster 2 had the lowest fruit firmness, significantly different to cluster 1, but not to cluster 3 (Pr>F: p=0.0033). Cluster group 3 of ‘Sapphire’ container 2 had significantly the lowest fruit firmness levels, although not different to cluster 2 (Pr>F: p=0.0061). The percentage internal defects observed per cluster group were significantly the highest for cluster 2 in container 1, although not different to cluster 3 (Table 17). No significant difference in the occurrence of internal defects was found in container 2; however, cluster 1 showed the highest levels of internal defects (Table 17).

No significant difference in fruit firmness could be found over cluster groups post-shipment in ‘Fortune’ (Table 17).

Cluster 3 of the ‘Laetitia’ trial showed significantly the lowest fruit firmness levels, although not different to cluster 2 (Pr>F: p=0.0153) and the highest levels of internal defects, although the difference in the occurrence of internal defects was not significant (Table 17). A decrease in fruit firmness could be observed from cluster 1, situated at the front of the container, to cluster 2, situated in the transition zone between cluster 1 and 3, and cluster 3, situated towards the door end of the container.

Step seven: Analysis of covariance (fruit quality data analysis)

Since significant differences in average fruit firmness were found between cluster groups prior to shipment in ‘Sapphire’ container 1 and 2 (Table 1), it was not clear whether the significant differences in fruit firmness found post-shipment were due to the identified temperature variation within the container or due to the variation in maturity levels prior to shipment. Firmness before, when used as a covariate, was only significant in ‘Sapphire’ container 2, while significant cluster (treatment) differences remained in both ‘Sapphire’ containers 1 and 2 (Table 18).

The significantly lowest fruit firmness was found post-shipment in the intermediate temperature zone (cluster 2) in ‘Sapphire’ container 1 and in the warmest temperature zone (cluster 3) in ‘Sapphire’ container 2, although not different to cluster 2 (Table 18). The fruit firmness generally decreased from the front of the container to the door end of the container (Table 18).

3.2. Discussion

3.2.1. ‘Sapphire’

Factor analysis was used to enable the identification of the underlying fundamental influences or characteristics of the pulp temperature data recorded (Cudeck, 2000), which enabled the grouping of the positions. Since dual temperature shipment is a dynamic process, three independent phases were identified to influence the ‘Sapphire’ pulp temperature profile of containers 1 and 2 (Table 3). In ‘Sapphire’ container 1 the heating up process accounted for the greatest amount of variance found, followed by over heating and lastly the cooling down process (Tables 2 and 5). In ‘Sapphire’ container 2 the cooling down process was the most influential underlying characteristic, followed by over heating and lastly the heating up process (Tables 2 and 5).

3.2.1.1. The formation of temperature zones

The heating up and cooling down processes were identified as important underlying characteristics of the ‘Sapphire’ pulp temperature data sets (Table 5). The cooling down process is necessary to lower the fruit pulp temperature after the heating up phase has been completed to prevent fruit from becoming over-ripe and decay to develop (Wang *et al*., 2003). The fruit pulp temperature, and therefore the efficacy of the heating up and cooling down processes, is determined by the delivery air temperature, the localised airflow past the specific fruit pallet, the heat produced by the product due to respiration and the packaging material's thermal characteristics (Billing *et al*., 1993; Billing *et al*., 1995).

3.2.1.1.1. Delivery air temperature and temperature variance found in the container

The delivery air temperature can be influenced by air ventilation, the rate of ventilation and outside atmospheric conditions (Amos and Sharp, 1999; Tanner and Amos, 2003a). The containers used in these plum trials were ventilated at 15 m^3 per hour (PPECB, 2006a), and the fresh air vent was located on the right hand side (facing from the door end) in all the containers used. Ventilation of dual temperature plum shipments was implemented due to the subsequent increase in the production of ethylene, being auto-stimulatory in the case of mature climacteric plums (Lelièvre *et al*., 1997), carbon dioxide and heat due to the stimulation of respiration brought about by the higher temperatures of the intermittent warming period (Kader, 2002).

A change in outside atmospheric conditions can result in a variation in delivery air temperature across the width of the container contributing to the development of temperature variances within the container (Tanner and Amos, 2003a). Typically, it was found by Tanner and Amos (2003a), on single temperature shipment trials, and by Punt and Huysamer (2005), on dual temperature shipment trials, that the air temperature within the container increased from the left to the right of the container (facing from the door end), from the front to the door end and from the bottom to the top of the container. Tanner and Amos (2003a) furthermore found that the fruit pulp temperature, measured during single temperature shipment, therefore, also increased across the width of the container, along the length of the container and up the height of the container system. It is expected that the temperature variance pattern found within the container system would influence the rate at which the fruit pulp temperature would heat up and cool down in the container.

The cluster analysis identified three cluster groups in the 'Sapphire' container trials shipped at a dual temperature storage regime (Figures 5A and 5B). Each cluster group, or temperature zone, represented a number of positions within the container that experienced similar pulp temperature conditions over the course of the shipment period. It was found that the fruit located in the temperature zone situated near the door end of both ‘Sapphire’ containers (cluster 3), took significantly the longest period of time to heat up and cool down again, and had the highest average pulp temperature, peaking at 9.1°C in the case of container 1 and 8.6°C in the case of container 2 (Table 7, Figures 7 and 8). Cluster 2 represented the intermediate temperature zone within each ‘Sapphire’ integral container. The location of positions assigned to this temperature zone in ‘Sapphire’ container 1 clearly accentuated the typical pattern of variance found within integral containers by Tanner and Amos (2003a), where the delivery air temperature varies across the width of the container (Figure 5A). However, in container 2 the members of this temperature zone were predominantly concentrated at the door end of the container (Figure 5B). The fruit situated in the temperature zone near the front of each ‘Sapphire’ container (cluster 1), took significantly the shortest period of time to heat up and cool down again, and had the lowest average pulp temperature during the first and third phases of the dual temperature cycle, peaking at 8.3°C in the case of container 1 and 7.7°C in the case of container 2 (Table 7, Figures 7 and 8). Positions assigned to this zone in container 1 were situated on the left hand side of the container, towards the front and predominantly at the lower levels of the container (Figure 5A), accentuating the temperature variance pattern found by Tanner and Amos (2003a), where the delivery air temperature varied across the width of the container. However, positions assigned to the ‘coolest’ temperature zone in container 2 occupied the front two-thirds of the integral container and the transition to the area occupied by the intermediate and warm temperature zones was very sudden (Figure 5B).

It is, therefore, evident that the pulp temperature variance pattern found in ‘Sapphire’ container 2 was different to that of container 1 and, therefore, also to what Tanner and Amos (2003a) found. However, the mere existence of a temperature variance pattern highlights the variable conditions found within the container, which in effect put much strain on the container system to effectively adjust the pulp temperature during the heating up and cooling down phases of a dual temperature storage regime.

3.2.1.1.2. Airflow

According to Tanner and Amos (2003b), the large distance from the fan, situated at the front of the container, to the door end of the container, results in lower airflow at the door end of the container due to short circuiting of air from the refrigeration end of the container along the length of the container. A lower volume of cold air is, therefore, delivered to the door end of the container resulting in higher air temperatures. Punt and Huysamer (2005) similarly concluded that even though the delivery air temperature was within the required tolerances during trials performed on dual temperature shipment of plums, inadequate airflow through palletized, climacteric plums with high metabolic rates, led to an excessive increased in pulp temperature.

The cooling down process was the most important fundamental influence in ‘Sapphire’ container 2 and less important in ‘Sapphire’ container 1 (Table 5). As previously mentioned, a substantially higher average pulp temperature was recorded at the door end of container 2, compared to container 1 (Figures 7 and 8). This difference was already evident prior to the second phase, or heating up phase, suggesting that another factor, other than cultivar and elevated respiration rates, resulted in the cooling down process being the most influential process in container 2 (Table 5 and Figure 8). Fruit located at positions assigned to this temperature zone (cluster 3), also took six hours longer to heat up and three hours longer to cool down again, compared to container 1 (Table 7). It is also clear from studying the positioning of the members of each cluster group situated near the door end of each container (cluster 3), that the performance of the two ‘Sapphire’ containers differed, which could furthermore explain why the cooling down process was more important in the case of ‘Sapphire’ container 2 (Figures 5A and 5B). It is important to note that the fresh air ventilation opening was similarly located at the top right hand side of both ‘Sapphire’ containers, when facing from the door end of the container. The above evidence suggests that container 2 was not able to control the pulp temperature at the door end of the container as well as in the case of container 1. It is, therefore, possible that poor airflow in container 2 resulted in the observed temperature variance pattern, different to that of container 1, and fruit positioned at the back of the container having an even higher average pulp temperature during the voyage, necessitating that the cooling down process played the predominant role in container 2.

3.2.1.1.3. Fruit respiration, over heating and influence of cultivar

Over heating, defined as temperatures higher than 8°C, played an important role in both containers (Tables 2 and 5). The cluster 3 situated near the door end of container 1 showed significantly the greatest amount of hours at pulp temperatures higher than 8°C and reached a peak of 9.1°C on the day that the cooling down phase commenced (Table 7 and Figure 7). No significant differences were found between cluster groups in container 2 (Table 7).

The heating up phase accelerates the respiration and ethylene production rates and, therefore, the ripening rate of the plums due to exposure to higher temperatures (Kader, 2002). An increased respiration rate results in an increased production of vital heat in the container (Kader, 2002). ‘Sapphire’ plums are classified as climacteric fruit, showing a considerably higher increase in respiration and ethylene production rates after harvest, compared to suppressed climacteric plums (Holcroft *et al*., 2002). Kruger (2002) also measured higher respiration rates on climacteric plums, compared to suppressed climacteric plums, with the difference being even greater at higher temperatures. According to Holcroft *et al*. (2002) the vital heat generated by climacteric plums, as opposed to suppressed climacteric plums, will be greater due to the higher respiration rates and fruit ripening more rapidly. The chance of temperatures rising rapidly during shipment is, therefore, much greater in the case of climacteric plums. Over heating taking place in the integral containers is, therefore, possibly the result of the inherent characteristic of ‘Sapphire’ plum to have high respiration and ethylene production rates.

Heat is introduced to the container through higher delivery air temperatures and heat produced by the fruit (vital heat) during the second phase, or heating up phase, of dual temperature shipment. Irving (1988) and Irving and Shepard (1982) stated that the total rate of air circulation determines, in part, the uniformity in temperature within the container, and that ideally the air should be distributed in such a way that the quantity of air flowing in each section should be proportional to the amount of heat to be removed to attain such temperature uniformity. In trials performed by Oosthuyse (1997) on mangoes, it was shown that an elevation of fruit respiration, and therefore, an increased production of heat, accentuated the effect of poor airflow and poor temperature management in the container. This was evident in the temperature zone located at the door end of ‘Sapphire’ container 2 (cluster 3), where the average pulp temperature measured during the cooling down phase was much greater compared to that of container 1 (Figures 5B, 7 and 8).

3.2.1.2. Identification of variables discriminating the temperature zones

The stepwise discriminant analysis was used to evaluate all created variables in an effort to identify the variables, and possibly the underlying processes, that discriminated the most significantly between the already identified cluster groups or temperature zones (Johnson, 1998). Variable CD (>0.5°C), representing the cooling down process (Table 2), was identified as the best discriminator of the three cluster groups, or temperature zones, in both ‘Sapphire’ containers (Tables 9 and 10).

A variable or group of variables that discriminates well can be identified by evaluating whether the population groups can be clearly distinguished, in other words, the populations should not overlap (Johnson, 1998). It is clear from examining the scatter plots, obtained through performing a canonical discriminant analysis, that canonical root one, having the greatest discriminatory power and being strongly influenced by variable CD (>0.5°C), discriminated the cluster group situated at the door end of each container from the other cluster groups in 'Sapphire' containers 1 and 2 (Figures 5A, 5B, 11 and 12). All three cluster groups, or temperature zones, could clearly be distinguished in both container trials (Figures 11 and 12). It is, therefore, verified that the cooling down process played a significant role in discriminating the different pulp temperature zones within the 'Sapphire' integral containers.

It is important to understand that a discriminant function, or canonical root, is formed by a linear combination of discriminator variables and is often more useful in differentiating groups than single variables (Brown and Wicker, 2000). It is, therefore, important to consider how the other identified variables discriminated between the different cluster groups or temperature zones (Tables 9 and 10).

Upon evaluating the group means for each identified discriminant variable in 'Sapphire' container 1, it was found that the pulp temperature of fruit located in the temperature zone located near the door end of the container (cluster 3) spent significantly the longest period of time off the prescribed set point temperature, had the highest average pulp temperature during the first and third phases of the dual temperature cycle and took the longest period of time to cool down (Table 13 and Figure 7). Since the warmest area within the container took the greatest number of hours to cool down (Table 14), it is expected that this area would also take the longest time to cool down from 1°C and 0°C, since the cooling down process slows down as 0°C is approached (personal observation). Initially the cooling down process is fast and slows down when the pulp temperature reaches 4°C to 3°C (personal observation). However, variable CD (1°C - 0°C) clearly shows that the temperature zone located near the door end of the container spent the shortest period of time between temperatures 1°C and 0°C during the cooling down process (Table 13). This can be explained by examining the group means for variable FR (1°C - 2°C) and Figure 7. The average pulp temperature of fruit located in the temperature zone near the door end of the container remained predominantly at temperatures between 1°C and 2°C towards the end of the cooling down phase and the pulp temperature lowered to temperatures below 1°C only four days before the container arrived at the destination point. The average pulp temperature for this temperature zone was 0.8°C on arrival and never reached the set point temperature of -0.5°C (Figure 7).

Similar to ‘Sapphire’ container 1, the temperature zone situated at the door end (cluster 3) of container 2 spent significantly the longest period of time off the prescribed set point temperature, had the highest average pulp temperature during the first and third phases of the dual temperature cycle and took the longest period of time to cool down (Table 14 and Figure 8). The average pulp temperature for this temperature zone was 1.6°C on arrival and never reached the set point temperature of -0.5°C (Figure 7).

3.2.1.3. Influence of identified temperature variances on fruit quality

At this stage the different temperature zones had been identified and it was determined how the underlying processes discriminated between the identified temperature zones. A very important aspect of quantifying the temperature variance within the container, was to understand the effect such temperature variance had on the fruit quality.

The fruit quality was evaluated prior to shipment to enable the determination of the influence of the temperature variances, and therefore the container’s performance, on fruit quality post-shipment. A significant difference was found in fruit firmness and TSS between A-size and AA-size fruit in both containers, where larger fruit was significantly softer with higher sugar levels (Table 1). Colour sorting also had a significant influence on fruit firmness and TSS in ‘Sapphire’ container 1, where ‘greener’ fruit were always softer with lower sugar levels (Table 1). A similar trend was observed in container 2, although the difference was not significant.

Marini *et al*. (1991) and Patten and Proebsting (1986) found that shading of fruit reduced the skin colour of peaches and cherries, respectively. Taylor *et al*. (1993) found that ‘Songold’ plums harvested from the bottom of the trees had significantly lower soluble solids and fruit firmness levels, compared to fruit harvested from the top of the trees and that the lower soluble solids levels were probably due to shading resulting in decreased rates of photosynthesis in the leaves in close proximity to the fruit. The lower fruit firmness levels were contributed to earlier flowering in the bottom part of the tree resulting in the fruit maturity being more advanced compared to the top fruit. It was unknown from what part of the tree the plums were harvested in our trials, however, our results show that better coloured fruit, probably having been exposed to more light, were less advanced in maturity, with fruit firmness is an indicator of maturity (Taylor *et al*., 1993), and had significantly higher soluble solids levels, probably due to more exposure to light resulting in optimal photosynthesis.

The fruit firmness and total soluble solids for each cluster group, or temperature zone, were compared prior to shipment. Significant differences in both quality variables were evident across temperature zones in both ‘Sapphire’ containers (Table 1). Differences found in fruit firmness between temperature zones post-shipment could, therefore, not be attributed to only the temperature variances identified in the container during shipment.

Through an analysis of covariance it was shown that the initial differences in fruit firmness did not significantly affect the differences found post-shipment in ‘Sapphire’ container 1 (Table 18). The difference found between cluster groups post-shipment was, therefore, due to the variation in temperature found throughout the container. However, in ‘Sapphire’ container 2 the difference in fruit firmness between cluster groups was large enough pre-shipment to influence the difference found post-shipment (Table 18). The significant difference in fruit firmness found between cluster groups in ‘Sapphire’ container 2 post-shipment was, therefore, partly due to the initial differences found prior to shipment and the variation in temperature during shipment. It has, therefore, been shown that the initial fruit maturity can also have a determining effect on post-shipment fruit quality.

The fruit firmness generally decreased from the front of the container to the door end of the container (Table 18). Temperature is the single most important factor influencing the deterioration rate of fruit commodities (Kader, 2002). Quality deteriorates at high temperatures due to increased respiration and ethylene production. It was found that the average pulp temperature increased along the length of the container, from the front to the door end, along the width of the container, from left to right, and up the height of the container system (Figure 5A, 5B, 7 and 8). It has, therefore, been shown that the rate of deterioration increased from the front to the door end of the container due to an increase in pulp temperature. It can, therefore, be recommended that more mature fruit should be loaded towards the front of the container and less mature fruit at the door end of the container. This separation in maturity can be achieved through ensuring that a pallet consists of fruit of similar size and colour sorting is performed (Table 1).

A significant difference in the occurrence of internal defects was evident in ‘Sapphire’ container 1 post-shipment (Table 17). Cluster 2, the intermediate temperature zone with the lowest average fruit firmness post-shipment, showed the highest levels of internal defects, although not different to cluster 3 located at the door end of the container

(Table 17 and Figure 5A). There was also no difference in the percentage internal defects observed between cluster 1, situated in the front of the container, and cluster 3, situated at the door end of the container (Table 17 and Figure 5A). No significant differences in the occurrence of internal defects were observed between cluster groups in 'Sapphire' container 2 (Table 17).

3.2.2. 'Fortune'

Factor analysis similarly identified the underlying characteristics of the 'Fortune' pulp temperature data recorded during a dual temperature storage trial (Cudeck, 2000). Similar to the 'Sapphire' trials, three independent processes were identified to influence the pulp temperature profile in the 'Fortune' container (Table 4). The heating up process accounted for the greatest amount of variance found, followed by the cooling down process and lastly over heating taking place (Tables 2 and 6).

3.2.2.1. The formation of temperature zones

3.2.2.1.1. Delivery air temperature and temperature variance found in the container

Similar to 'Sapphire' container 1, the heating up process was identified as the most influential characteristic of the 'Fortune' pulp temperature data set (Table 6). In both cases the cluster 1, representing the temperature zone located near the front of the container, heated up to 7.5°C in the fewest number of hours (Table 7 and 8). The heating up process was prolonged with increasing distance from the refrigeration unit located in the front of the container (Table 8).

Three cluster groups or temperature zones were identified in the 'Fortune' container (Figure 6A). It was found that the fruit located in the temperature zone situated near the door end of the container (cluster 3), took significantly the longest period of time to heat up (not different to cluster 2), cool down again and had the highest average pulp temperature during the first and third phases of the dual temperature cycle (Table 8 and Figure 9). Cluster 2 represented the intermediate temperature zone and similarly to 'Sapphire' container 1, accentuated the typical pattern of variance found within integral containers by Tanner and Amos (2003a), where the delivery air temperature varied across the width of the container (Table 8 and Figure 6A). The fruit situated in the temperature zone near the front of the container took significantly the shortest period of time to heat up, cool down again and had the lowest average pulp temperature during the first and third phases of the dual temperature cycle (Table 8 and Figure 9). Positions assigned to this zone were situated predominantly on the left hand side of the container, towards the front and at the lower levels of the container (Figure 6A), accentuating the temperature variance pattern found by Tanner and Amos (2003a).

A similar temperature variance pattern was found in ‘Sapphire’ container 1, where the heating up process was also identified as the most influential underlying process in the container. It is, therefore, possible that the delivery air temperature varied across the width of the container in both cases, due to exposure to more adverse temperature conditions, resulting in the temperature variance pattern found by Tanner and Amos (2003a). If the fresh air vent is situated on the right hand side of the container (facing from the door end), as in our trials, differential coil frosting will result in higher delivery air temperatures on the right hand side of the container and lower delivery air temperatures on the left hand side (Tanner and Amos, 2003a). It is, therefore, possible that the heating up process was influenced in a similar manner as the temperature variance pattern identified by Tanner and Amos (2003a) and was, therefore, the most influential process in both the ‘Fortune’ and ‘Sapphire’ container 1 trials.

The cooling down process was the second most important underlying process in the ‘Fortune’ container (Table 6). The temperature zone represented by cluster 3, took longer to cool down than the intermediate temperature zone (cluster 2) and the temperature zone located near the front of the container (cluster 1; Table 8). However, each respective temperature zone in the ‘Fortune’ trial still took less time to cool down than in the case of ‘Sapphire’ container 1. It can, therefore, be concluded that since the cooling down process could progress much faster in the case of the ‘Fortune’ trial, due to an inherently lower respiration rate, the cooling down process was a less important process.

3.2.2.1.2. Fruit respiration, over heating and the influence of the cultivar

Contrary to the ‘Sapphire’ trials, over heating was not an important characteristic of the ‘Fortune’ pulp temperature data set (Table 6). In work performed by Punt (2002), it was shown that ‘Fortune’ plums developed no internal defects after a 42-day dual temperature storage period or a 42- day single temperature storage period at -0.5°C, and subsequent shelf life storage, showing only reduced levels of juiciness. ‘Fortune’, therefore, shares similar characteristics to suppressed climacteric plums known to have a reduced respiratory climacteric and a reduced ethylene peak towards the latter part of the ripening period (Albi *et al*., 1998). It is also known that true suppressed climacteric plum cultivars, as for example ‘Angeleno’, can be shipped at -0.5°C without the danger of chilling injury taking place (Kruger, 2002).

Upon comparing the ‘Fortune’ and ‘Sapphire’ container 1 results, the effect of suppressed-climacteric versus climacteric plum cultivars on container performance can be observed (Tables 7 and 8). The intermediate temperature zone (cluster 2) and temperature zone located near the door end of the container (cluster 3) in ‘Sapphire’ container 1, took 77 and 79 hours, respectively, to heat up to 7.5°C (Table 7). Similar positioned temperature zones in the ‘Fortune’ container took 80 and 93 hours, respectively, to heat up (Table 8). It can, therefore, be observed that the temperature rise triggered the respiratory and ethylene production rates of the ‘Sapphire’ plums, resulting in an increased production of vital heat and ethylene. The produced heat and ethylene further stimulated the respiration and ethylene production rates since ethylene is auto-stimulatory (Lelièvre *et al*., 1997). The heating up process in ‘Sapphire’ container 1 was, therefore a very rapid process. ‘Fortune’ plum fruit of similar classified cluster groupings located towards the door end of the container, took much longer to heat up to 7.5°C, which confirms the idea that ‘Fortune’ could be classified as a suppressed-climacteric plum cultivar, showing a reduced respiratory climacteric and a reduced ethylene peak (Table 8).

No significant differences were found between cluster groups with regard to the number of hours spent at temperatures higher than 8°C (Table 8). It was also found that the period spent at temperatures higher than 8°C was on average much shorter than in the case of ‘Sapphire’ container 1. This confirms that over heating was, therefore, the least importance characteristic or underlying process of the ‘Fortune’ pulp temperature data set.

3.2.2.2. Identification of variables discriminating the temperature zones

The stepwise discriminant analysis identified variables FR (1°C - 2°C) and CD (2°C - 1°C), as described in Table 2, as the best discriminators of the three cluster groups, or temperature zones, in the ‘Fortune’ trial (Table 11). Cluster 3 spent significantly the greatest number of hours between 1°C and 2°C and cluster 1 significantly the least, as calculated over the full dual temperature cycle and during the cooling down process (Table 15).

It is clear from examining the scatter plots that canonical root one, having the greatest discriminatory power, discriminated the cluster group situated at the door end of the container (cluster 3) from the other cluster groups in the ‘Fortune’ trial (Figures 6A and

13). It should be mentioned that only four positions within the container represented cluster 3 (Figure 6A). All three cluster groups, or temperature zones, could clearly be distinguished, proving that the selected discriminant variables discriminated the cluster groups well (Johnson, 1998; Figure 13).

3.2.2.3. Influence of identified temperature variances on fruit quality

At this stage the different temperature zones had been identified and it was determined how the identified variables discriminated between the temperature zones. A very important aspect of quantifying the temperature variance within the ‘Fortune’ container, was to understand the effect such temperature variance had on the fruit quality.

Similar to the ‘Sapphire’ container trials, fruit size had a significant influence on the fruit firmness and total soluble solids measured prior to shipment, where larger fruit were significantly softer with higher soluble solids levels (Table 1). No colour sorting was performed on the ‘Fortune’ plums, since the fruit was fully coloured at harvest. Furthermore, upon evaluating the fruit firmness and TSS prior to shipment, no significant differences were found between cluster groups (Table 1).

Upon evaluating the average fruit firmness levels post-shipment is was very interesting to see that no significant differences in fruit firmness were found between cluster groups, even though three unique temperature zones were identified (Table 17 and Figure 6A). This confirms the theory that ‘Fortune’ can be classified as a true suppressed-climacteric plum cultivar. The fruit firmness levels of the ‘Fortune’ plums decreased on average by only 0.23 kg during the dual temperature shipment (data not shown).

3.2.3. ‘Laetitia’

Before the ‘Laetitia’ results are discussed, it is important to note that the shipping of this trial did not proceed according to protocol. The vessel was delayed by six days and the set point temperature was adjusted from -0.5°C to 7.5°C only after five days instead of two days. The fruit was, therefore, stored at -0.5°C for 14 days before the intermittent warming phase commenced.

Similarly to the ‘Sapphire’ and ‘Fortune’ container trials, the factor analysis identified three underlying characteristics of the ‘Laetitia’ pulp temperature data recorded over a dual temperature storage period (Cudeck, 2000; Table 4). The cooling down process accounted for 53% of the variance found, followed by the heating up process, accounting for 20%, and lastly over heating taking place, accounting for only 9% (Table 6). It should be noted that the first factor extracted, namely the cooling down process, accounted for less variance than found in the other dual temperature trials, and the second factor extracted, namely the heating up process, accounted for more variance than previously found (Tables 3 and 4).

3.2.3.1. Formation of temperature zones

The respective temperature zones in the 'Laetitia' container heated up and cooled down faster than found in the 'Sapphire' container trials and the 'Fortune' container trial (Table 8). It should be noted that due to the delay in set point change from the first to the second phase of the dual temperature cycle in the 'Laetitia' trial, the cooling down process took place over only eight days, whereas it took 13 days in the case of the 'Sapphire' trials and 11 days in the case of the 'Fortune' trial. The hours it took for the fruit to cool down was, therefore, calculated over a much shorter period of time and the values are, therefore, not a true representative to enable comparison.

It can be observed, through evaluating the average daily pulp temperature for each temperature zone during the heating up phase in the 'Laetitia' container, that the initial stages of the heating up process were very rapid, slowing down as it reached the 7.5°C point slightly less than half a day earlier than fruit shipped in 'Sapphire' container 1, proven to show the second most rapid heating up process in our trials (Figures 7 and 10). Figure 14 furthermore shows that once the pulp temperature reached the 7.5°C level, the pulp temperature stabilized and a plateau was evident. This was clearest in the temperature zone located near the front of the container (Figure 10). Two components can, therefore, be identified, namely 'Laetitia' plum showing an accelerated ripening response to increased temperatures and good temperature control within the container. Over heating did not play an important role in the 'Laetitia' trial, and suggests that the response to increased temperatures is not as prominent as found in the case of 'Sapphire' plum (Kruger *et al*., 2003; Tables 5 and 6).

Little variation in average pulp temperature prior to the heating up phase was evident due to the prolonged storage period at -0.5°C, resulting in the pulp temperature being stabilized throughout the container (Figure 10). However, a delayed response in heating up and cooling down was still observed within the container with increasing distance from the refrigeration unit, with clearly defined temperature zones evident (Table 8, Figures 6B and 10). The container was able to cool the pulp temperature down to a similar level as recorded on the first day of shipment by the time the container reached the destination point (Figure 10).

Three clearly defined cluster groups, or temperature zones, were identified in the ‘Laetitia’ container (Figure 6B). It was found that the fruit located in the temperature zone situated near the door end of the container (cluster 3), took significantly the longest period of time to heat up and cool down again, had the highest average pulp temperature throughout the dual temperature cycle and spent significantly the longest time at temperatures higher than 8°C (although not different to the intermediate temperature zone; Table 8, Figures 6B and 10). Cluster 2 represented the intermediate temperature zone (Table 8 and Figure 6B). The fruit situated in the temperature zone near the front of the container took significantly the shortest period of time to heat up (although not different to the intermediate zone) and cool down again and had the lowest average pulp temperature during the first and third phases of the dual temperature cycle (Table 8, Figures 6B and 10). Therefore, although it seems that good temperature control took place in the container, a combination of variation in delivery air temperature across the width of the container, as found by Tanner and Amos (2003a), and reduced airflow towards the back of the container, possibly still created a temperature variance pattern throughout the container (Figure 6B). According to Heap (1989) there is of necessity a temperature variance pattern within the container due to outside conditions, and is it rather important to understand what an acceptable temperature variation is.

3.2.3.2. Identification of variables discriminating temperature zones

The stepwise discriminant analysis identified variable CD (> 0.5°C), as described in Table 2, as the best discriminator of the three cluster groups, or temperature zones, in the ‘Laetitia’ trial (Table 12). Fruit represented by cluster 3 took significantly the greatest number of hours to cool down and cluster 1 significantly the least (Table 16).

It is clear from examining the scatter plots that canonical root one, having the greatest discriminatory power, discriminated the cluster group situated at the door end of the container (cluster 3) from the other cluster groups in the ‘Laetitia’ trial (Figures 6B and 14). All three cluster groups, or temperature zones, could clearly be distinguished, proving that the selected discriminant variables discriminated the cluster groups well (Johnson, 1998; Figure 14).

3.2.3.3. Influence of temperature variances on fruit quality

At this stage the different temperature zones had been identified and it was determined how the identified variables discriminated between the temperature zones. A very important aspect of quantifying the temperature variance within the 'Laetitia' container, was to understand the effect such temperature variance had on fruit quality.

Fruit size had a significant influence on the fruit firmness and total soluble solids measured prior to shipment, where smaller fruit were significantly softer with higher soluble solids levels (Table 1). The opposite trend was observed in the 'Sapphire' and 'Fortune' trials (Table 1). No colour sorting was performed on the 'Laetitia' plums, since the fruit was fully coloured at harvest. Furthermore, upon evaluating the fruit firmness and TSS prior to shipment, no significant differences were found between the cluster groups (Table 1).

Post-shipment the average fruit firmness of the temperature zone located at the door end of the container (cluster 3), was significantly the lowest, but not different to the intermediate temperature zone (cluster 2; Table 17). The average fruit firmness decreased from the front of the container to the door end of the container (Table 17). It has been shown that the average pulp temperature increased from the front of the container to the door end of the container (Figure 10). Since exposure to higher temperatures trigger ripening, the increasing temperature measured towards the door end, accelerated ripening in a similar manner (Kader, 2002). Therefore, plums shipped at the door end of the container arrived in a more advanced level of ripeness and plums located at the front of the container were more firm (Table 17).

High levels of advanced gel breakdown were found in the 'Laetitia' plum fruit exported from South Africa during the 2004/2005 stone fruit season (Kapp and Jooste, 2006). Gel breakdown is classified as a type of chilling injury where plums with a normal external appearance develop a gelatinous breakdown on the inner mesocarp surrounding the stone, while the outer mesocarp still has a healthy appearance, when plums are exposed to shelf-life temperatures after cold storage at either dual- or single-temperature regimes (Taylor, 1996). In severe cases the gelatinous breakdown spreads outwards, changing from translucent to a brown discolouration, associated with a loss of juiciness (Taylor, 1996). Taylor *et al.* (1994) furthermore found that gel breakdown was already evident in fruit harvested at an advanced maturity indicating that gel breakdown cannot be classified as a true cold storage chilling disorder. High levels of predominantly advanced gel breakdown were found in our trials during the shelf life evaluation performed by Marine Management Surveys, where fruit showed a brown discolouration and a lack of juiciness (data not shown). No significant difference in the occurrence of internal defects was found between temperature zones (Table 17). There was, however, a trend that fruit located in the temperature zone located at the door end of the container, showed higher levels of internal defects (Table 17). Kapp and Jooste (2006) concluded that extremely warm and dry conditions in combination with high evapotranspiration levels and low humidity conditions, resulted in moisture stress within the trees, which could have contributed to advanced fruit maturity and subsequent development of gel breakdown. Rapid cooling of fruit to -0.5°C increased the risk of gel breakdown and internal browning developing (Khumalo and De Kock, 2005). The non-significance of the levels of internal defects observed between cluster groups can, therefore, possibly be due to the gel breakdown already having been triggered prior to shipment and that the warmer temperature zone stimulated the expression of the defect more than the other temperature zones (Table 17).

4. Conclusion

Three processes were identified as important fundamental influences or characteristics of pulp temperature data sets of plums shipped at dual temperature, namely the cooling down process, the heating up process and the role of over heating in the container. The order of importance differed depending on the cultivar shipped and the integral container's performance.

The temperature zones were identified through cluster analysis using the processes identified through factor analysis. The formation of the temperature zones could be explained by considering the factors that influence pulp temperature, namely the delivery air temperature, localised airflow and the influence of the heat of respiration produced by the product (Billing *et al*., 1993; Billing, *et al*., 1995).

Tanner and Amos (2003a) have shown that a change in atmospheric conditions can result in a variation in delivery air temperature across the width of the container, contributing to the development of temperature variances within the container. It was typically found that the pulp temperature increased across the width of the container, along the length from the front to the door end of the container, and up the container system. Similar results were found in our dual temperature shipment trials. The average pulp temperature measured during the first and third phases of the dual temperature cycle and average number of hours it took for the fruit to heat up and cool down again, increased from the front of the container to the door end of the container, across the width of the container from the left to the right (facing from the door end) and from the bottom to the top of the fruit pallets. This temperature variance pattern was the most clearly visible in the 'Sapphire' container 1 and 'Fortune' trials.

The second factor determining the fruit pulp temperature is localised airflow. Results of 'Sapphire' container 2 shows that poor airflow possibly resulted in the different temperature variance pattern observed and the higher average pulp temperature recorded in the temperature zone located at the door end of the container. According to Tanner and Amos (2003b), the large distance from the fan, situated at the front of the container, to the door end of the container, results in lower airflow at the door end of the container due to short circuiting of air from the refrigeration end of the container along the length of the container. A lower volume of cold air is, therefore, delivered to the door end of the container resulting in higher air temperatures.

Thirdly, factor analysis identified that over heating played an important role in characterising the pulp temperature data sets, depending on the plum cultivar shipped. The higher temperatures experienced during the heating up phase of dual temperature shipment, results in an increase of the respiration and ethylene production rates (Kader, 2002). 'Sapphire' plum fruit can be classified as a climacteric fruit, showing higher respiration rates than suppressed climacteric fruit, with the difference being even greater at higher temperatures (Holcroft *et al*., 2002; Kruger, 2002). It was found that the temperatures increased more rapidly during shipment in the case of 'Sapphire' plum, which can be attributed to the greater production of vital heat and fruit ripening more rapidly (Holcroft, *et al*., 2002). Over heating taking place was, therefore, an important characteristic of the 'Sapphire' pulp temperature data sets. 'Laetitia' showed a similar rapid rise in pulp temperatures. However, lower respiration rates and less vital heat produced were possible factors preventing over heating from taking place in the container. It is thought that 'Fortune' plum can possibly be characterised as a true suppressed climacteric fruit, similar to 'Angeleno' plum, showing considerably less and delayed ethylene production (Holcroft, *et al*., 2002). 'Fortune' plum took the longest period of time to heat up, possibly due to inherently lower respiration levels resulting in much lower levels of vital heat and ethylene produced. This can also be observed in a much faster cooling rate than observed in the case of 'Sapphire' plum. Over heating was, therefore, not an important characteristic of the 'Fortune' pulp temperature data set.

The discriminant analysis identified variable CD (>0.5°C), defining the cooling down process, as the most important variable discriminating the cluster groups, or temperature zones, within integral containers shipping climacteric plums at dual temperature. This could be observed from the daily average pulp temperature per temperature zone and the analysis of variance performed, where it is clear that the temperature zones always differed significantly with regard to the number of hours the identified temperature zones took to cool down. A very different selection of discriminant variables was found in the case of the ‘Fortune’ trial and could possibly be attributed to the cultivar showing the characteristics of suppressed climacteric fruit, resulting in a more stable container environment.

Fruit size had a significant influence on the average fruit firmness and TSS prior to shipment in all trials performed. Larger fruit showed significantly lower fruit firmness and higher total soluble solids levels, except in the case of ‘Laetitia’.

In the ‘Sapphire’ trials it was shown that the significant difference in fruit firmness found between cluster groups post shipment was either due to temperature variation during shipment or due to a combination effect of temperature variation and differences in fruit firmness found prior to shipment. It has, therefore, been shown that the initial fruit maturity can also have a determining effect on post-shipment fruit quality. The fruit firmness generally decreased from the front of the container to the door end of the container and average pulp temperature increased along the length of the container, from the front to the door end, along the width of the container, from left to right, and up the height of the container system. It was, therefore, shown that the rate of deterioration increased from the front to the door end of the container due to an increase in pulp temperature.

The temperature variance found within the ‘Fortune’ container had no significant influence on the fruit firmness post-shipment, confirming the thought that ‘Fortune’ can be classified as a true suppressed climacteric plum cultivar. In the ‘Laetitia’ trials it could be concluded that the average fruit firmness decreased from the front of the container towards the door end of the container due to the variable temperature conditions found within the container.

Although there was a trend in all the dual temperature container trials performed that the fruit situated in the temperature zone at the door end of the container showed the highest levels of internal defects, the differences found were mostly insignificant. Gel breakdown caused widespread quality problems in a high percentage of ‘Laetitia’ plums shipped from South Africa in the 2004/2005 stone fruit season (Kapp and Jooste, 2006), and this internal defect was also evident in our trial. There was a trend that higher temperatures, as found predominantly at the door end of the container, expressed the already present gel breakdown better. Taylor *et al*. (1994) stated that gel breakdown cannot be classified as a true storage chilling disorder since it was already evident prior to harvest in more mature 'Songold' plums. It can, therefore, be concluded that the greatest effect the variable temperature conditions had, was on the fruit firmness levels.

Three distinct temperature zones were identified within integral containers shipping plums at a dual temperature regime. The formation of the temperature zones was possibly influenced by the delivery air temperature, the localised airflow and the effect of different respiration rates due to cultivar differences. The average pulp temperature measured during the first and third phases of the dual temperature cycle, the time it took for the fruit to heat up and the time it took to cool down again, increased along the length of the container, across the width of the container and up the container system. The cooling down process was identified as the most important factor discriminating the temperature zones when climacteric plums were shipped. Variable temperature conditions found within the container had a significant influence on the fruit firmness levels, and less so on the percentage internal defects found.

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Table 1

Average fruit firmness and total soluble solids (TSS) data of ‘Sapphire’ container 1, ‘Sapphire’ container 2, ‘Fortune’ and ‘Laetitia’ measured prior to shipment of the four plum containers.

	‘Sapphire’ 1		‘Sapphire’ 2		‘Fortune’		‘Laetitia’	
	Fruit firmness (kg)	TSS (°Brix)	Fruit firmness (kg)	TSS (°Brix)	Fruit firmness (kg)	TSS (°Brix)	Fruit firmness (kg)	TSS (°Brix)
Fruit size A	8.1 [z] a	12.7 a	8.1 a	13.10 a	7.9 a	13.3 a	7.5 a	13.3 a
Fruit size AA	7.7 b	13.0 b	7.4 b	13.40 b	7.3 b	13.8 b	7.8 b	13.0 b
Pr > F	<0.0001	0.0004	<0.0001	0.0005	<0.0001	<0.0001	0.0010	<0.0001
Maturity green	7.7 a	12.1 a	7.7 a	13.15 a	n/a	n/a	n/a	n/a
Maturity red	8.0 b	13.2 b	7.8 a	13.28 a	n/a	n/a	n/a	n/a
Pr > F	0.0008	<0.0001	0.3858	0.1994	n/a	n/a	n/a	n/a
Cluster 1	7.9 ab	12.6 a	7.8 ab	13.01 a	7.7 a	13.6 a	7.8 a	12.5 a
Cluster 2	8.0 a	12.7 a	9.0 a	14.00 b	7.6 a	13.6 a	7.6 a	13.2 b
Cluster 3	7.7 b	13.3 b	7.6 b	13.28 c	7.5 a	13.5 a	7.7 a	13.2 b
Pr > F	0.0207	<0.0001	0.0269	<0.0001	0.4406	0.3792	0.4543	0.4543

n/a No colour sorting was performed on ‘Fortune’ and ‘Laetitia’ plums.

z Mean separation within columns followed by different letters according to Bonferroni (5% level).

Table 2

Forty response variables were created to enable data analysis through multivariate exploratory techniques. Each variable describes the number of hours at a certain temperature or within a certain temperature range. Variable values were calculated for each of the sixty positions on the pulp temperature data.

Variable	Description
< -0.5°C FR	Hours at temperatures below -0.5°C, calculated over the three phases or full range (FR) of the dual temperature cycle
> -0.5°C (excluding DT phase)	Hours at temperatures above -0.5°C, excluding the second phase of the dual temperature (DT) cycle where the set point is 7.5°C
≥ 0.5°C (excluding DT phase)	Hours at temperatures greater than or equal to 0.5°C, excluding the second phase of the dual temperature cycle where the set point is 7.5°C
2°C ≤ x ≤ 7°C FR	Hours at temperatures greater than or equal to 2°C and less than or equal to 7°C , calculated over all three phases of the dual temperature cycle
≤ 3°C FR	Hours at temperatures less than or equal to 3°C, calculated over all three phases of the dual temperature cycle
> 3°C FR	Hours at temperatures above 3°C, calculated over all three phases of the dual temperature cycle
± 1°C outside FR	Hours at temperatures 1°C above or below the set point temperature, calculated over all three phases of the dual temperature cycle, i.e. x ≤ -1.5°C and x ≥ 0.5°C when the set point temperature is -0.5°C, and x ≤ 6.5°C and x ≥ 8.5°C when the set point temperature is 7.5°C
± 2°C outside FR	Hours at temperatures 2°C above or below the set point temperature, calculated over all three phases of the dual temperature cycle, i.e. x ≤ -2.5°C and x ≥ 1.5°C when the set point temperature is -0.5°C, and x ≤ 5.5°C and x ≥ 9.5°C when the set point temperature is 7.5°C
≥ 1°C outside FR	Hours at temperatures 1°C above the set point temperature, calculated over all three phases of the dual temperature cycle, i.e. x ≥ 0.5°C when the set point temperature is -0.5°C, and x ≥ 8.5°C when the set point temperature is 7.5°C
≥ 2°C outside FR	Hours at temperatures 2°C above the set point temperature, calculated over all three phases of the dual temperature cycle, i.e. x ≥ 1.5°C when the set point temperature is -0.5°C, and x ≥ 8.5°C when the set point temperature is 7.5°C
≤ 1°C outside FR	Hours at temperatures 1°C below the set point temperature, calculated over all three phases of the dual temperature cycle, i.e. x ≤ -1.5°C when the set point temperature is -0.5°, and x ≤ 6.5°C when the set point temperature is 7.5°C
≤ 2°C outside FR	Hours at temperatures 2°C below the set point temperature, calculated over all three phases of the dual temperature cycle, i.e. x ≤ -2.5°C when the set point temperature is -0.5°C, and x ≤ 5.5°C when the set point temperature is 7.5°C
HU (≤ 7.5°C)	Hours at temperatures less than or equal to 7.5°C, calculated only during the second phase or heating up (HU) phase of the dual temperature cycle where the set point temperature is 7.5°C
HU (≤ 1°C)	Hours at temperatures less than or equal to 1°C, calculated only during the second phase of the dual temperature cycle where the set point temperature is 7.5°C
HU (1°C - 2°C)	Hours at temperatures less than or equal to 2°C and greater than or equal to 1°C, calculated only during the second phase of the dual temperature cycle where the set point temperature is 7.5°C

HU (2°C – 3°C)	Hours at temperatures less than or equal to 3°C and greater than or equal to 2°C, calculated only during the second phase of the dual temperature cycle where the set point temperature is 7.5°C
HU (3°C – 4°C)	Hours at temperatures less than or and equal to 4°C and greater than or equal to 3°C, calculated only during the second phase of the dual temperature cycle where the set point temperature is 7.5°C
HU (4°C – 5°C)	Hours at temperatures less than or equal to 5°C and greater than or equal to 4°C, calculated only during the second phase of dual temperature shipment where the set point temperature is 7.5°C
HU (5°C – 6°C)	Hours at temperatures less than or equal to 6°C and greater than or equal to 5°C, calculated only during the second phase of the dual temperature cycle where the set point temperature is 7.5°C
HU (6°C – 7°C)	Hours at temperatures less than or equal to 7°C and greater than or equal to 6°C, calculated only during the second phase of the dual temperature cycle where the set point temperature is 7.5°C
HU (7°C – 7.5°C)	Hours at temperatures less than or equal to 7.5°C and greater than or equal to 7°C, calculated only during the second phase of the dual temperature cycle where the set point temperature is 7.5°C
CD (> 0.5°C)	Hours at temperatures greater than 0.5°C, calculated only during the third phase or cooling down (CD) phase of the dual temperature cycle where the set point temperature is reset back to -0.5°C
CD (≥ 7°C)	Hours at temperatures greater than or equal to 7°C, calculated only during the third phase of the dual temperature cycle where the set point temperature is reset back to -0.5°C
CD (7°C - 6°C)	Hours at temperatures less than or equal to 7°C and greater than or equal to 6°C, calculated only during the third phase of the dual temperature cycle where the set point temperature is reset back to -0.5°C
CD (6°C - 5°C)	Hours at temperatures less than or equal to 6°C and greater than or equal to 5°C, calculated only during the third phase of the dual temperature cycle where the set point temperature is reset back to -0.5°C
CD (5°C - 4°C)	Hours at temperatures less than or equal to 5°C and greater than or equal to 4°C, calculated only during the third phase of the dual temperature cycle where the set point temperature is reset back to -0.5°C
CD (4°C - 3°C)	Hours at temperatures less than or equal to 4°C and greater than or equal to 3°C, calculated only during the third phase of the dual temperature cycle where the set point temperature is reset back to -0.5°C
CD (3°C - 2°C)	Hours at temperatures less than or equal to 3°C and greater than or equal to 2°C, calculated only during the third phase of the dual temperature cycle where the set point temperature is reset back to -0.5°C
CD (2°C - 1°C)	Hours at temperatures less than or equal to 2°C and greater than or equal to 1°C, calculated only during the third phase of the dual temperature cycle where the set point temperature is reset back to -0.5°C
CD (1°C - 0°C)	Hours at temperatures less than or equal to 1°C and greater than or equal to 0°C, calculated only during the third phase of the dual temperature cycle where the set point temperature is reset back to -0.5°C
FR (0°C - 1°C)	Hours at temperatures less than or equal to 1°C and greater than or equal to 0°C, calculated over all three phases of the dual temperature cycle
FR (1°C - 2°C)	Hours at temperatures less than or equal to 2°C and greater than or equal to 1°C, calculated over all three phases of the dual temperature cycle

FR (2°C - 3°C)	Hours at temperatures less than or equal to 3°C and greater than or equal to 2°C, calculated over all three phases of the dual temperature cycle
FR (3°C - 4°C)	Hours at temperatures less than or equal to 4°C and greater than or equal to 3°C, calculated over all three phases of the dual temperature cycle
FR (4°C - 5°C)	Hours at temperatures less than or equal to 5°C and greater than or equal to 4°C, calculated over all three phases of the dual temperature cycle
FR (5°C - 6°C)	Hours at temperatures less than or equal to 6°C and greater than or equal to 5°C, calculated over all three phases of the dual temperature cycle
FR (6°C - 7°C)	Hours at temperatures less than or equal to 7°C and greater than or equal to 6°C, calculated over all three phases of the dual temperature cycle
FR (7°C - 8°C)	Hours at temperatures less than or equal to 8°C and greater than or equal to 7°C, calculated over all three phases of the dual temperature cycle
> 7.5°C FR	Hours at temperatures greater than 7.5°C, calculated over all three phases of the dual temperature cycle
> 8°C FR	Hours at temperatures greater than 8°C, calculated over all three phases of the dual temperature cycle

Table 3

The Scree test of Catell was used to determine the number of factors to be extracted during the factor analysis procedure performed on the 'Sapphire' pulp temperature data (containers 1 and 2). The eigenvalues were determined and the position where the decreasing eigenvalues seemed to level off was identified as the cut off point.

	'Sapphire' Container 1			'Sapphire' Container 2		
Factor	Eigenvalue	Percentage Total Variance	Cumulative Percentage Total variance	Eigenvalue	Percentage Total Variance	Cumulative Percentage Total variance
1	22.94	60.36	60.36	24.78	65.21	65.21
2	6.13	16.12	76.48	4.96	13.04	78.25
3	3.18	8.36	84.84	3.72	9.78	88.03
4	1.56	4.11	88.95	1.58	4.15	92.18
5	0.98	2.58	91.53	0.77	2.02	94.21

Table 4

The Scree test of Catell was used to determine the number of factors to be extracted during the factor analysis procedure performed on the 'Fortune' and 'Laetitia' pulp temperature data. The eigenvalues were determined and the position where the decreasing eigenvalues seemed to level off was identified as the cut off point.

	'Fortune'			'Laetitia'		
Factor	Eigenvalue	Percentage Total Variance	Cumulative Percentage Total variance	Eigenvalue	Percentage Total Variance	Cumulative Percentage Total variance
1	23.86	61.17	61.17	20.28	53.38	53.38
2	5.33	13.67	74.84	7.57	19.93	73.31
3	3.51	8.99	83.83	3.39	8.92	82.23
4	1.98	5.08	88.91	2.63	6.93	89.15
5	1.04	2.68	91.59	1.17	3.07	92.22

Table 5

Varimax normalized factor loadings were computed for each extracted factor to determine the variable–factor association for ‘Sapphire’ container 1 and 2 pulp temperature data (variables described in Table 2). Loadings greater than 0.61 (‘Sapphire’ container 1) and 0.59 (‘Sapphire’ container 2) represent variables defining the nature of the respective factors (loadings marked).

Variable	Sensitivity [z]	‘Sapphire’ container 1			‘Sapphire’ container 2		
		Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
> -0.5°C (excluding DT [v] phase)	CD	0.06356	-0.18946	0.07686	0.02434	***0.63801***	0.14457
≥ 0.5°C (excluding DT phase)	CD	0.47468	0.48895	***0.62194***	***0.67289***	0.35845	0.53721
2°C ≤ x ≤ 7°C FR [w]	HU and CD	***0.71410***	-0.00813	***0.68427***	***0.82684***	-0.00984	0.53368
≤ 3°C FR	CD	-0.55243	-0.15455	***-0.80003***	***-0.82091***	-0.05578	-0.54087
> 3°C FR	HU	0.55243	0.15455	***0.80003***	***0.82091***	0.05578	0.54087
± 1°C outside FR	HU, CD, OH	0.49535	0.49417	***0.61137***	***0.65324***	0.38085	0.54585
± 2°C outside FR	HU, CD, OH	0.60416	0.09291	***0.74759***	***0.86309***	0.12767	0.39250
≥ 1°C outside FR	CD	0.44771	0.51096	***0.62479***	***0.67239***	0.39142	0.50085
≤ 1°C outside FR	HU	***0.96003***	-0.00473	0.10586	0.22273	0.13729	***0.94252***
≤ 2°C outside FR	HU	***0.94521***	0.06193	0.09981	0.16164	0.18871	***0.93321***
HU (≤ 7.5°C) [x]	HU	***0.93476***	-0.20377	0.06599	0.23436	-0.09322	***0.93949***
HU (≤ 1°C)	CD	0.23893	0.12086	-0.58679	***-0.71361***	0.25518	0.25927
HU (1°C - 2°C)	CD	0.54366	0.10461	0.58104	***0.76600***	0.18640	0.48317
HU (2°C – 3°C)	CD	***0.92536***	0.00451	0.18614	0.34817	0.14322	***0.87674***
HU (3°C – 4°C)	CD	***0.93633***	-0.00368	0.20503	0.38089	-0.02089	***0.86771***
HU (4°C – 5°C)	HU and CD	***0.91675***	-0.04912	0.21208	0.43854	-0.09063	***0.84265***
HU (5°C – 6°C)	HU	***0.85232***	-0.27306	0.19812	0.54204	-0.13608	***0.78665***
HU (6°C – 7°C)	OH	0.26145	***-0.83352***	-0.01438	0.41333	-0.55773	***0.59085***
HU (7°C – 7.5°C)	OH	-0.31803	***-0.83877***	-0.24473	-0.01339	***-0.87597***	-0.16650
CD (> 0.5°C) [y]	CD	0.50693	0.37770	***0.70161***	***0.75176***	0.22353	0.56025
CD (≥ 7°C)	HU	***0.61130***	0.29805	0.57416	0.37781	0.37572	***0.66695***
CD (7°C - 6°C)	HU	***0.80421***	-0.04201	0.47522	0.49308	0.01171	***0.79938***
CD (6°C - 5°C)	HU	***0.66977***	-0.05619	0.65306	0.68815	0.00818	***0.66660***
CD (5°C - 4°C)	HU and CD	0.64488	0.02045	***0.73753***	***0.76683***	-0.06446	0.54744
CD (4°C - 3°C)	CD	0.55008	0.08967	***0.80791***	***0.84296***	0.03617	0.49464
CD (3°C - 2°C)	CD	0.44065	0.11387	***0.84910***	***0.90722***	0.04179	0.38945
CD (2°C - 1°C)	CD	0.39655	0.28630	***0.81110***	***0.92470***	0.07179	0.25943
CD (1°C - 0°C)	CD	-0.02153	0.56195	-0.59058	***-0.66846***	0.55936	-0.16787
FR (0°C - 1°C)	CD	-0.03291	0.40596	***-0.81059***	***-0.77101***	0.51092	-0.05996
FR (1°C - 2°C)	CD	0.21904	0.16833	***0.86346***	***0.92491***	0.11278	0.21858
FR (2°C - 3°C)	CD	0.58041	0.10222	***0.77347***	***0.89248***	0.06324	0.28877
FR (3°C - 4°C)	CD	***0.70195***	0.07098	0.69286	***0.77873***	-0.01928	0.60086
FR (4°C - 5°C)	HU and CD	***0.76920***	-0.00071	0.61121	***0.71202***	-0.08480	0.65986
FR (5°C - 6°C)	HU	***0.77864***	-0.13092	0.55322	0.65347	-0.04503	***0.72992***
FR (6°C - 7°C)	HU	***0.77340***	-0.38820	0.38537	0.50895	-0.20455	***0.79487***
FR (7°C - 8°C)	OH	0.07358	***-0.88088***	-0.09265	-0.06955	***-0.88922***	-0.06228
> 7.5°C FR	HU	-0.31131	0.60695	***0.62675***	0.08292	0.60938	***-0.66570***
> 8°C FR	OH	-0.19061	***0.77640***	0.54064	0.13546	***0.90540***	-0.26206

v Second phase or heating up phase of dual temperature shipment cycle.

w Full range or all three phase of the dual temperature cycle.

x Heating up process taking place during the second phase of the dual temperature cycle.

y Cooling down process taking place during the third phase of the dual temperature cycle.

z The sensitivity of each variable to the heating up- (HU), cooling down- (CD) or general over heating (OH) phases was determined by comparing the variables to each other in terms of their duration (data not presented).

Table 6

Varimax normalized factor loadings were computed for each extracted factor to determine the variable-factor association for the 'Fortune' and 'Laetitia' pulp temperature data (variables described in Table 2). Loadings greater than 0.65 ('Fortune') and 0.61 ('Laetitia') represent variables defining the nature of the respective factors (loadings marked).

Variable	Sensitivity [z]	'Fortune'			'Laetitia'		
		Factor 1	Factor 2	Factor 3	Factor 1	Factor 2	Factor 3
> -0.5°C (excluding DT [v] phase)	CD	0.04435	0.10907	0.27227	-	-	-
≥ 0.5°C (excluding DT phase)	CD	0.29348	***0.85352***	0.34727	***0.80049***	0.17288	0.34424
2°C ≤ x ≤ 7°C FR [w]	HU and CD	***0.85353***	0.47656	0.15166	0.67137	***0.72810***	0.06292
≤ 3°C FR	CD	-0.63470	***-0.67842***	-0.23585	***-0.91275***	-0.26992	-0.17512
> 3°C FR	HU	0.63470	***0.67842***	0.23585	***0.91275***	0.26992	0.17512
± 1°C outside FR	HU, CD, OH	0.39218	***0.83188***	0.32286	***0.80152***	0.23170	0.34686
± 2°C outside FR	HU, CD, OH	***0.71315***	0.67246	0.17016	***0.77028***	0.46787	0.25761
≥ 1°C outside FR	CD	0.28492	***0.85620***	0.34690	***0.80567***	0.17184	0.35459
≥ 2°C outside FR	CD	0.58035	***0.78153***	0.18820	***0.82854***	0.24607	0.26173
≤ 1°C outside FR	HU	***0.90632***	0.34635	0.04306	0.37554	***0.90545***	0.08511
≤ 2°C outside FR	HU	***0.92072***	0.29854	0.09879	0.30594	***0.92481***	0.14647
HU (≤ 7.5°C) [x]	HU	***0.85290***	0.37642	-0.20412	0.43105	***0.86403***	-0.12902
HU (≤ 1°C)	CD	0.51713	0.17168	-0.15883	-0.33319	0.09359	-0.28963
HU (1°C - 2°C)	CD	0.51446	***0.72931***	0.01175	***0.82734***	0.18317	0.22782
HU (2°C – 3°C)	CD	***0.65643***	0.62582	0.01937	***0.68869***	0.55005	0.01477
HU (3°C – 4°C)	CD	***0.83328***	0.45414	0.07594	0.21326	***0.94820***	0.17873
HU (4°C – 5°C)	HU and CD	***0.96083***	0.14969	0.16905	-0.19894	***0.92736***	0.24642
HU (5°C – 6°C)	HU	***0.95451***	-0.04147	0.20321	***0.77745***	-0.19845	-0.45808
HU (6°C – 7°C)	OH	-0.25136	0.40963	***-0.66003***	0.31706	-0.59438	***-0.67370***
HU (7°C – 7.5°C)	OH	-0.46092	-0.11963	***-0.79849***	-0.04461	-0.50724	***-0.78072***
CD (> 0.5°C) [y]	CD	0.45466	***0.83704***	0.25745	***0.89559***	0.18729	0.18160
CD (≥ 7°C)	HU	-0.06645	***0.88539***	-0.04423	***0.87469***	0.00148	0.16091
CD (7°C - 6°C)	HU	***0.89609***	0.25602	0.21524	***0.83416***	0.02956	-0.13227
CD (6°C - 5°C)	HU	0.62117	0.60061	0.13775	***0.77886***	-0.01313	-0.21218
CD (5°C - 4°C)	HU and CD	***0.73846***	0.41934	0.14924	0.48175	***0.75762***	0.09339
CD (4°C - 3°C)	CD	***0.79067***	0.34574	0.24312	***0.82095***	0.36798	0.10766
CD (3°C - 2°C)	CD	0.39742	***0.75776***	0.16562	***0.89731***	0.33045	0.14023
CD (2°C - 1°C)	CD	0.22521	***0.85086***	0.18226	***0.90648***	0.24740	0.24918
CD (1°C - 0°C)	CD	-0.09087	0.26757	***0.78217***	***-0.70504***	-0.13635	0.23964
FR (0°C - 1°C)	CD	-0.04871	0.14247	***0.80537***	***-0.61360***	-0.08274	0.02897
FR (1°C - 2°C)	CD	0.13336	***0.88312***	0.11852	***0.74307***	0.08887	0.30829
FR (2°C - 3°C)	CD	0.48231	***0.77176***	0.14094	***0.84704***	0.46590	0.11888
FR (3°C - 4°C)	CD	***0.82568***	0.38123	0.21335	0.57885	***0.76247***	0.17089
FR (4°C - 5°C)	HU and CD	***0.89349***	0.31183	0.16816	-0.05790	***0.95154***	0.23015
FR (5°C - 6°C)	HU	***0.92908***	0.23203	0.20019	***0.82769***	-0.07381	-0.30502
FR (6°C - 7°C)	HU	***0.82396***	0.47943	-0.10601	***0.76293***	-0.26289	-0.41943
FR (7°C - 8°C)	OH	-0.28736	-0.21671	***-0.84488***	-0.17291	-0.24277	***-0.79003***
> 7.5°C FR	HU	***-0.93331***	0.08435	0.19964	0.18027	***-0.86361***	0.36305
> 8°C FR	OH	-0.36975	0.33254	***0.79046***	0.32643	-0.26560	***0.81119***

v Second phase or heating up phase of dual temperature shipment cycle.

w Full range or all three phase of the dual temperature cycle.

x Heating up process taking place during the second phase of the dual temperature cycle.

y Cooling down process taking place during the third phase of the dual temperature cycle.

z The sensitivity of each variable to the heating up- (HU), cooling down- (CD) or general over heating (OH) phases was determined by comparing the variables to each other in terms of their duration (data not presented).

Table 7

Mean number of hours within each temperature range for clusters 1 to 3 in 'Sapphire' containers 1 and 2.

	'Sapphire' container 1			'Sapphire' container 2		
Variable	HU (≤ 7.5°C) [w]	CD (> 0.5°C) [x]	> 8°C FR [y]	HU (≤ 7.5°C)	CD (> 0.5°C)	> 8°C FR
Cluster 1	69 [z] a	95 a	48 a	64 a	83 a	52 a
Cluster 2	77 b	205 b	56 a	76 b	188 b	62 a
Cluster 3	79 b	309 c	68 b	85 b	312 c	53 a
P>F	0.0031	<0.0001	<0.0001	<0.0001	<0.0001	0.1309
F	6.4	483.6	13.2	21.6	468.3	2.1

w Variable HU (≤ 7.5°C) represents hours at temperatures less and equal to 7.5°C, calculated only during the second phase or heating up (HU) phase of the dual temperature cycle where the set point temperature is 7.5°C.

x Variable CD (> 0.5°) represents hours at temperatures greater than 0.5°C, calculated only during the third phase or cooling down (CD) phase of the dual temperature cycle where the set point temperature is reset back to -0.5°C.

y Variable >8°C FR represents hours at temperatures greater than 8°C, calculated throughout all three phases of the dual temperature cycle.

z Mean separation within columns followed by different letters according to Bonferroni (5% level).

Table 8

Mean number of hours within each temperature range for clusters 1 to 3 in 'Fortune' and 'Laetitia.

	'Fortune'			'Laetitia'		
Variable	HU (≤ 7.5°C) [w]	CD (> 0.5°C) [x]	> 8°C FR [y]	HU (≤ 7.5°C)	CD (> 0.5°C)	> 8°C FR
Cluster 1	68 [z] a	86 a	30 a	61 a	68 a	34 a
Cluster 2	80 b	142 b	39 a	66 a	110 b	46 ab
Cluster 3	93 b	237 c	37 a	73 b	180 c	53 b
P>F	<0.0001	<0.0001	0.1532	0.0005	<0.0001	0.0019
F	18.1	156.8	1.9	8.6	303.7	7.0

w Variable HU (≤ 7.5°C) represents hours at temperatures less and equal to 7.5°C, calculated only during the second phase or heating up (HU) phase of the dual temperature cycle where the set point temperature is 7.5°C.

x Variable CD (> 0.5°) represents hours at temperatures greater than 0.5°C, calculated only during the third phase or cooling down (CD) phase of the dual temperature cycle where the set point temperature is reset back to -0.5°C.

y Variable >8°C FR represents Hours at temperatures greater than 8°C, calculated throughout all three phases of the dual temperature cycle.

z Mean separation within columns followed by different letters according to Bonferroni (5% level).

Table 9

Discriminant variables (as described in Table 2) selected, in order of importance, by the stepwise discriminant analysis of the created pulp temperature variables of ‘Sapphire’ container 1 for the three cluster groups.

Step	Discriminant variable	Partial Wilks’s Lambda*	F-value	Pr > F
1	CD (>0.5°C)	0.1932	483.6	<0.0001
2	± 1°C outside FR	0.7336	128.5	<0.0001
3	HU (5°C – 6°C)	0.9250	98.9	0.0006
4	FR (1°C - 2°C)	0.9712	82.2	0.0037
5	CD (1°C - 0°C)	0.9202	72.1	0.0062
6	≥ 0.5°C (excluding DT phase)	0.8132	63.2	0.0432
7	FR (7°C - 8°C)	0.9146	57.1	0.0368

* Contribution to overall discrimination where the smaller the value is, the greater the contribution to discrimination between groups.

Table 10

Discriminant variables (as described in Table 2) selected, in order of importance, by the stepwise discriminant analysis of the created pulp temperature variables of ‘Sapphire’ container 2 for the three cluster groups.

Step	Discriminant variable	Partial Wilks’s Lambda*	F-value	Pr > F
1	CD (>0.5°C)	0.3109	468.3	<0.0001
2	± 1°C outside FR	0.8610	140.7	<0.0001
3	CD (≥ 7°C)	0.8298	104.3	0.0031
4	≥ 0.5°C (excluding DT phase)	0.9003	83.3	0.0236

* Contribution to overall discrimination where the smaller the value is, the greater the contribution to discrimination between groups.

Table 11

Discriminant variables (as described in Table 2) selected, in order of importance, by the stepwise discriminant analysis of the created pulp temperature variables of the 'Fortune' container for the three cluster groups.

Step	Discriminant variable	Partial Wilks's Lambda*	F-value	Pr > F
1	≥ 2°C outside FR	0.8578	163.7	<0.0001
2	CD (4°C - 3°C)	0.7920	70.7	<0.0001
3	FR (1°C - 2°C)	0.5343	80.1	<0.0001
4	CD (2°C - 1°C)	0.5274	78.3	<0.0001
5	CD (7°C - 6°C)	0.8678	79.8	<0.0001
6	FR (2°C - 3°C)	0.9340	72.3	0.0087
7	HU (6°C – 7°C)	0.7590	64.0	0.1000
8	≥ 1°C outside FR	0.8626	62.2	0.0034
9	CD (>7.5°C - 7°C)	0.8251	58.9	0.0243
10	FR (0°C - 1°C)	0.7746	57.3	0.0131

* Contribution to overall discrimination where the smaller the value is, the greater the contribution to discrimination between groups.

Table 12

Discriminant variables (as described in Table 2) selected, in order of importance, by the stepwise discriminant analysis of the created pulp temperature variables of the 'Laetitia' container for the three cluster groups.

Step	Discriminant variable	Partial Wilks's Lambda*	F-value	Pr > F
1	CD (>0.5°C)	0.4525	303.7	<0.0001
2	CD (1°C - 0°C)	0.7546	81.6	0.0005
3	CD (7°C - 6°C)	0.8766	66.7	0.0001
4	CD (6°C - 5°C)	0.9467	53.7	0.0215
5	± 1°C outside FR	0.8119	45.9	0.0274
6	≥ 0.5°C (excluding DT phase)	0.9177	40.5	0.0402

* Contribution to overall discrimination where the smaller the value is, the greater the contribution to discrimination between groups.

Table 13

Mean number of hours within each temperature range (as described in Table 2) for clusters 1 to 3 in 'Sapphire' container 1.

	CD (>0.5°)	±1°C outside FR	HU(5-6°C)	FR(1-2°C)	CD(1-0°C)	≥0.5°C (excluding DT phase)	FR(7-8°C)
Cluster 1	94.5 [z] a	224.8 a	9.0 a	34.9 a	180.8 a	167.2 a	33.1 a
Cluster 2	204.9 b	476.2 b	10.0 ab	71.9 b	179.2 a	398.3 b	31.9 a
Cluster 3	309.1 c	582.7 c	10.4 b	212.1 c	111.4 b	497.0 c	29.0 a
Pr>F	<0.0001	<0.0001	0.0096	<0.0001	0.0029	<0.0001	0.1861

z Mean separation within columns followed by different letters according to Bonferroni (5% level).

Table 14

Mean number of hours within each temperature range (as described in Table 2) for clusters 1 to 3 in 'Sapphire' container 2.

	CD (>0.5°)	±1°C outside FR	CD(≥ 7°C)	≥0.5°C (excluding DT phase)
Cluster 1	83 [z] a	208 a	20 a	151 a
Cluster 2	188 b	467 b	36 b	383 b
Cluster 3	312 c	579 c	40 b	496 c
Pr>F	<0.0001	<0.0001	<0.0001	<0.0001

z Mean separation within columns followed by different letters according to Bonferroni (5% level).

Table 15

Mean number of hours within each temperature range (as described in Table 2) for clusters 1 to 3 in 'Fortune'.

	≥ 2°C outside FR	CD (4-3°C)	FR (1-2°C)	CD (2-1°C)	CD (7-6°C)	FR (2-3°C)	HU (6-7°C)	≥ 1°C outside FR	CD (≥ 7°C)	FR (0-1°C)
Cluster 1	58 [z] a	9 a	21 a	15 a	5 a	15 a	14 ab	111 a	17 a	202 a
Cluster 2	96 b	11 b	44 b	33 b	9 b	25 b	15 a	213 b	26 b	276 b
Cluster 3	154 c	31 c	117 c	48 c	20 c	38 c	12 b	356 c	30 b	185 a
Pr>F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0451	<0.0001	<0.0001	0.0004

z Mean separation within columns followed by different letters according to Bonferroni (5% level).

Table 16

Mean number of hours within each temperature range (as described in Table 2) for clusters 1 to 3 in 'Fortune'.

	CD (>0.5°)	CD(1-0°C)	CD(7-6°C)	CD(6-5°C)	±1°C outside FR	≥0.5°C (excluding DT phase)
Cluster 1	68[z] a	96 a	4 a	4 a	143 a	97 a
Cluster 2	110 b	109 a	7 b	8 b	271 b	221 b
Cluster 3	180 c	64 b	9 c	9 b	474 c	410 c
Pr>F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

[z] Mean separation within columns followed by different letters according to Bonferroni (5% level).

Table 17

Mean firmness upon arrival and internal defects after a seven day shelf life period as influenced by cluster analyses of 'Sapphire' container 1 and 2, 'Fortune' and 'Laetitia'.

	'Sapphire' 1		'Sapphire' 2		'Fortune'	'Laetitia'	
Variable	Firmness (kg)	% Internal defects	Firmness (kg)	% Internal defects	Firmness (kg)	Firmness (kg)	% Internal defects
Cluster 1	6.7[z] a	10.2 a	6.2 a	23.2 a	7.5 a	6.3 a	21.1 a
Cluster 2	5.7 b	21.2 b	6.0 ab	12.8 a	7.4 a	6.1 ab	20.4 a
Cluster 3	6.2 ab	12.5 ab	5.4 b	13.6 a	7.3 a	5.8 b	33.7 a
Pr > F	0.0033	0.0363	0.0061	0.0921	0.3282	0.0153	0.0469

[z] Mean separation within columns followed by different letters according to Bonferroni (5% level).

Table 18

Adjusted mean fruit firmness upon arrival, as determined by an analysis of covariance between cluster groups with the average fruit firmness prior to shipment as the covariate, in 'Sapphire' container 1 and 2.

	'Sapphire' 1	'Sapphire' 2
Variable	Firmness (kg)	Firmness (kg)
Cluster 1	6.7[z] a	6.2 a
Cluster 2	5.7 b	6.0 b
Cluster 3	6.2 c	5.5 b
Pr > F		
Firmness Before	0.1371	0.0017
Cluster	<0.0001	<0.0001

[z] Mean separation within columns followed by different letters according to Bonferroni (5% level).

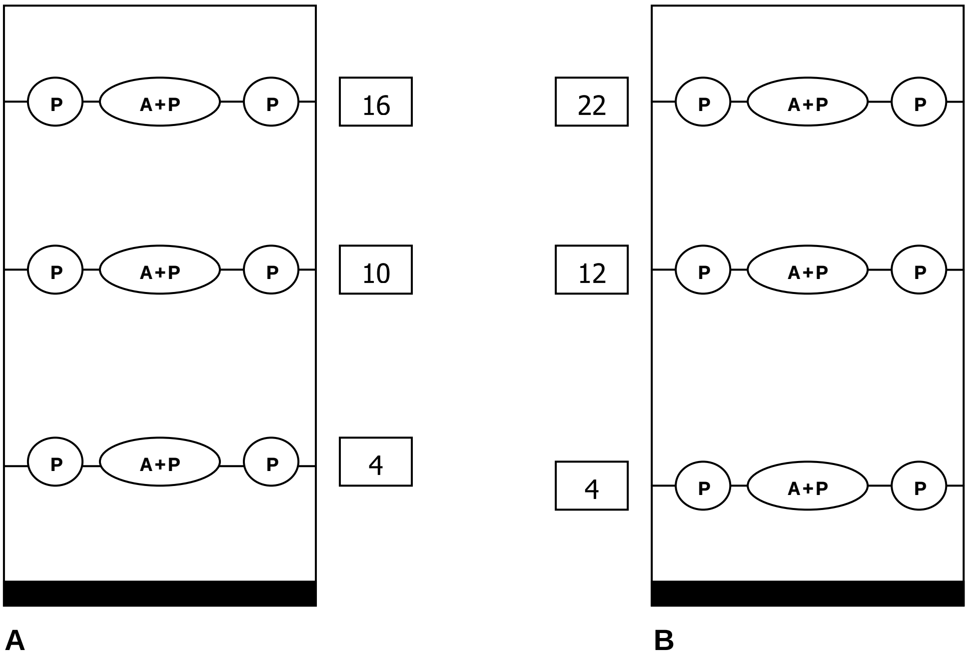


Figure 1: Positioning of one air temperature logger (A) and three pulp temperature loggers (P) on the 4th, 10th and 16th layers of a pallet containing A-size plums packed in 104 mm X 300 mm X 400 mm double layer (A) cartons and on the 4th, 12th and 22nd layer of a pallet containing AA-size plums packed in 76 mm X 400 mm X 600 mm single layer cartons (B).

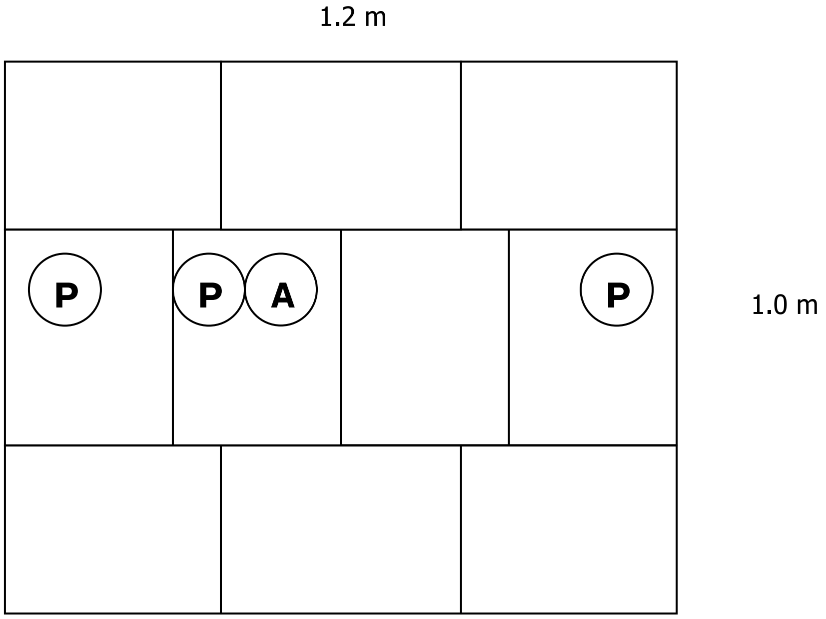


Figure 2: Positioning of the one air temperature logger (A) and the three pulp temperature loggers (P) on each of the assigned layers of a pallet containing A-size plums packed in 104 mm X 300 mm X 400 mm cartons.

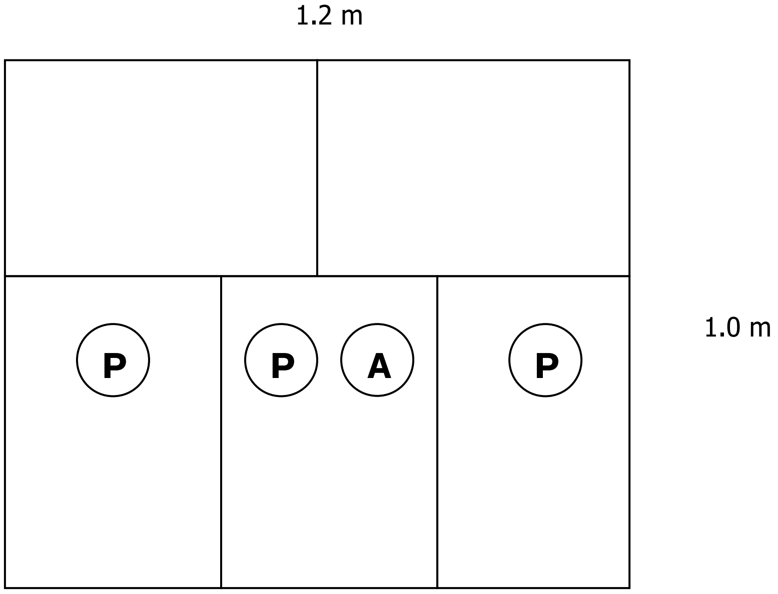


Figure 3: Positioning of the one air temperature logger (A) and the three pulp temperature loggers (P) on each of the assigned layers of a pallet containing AA-size plums packed in 76 mm X 300 mm X 400 mm cartons.

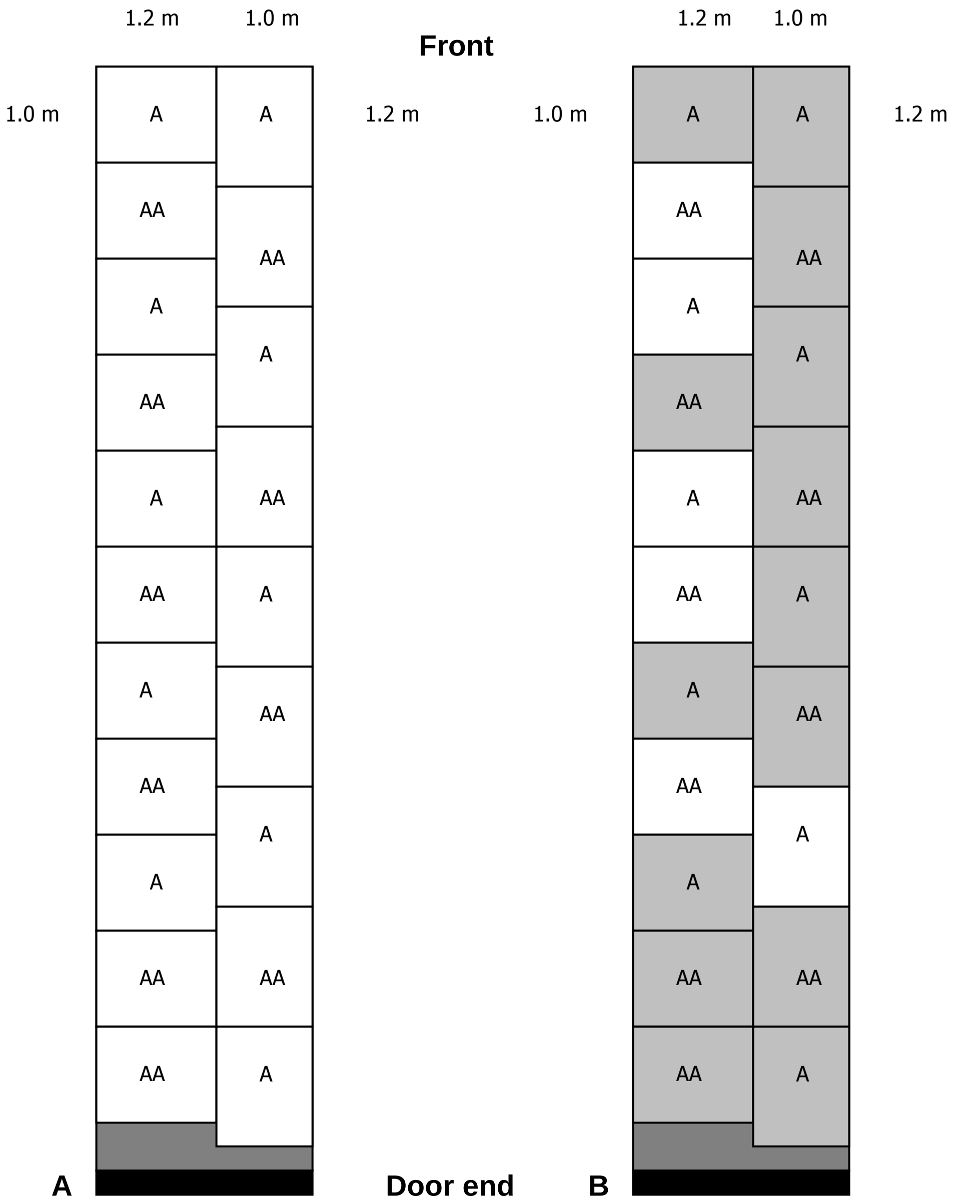
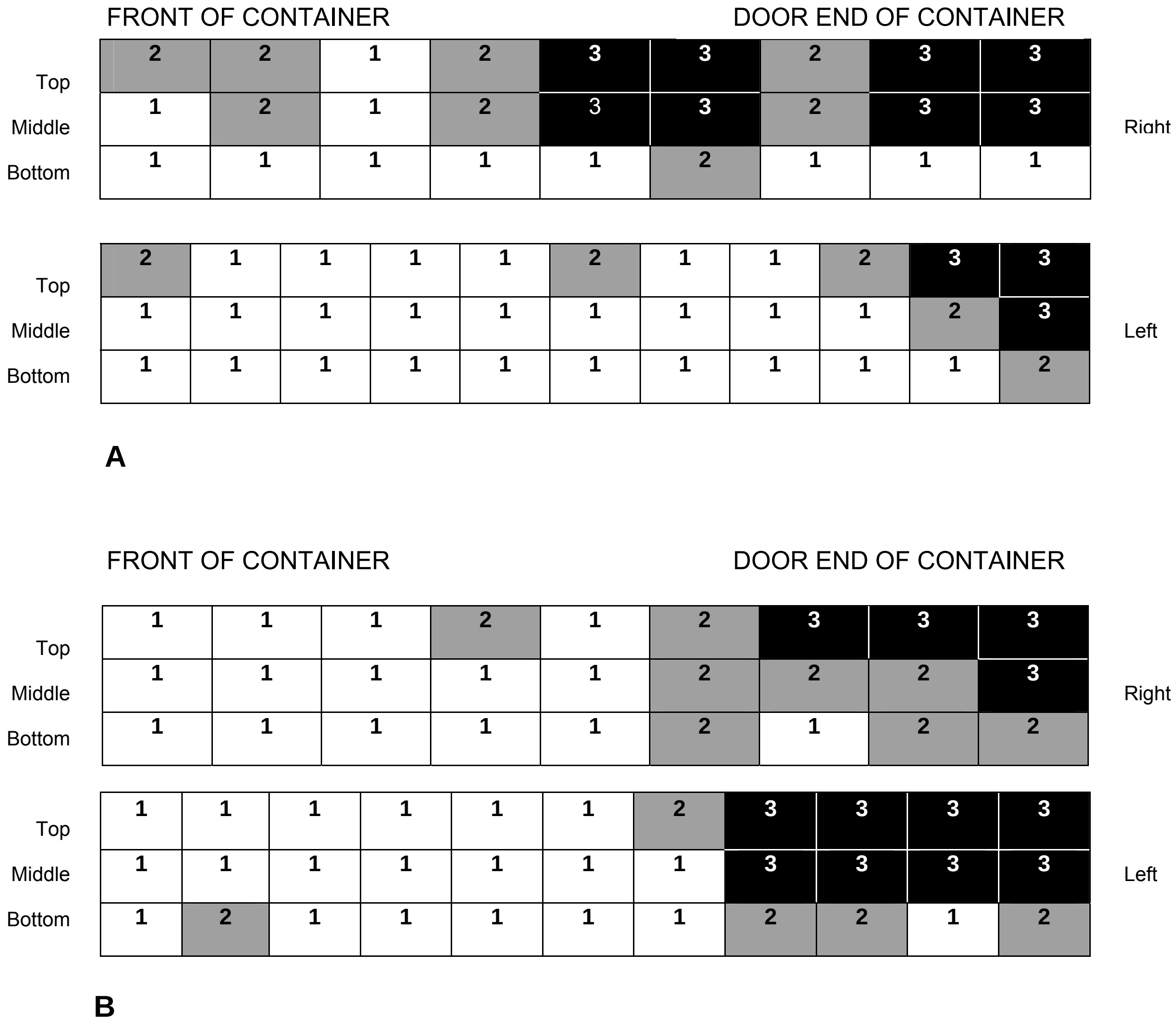


Figure 4 (A): Ten pallets of A-size fruit and 10 pallets of AA-size fruit were loaded and randomly distributed throughout each integral reefer container.

Figure 4 (B): ‘Red’ pallets (indicated in grey) and ‘green’ pallets (indicated in white) were created in the ‘Sapphire’ trial by performing colour sorting. Both fruit size and colour sorting were taken into consideration during the random distribution of pallets throughout the integral container.



FRONT OF CONTAINER DOOR END OF CONTAINER

Top	2	2	1	2	3	3	2	3	3	
Middle	1	2	1	2	3	3	2	3	3	Right
Bottom	1	1	1	1	1	2	1	1	1	

Top	2	1	1	1	1	2	1	1	2	3	3	
Middle	1	1	1	1	1	1	1	1	1	2	3	Left
Bottom	1	1	1	1	1	1	1	1	1	1	2	

A

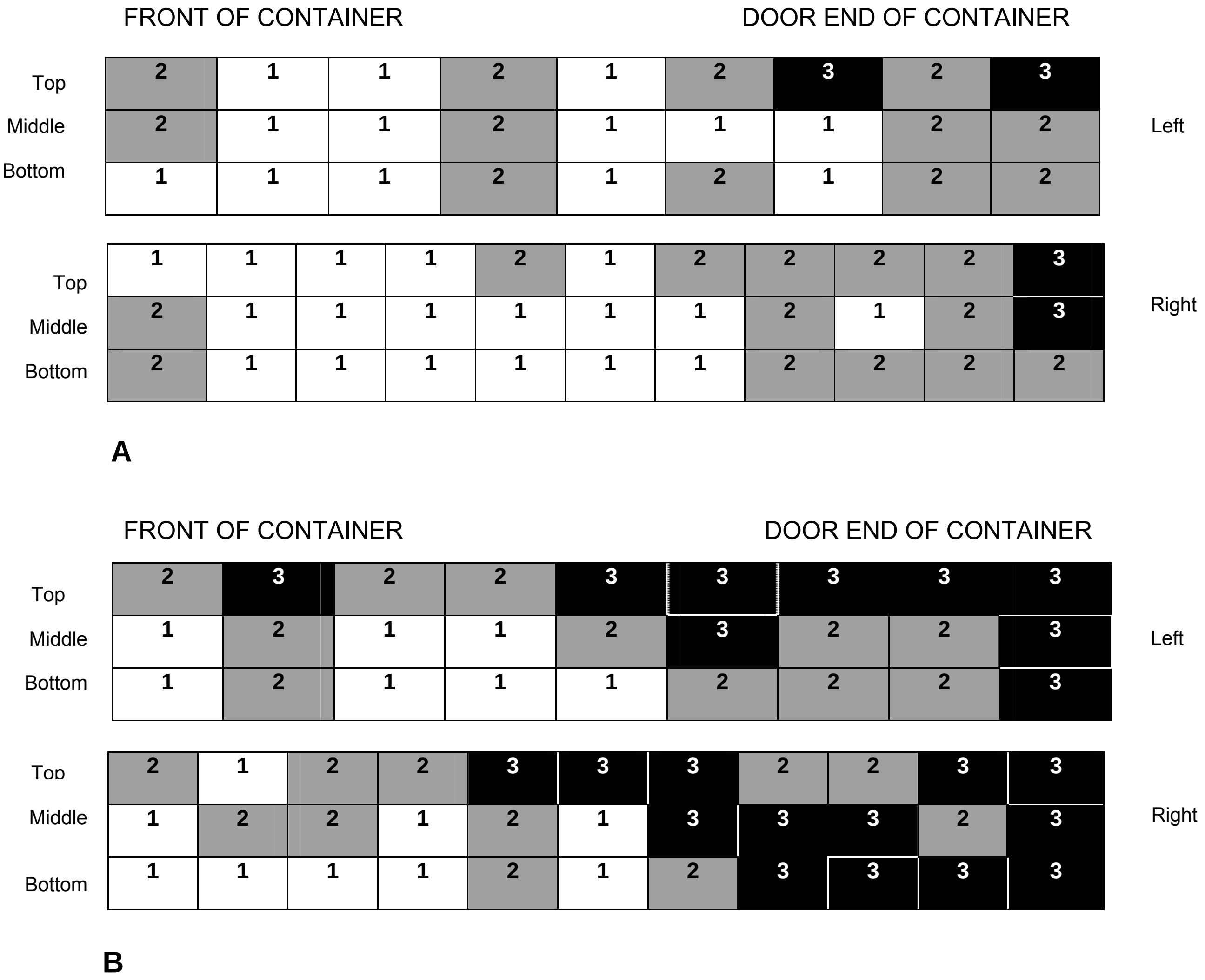
FRONT OF CONTAINER DOOR END OF CONTAINER

Top	1	1	1	2	1	2	3	3	3	
Middle	1	1	1	1	1	2	2	2	3	Right
Bottom	1	1	1	1	1	2	1	2	2	

Top	1	1	1	1	1	1	2	3	3	3	3	
Middle	1	1	1	1	1	1	1	3	3	3	3	Left
Bottom	1	2	1	1	1	1	1	2	2	1	2	

B

Figure 5: The sixty positions within 'Sapphire' container 1 (Figure 5A) and container 2 (Figure 5B) were classified into three pulp temperature zones by performing a cluster analysis procedure. Positions in black indicate warm areas within the integral container, positions in grey intermediate temperature areas and positions in white, cool areas.



FRONT OF CONTAINER DOOR END OF CONTAINER

Top	2	1	1	2	1	2	3	2	3
Middle	2	1	1	2	1	1	1	2	2
Bottom	1	1	1	2	1	2	1	2	2

Left

Top	1	1	1	1	2	1	2	2	2	2	3
Middle	2	1	1	1	1	1	1	2	1	2	3
Bottom	2	1	1	1	1	1	1	2	2	2	2

Right

A

FRONT OF CONTAINER DOOR END OF CONTAINER

Top	2	3	2	2	3	3	3	3	3
Middle	1	2	1	1	2	3	2	2	3
Bottom	1	2	1	1	1	2	2	2	3

Left

Top	2	1	2	2	3	3	3	2	2	3	3
Middle	1	2	2	1	2	1	3	3	3	2	3
Bottom	1	1	1	1	2	1	2	3	3	3	3

Right

B

Figure 6: The sixty positions within the ‘Fortune’ container (Figure 6A) and ’Laetitia’ container (Figure 6B) were classified into three pulp temperature zones by performing a cluster analysis procedure. Positions in black indicate warm areas within the integral container, positions in grey intermediate temperature areas and positions in white, cool areas.

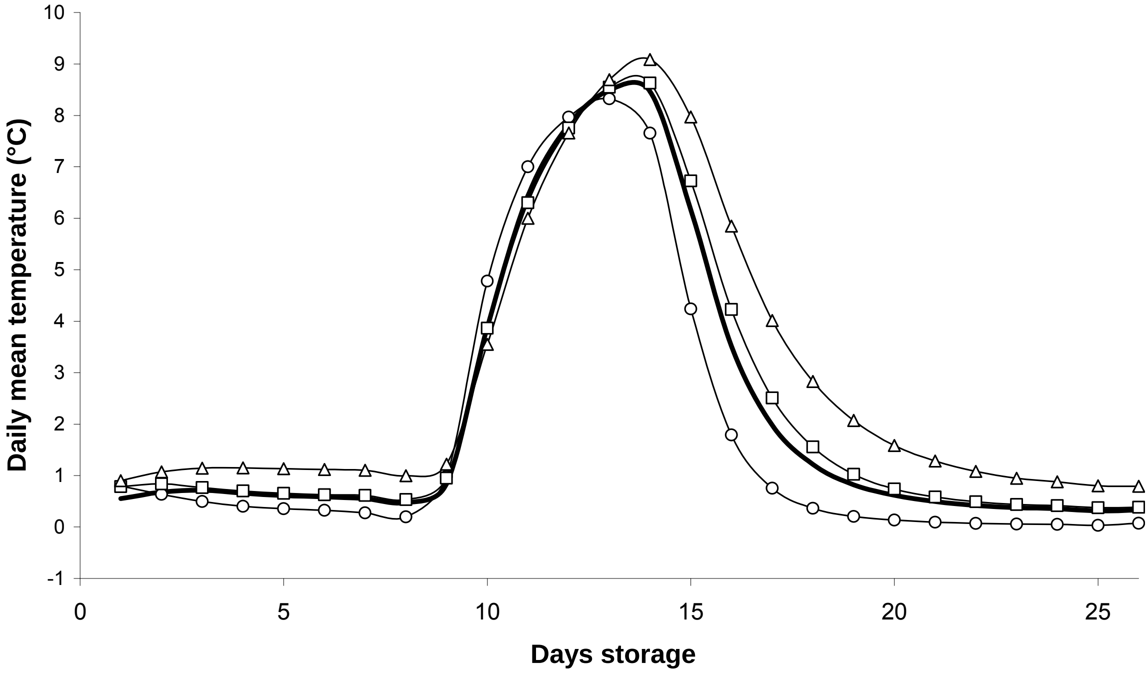


Figure 7: Daily mean pulp temperature (°C) of cluster 1 (circles), cluster 2 (squares) and cluster 3 (triangles), and daily mean container air temperature (°C; bold line) in 'Sapphire' container 1 during commercial dual temperature shipping.

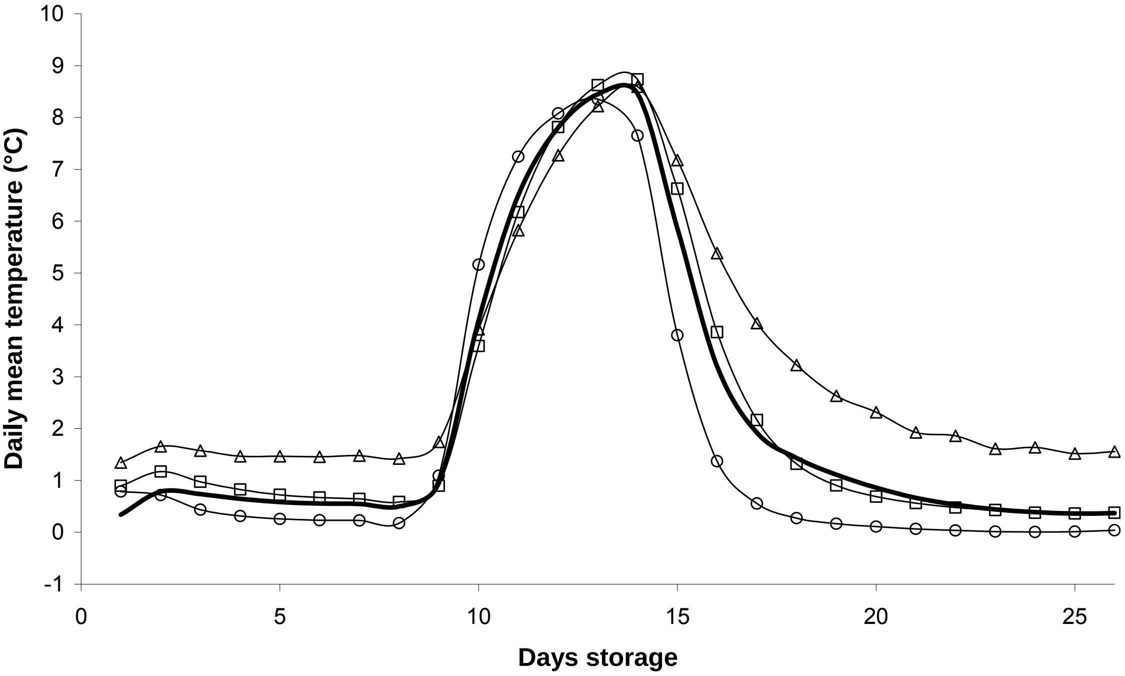


Figure 8: Daily mean pulp temperature (°C) of cluster 1 (circles), cluster 2 (squares) and cluster 3 (triangles), and daily mean container air temperature (°C; bold line) in 'Sapphire' container 2 during commercial dual temperature shipping.

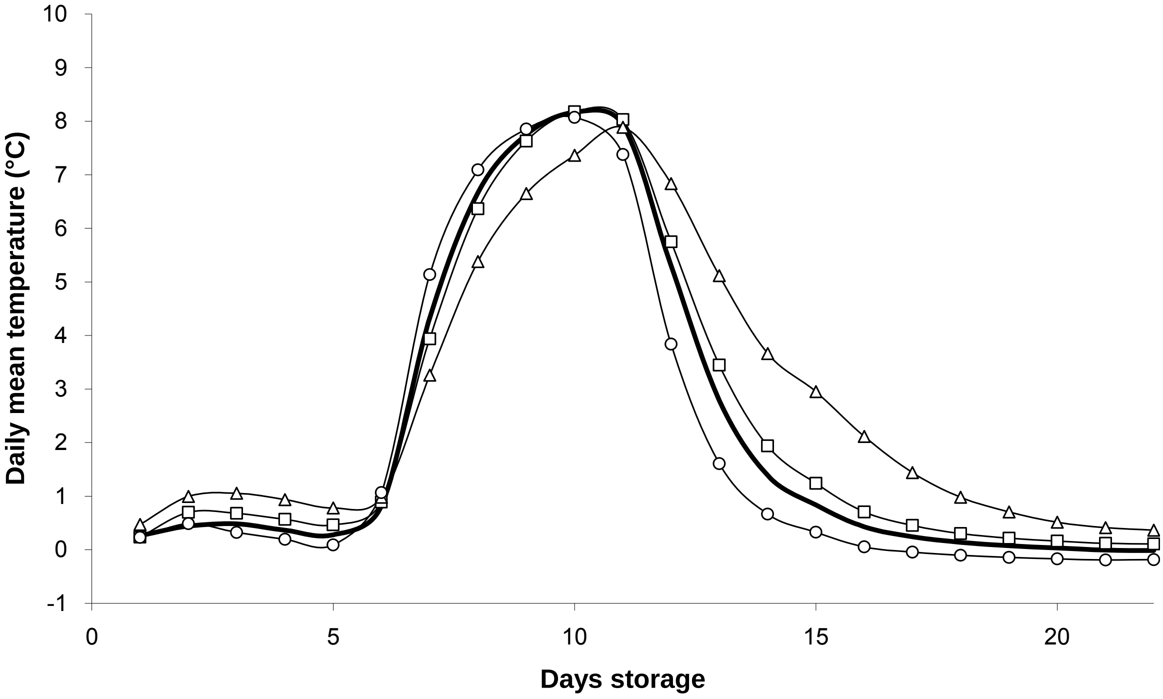


Figure 9: Daily mean pulp temperature (°C) of cluster 1 (circles), cluster 2 (squares) and cluster 3 (triangles), and daily mean container air temperature (°C; bold line) in the ‘Fortune’ container during commercial dual temperature shipping.

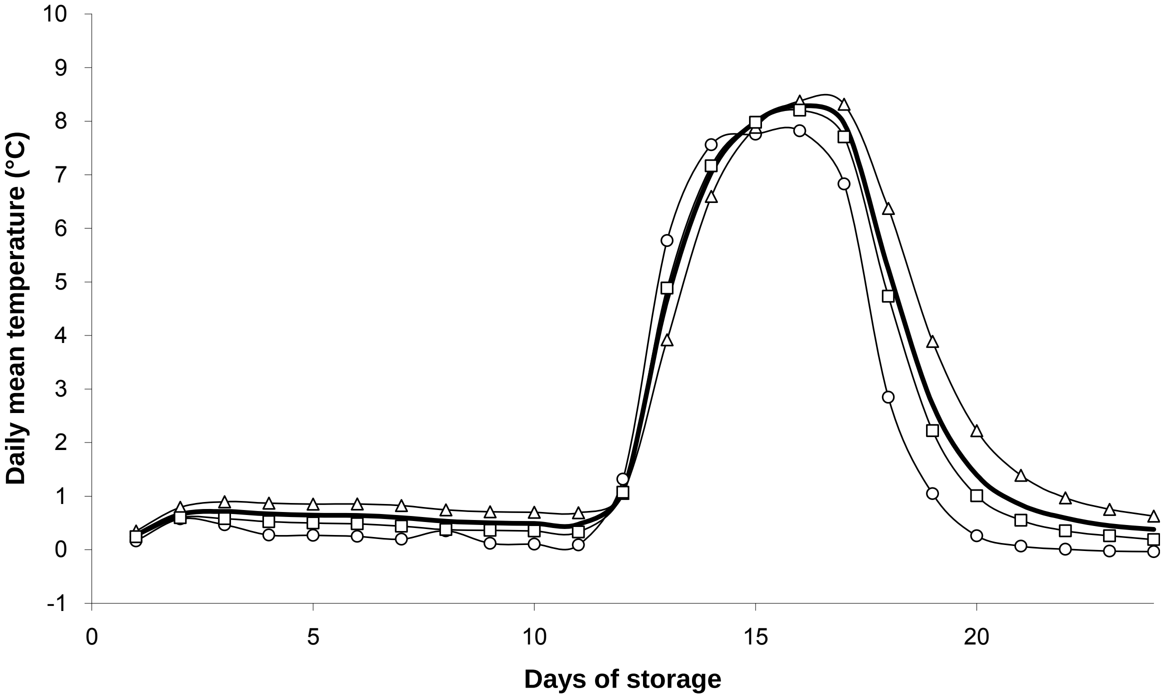


Figure 10: Daily mean pulp temperature (°C) of cluster 1 (circles), cluster 2 (squares) and cluster 3 (triangles), and daily mean container air temperature (°C; bold line) in the ‘Laetitia’ container during commercial dual temperature shipping.

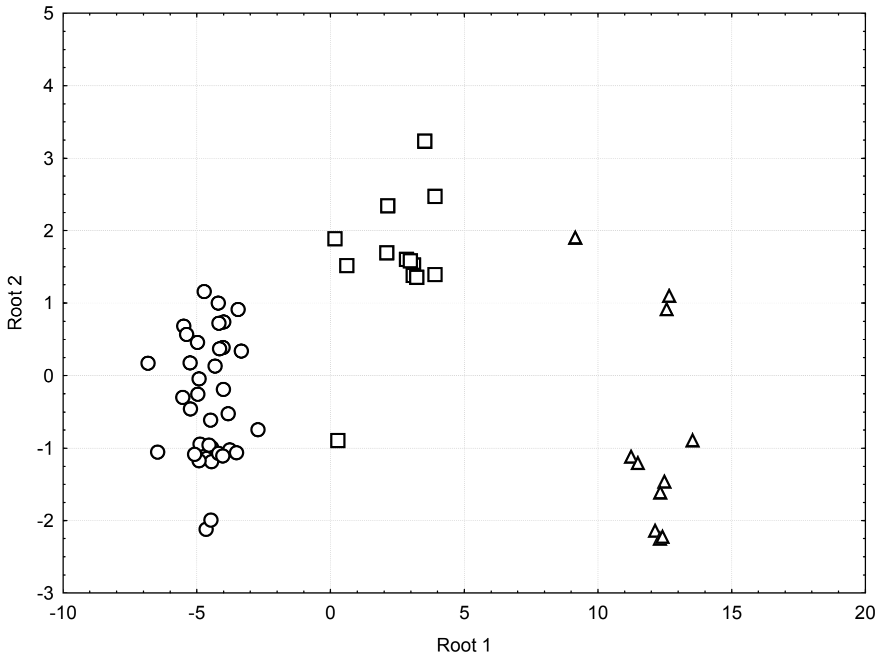


Figure 11: Discrimination between clusters one (circles), two (squares) and three (triangles) of ‘Sapphire’ container 1, using variables CD (>0.5°C), ± 1°C outside FR, HU (5°C – 6°C), FR (1°C - 2°C), CD (1°C - 0°C), ≥ 0.5°C (excluding DT phase) and FR (7°C - 8°C) in a canonical analysis.

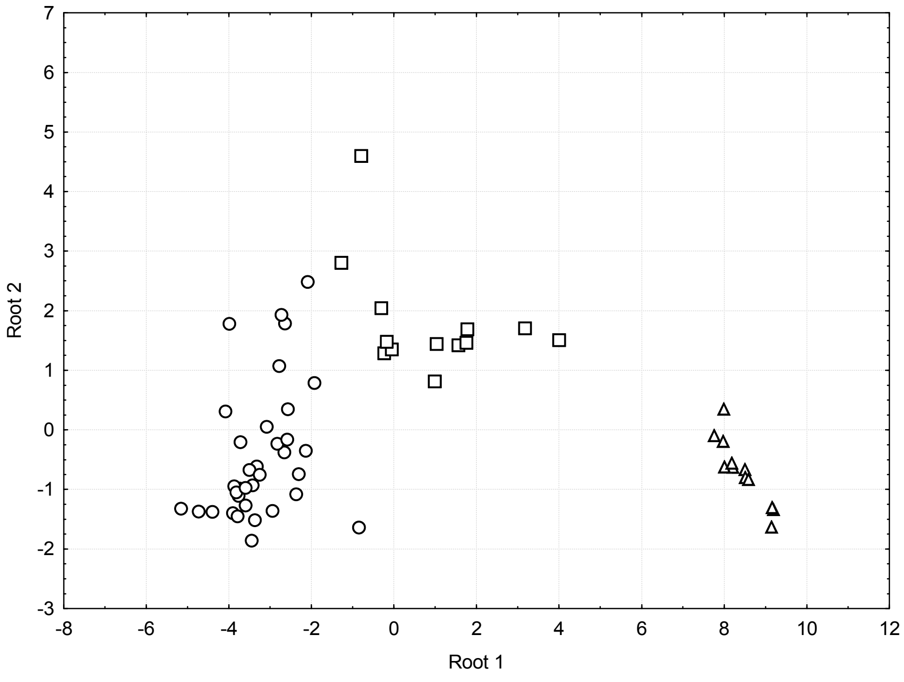


Figure 12: Discrimination between clusters one (circles), two (squares) and three (triangles) of ‘Sapphire’ container 2, using variables CD (>0.5°C), ± 1°C outside FR, CD (≥ 7°C) and ≥ 0.5°C (excluding DT phase) in a canonical analysis.

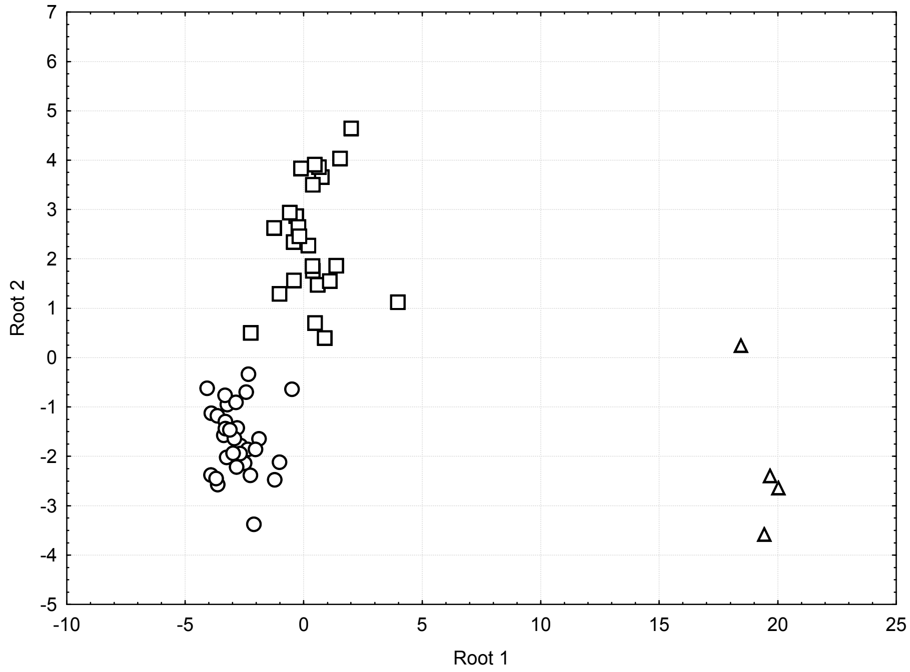


Figure 13: Discrimination between clusters one (circles), two (squares) and three (triangles) of 'Fortune', using variables ≥ 2°C outside FR, CD (4°C - 3°C), FR (1°C - 2°C), CD (2°C - 1°C), CD (7°C - 6°C), FR (2°C - 3°C), HU (6°C – 7°C), ≥ 1°C outside FR, CD (≥ 7°C) and FR (0°C - 1°C) in a canonical analysis.

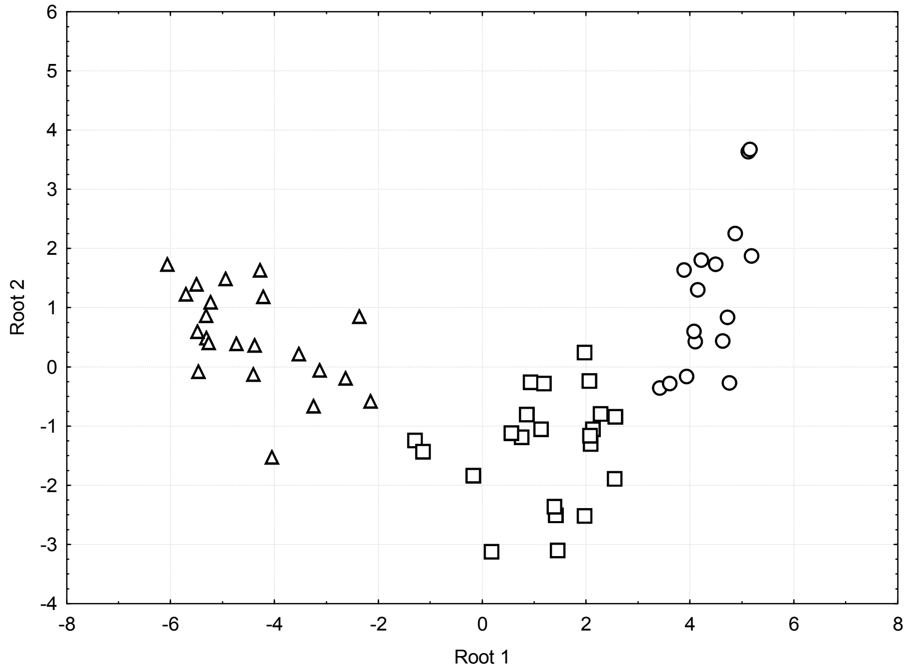


Figure 14: Discrimination between clusters one (circles), two (squares) and three (triangles) of 'Laetitia', using variables CD (>0.5°C), CD (1°C - 0°C), CD (7°C - 6°C), CD (6°C - 5°C), ± 1°C outside FR and ≥ 0.5°C (excluding DT phase) in a canonical analysis.

An evaluation of the temperature variances found within integral reefer containers shipping Japanese plums (*Prunus salicina Lindl.*) at single temperature and the effect thereof on fruit quality

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Abstract

‘Fortune’ and ‘Angeleno’ (*Prunus salicina* Lindl.) were identified as suitable plum fruit cultivars for the commercial single temperature storage trials and were harvested at an optimum maturity. Only A-size (50-55mm) and AA-size (55-60mm) plums were used. A digital temperature logger, namely the ‘Thermocron® iButton®’ with a temperature range of -5°C to +26°C, was used to log the air- and pulp temperature data at three different heights within the fruit pallet, in all 20 pallets shipped within each integral container. The trials were packed, loaded and shipped using a PD1 single temperature regime, at a set point of -0.5°C, from Cape Town, South Africa to Antwerp, Belgium. Average fruit firmness and total soluble solids were measured prior to shipment, only average fruit firmness was measured on the day of arrival and the occurrence of internal defects was evaluated post-shipment after a shelf life period of seven days. Temperature zones could not be identified within the containers suggesting that refrigerated integral containers are able to maintain the temperature well throughout the container area. Average voyage fruit pulp temperature increased slightly from the front to the door end of the container, and from the left to the right hand side of the container, in the ‘Fortune’ trial. Little temperature variance was found in the ‘Angeleno’ container. The limited temperature variances found could possibly be due to exposure to outside atmospheric conditions resulting in a variation in delivery air temperature across the width of the container, insufficient airflow to the door end of the container or the effect of the varying production of vital heat by either plum cultivar, where an elevated fruit respiration and an increased production of vital heat is known to accentuate the effects of poor airflow. Higher average voyage pulp temperatures did not result in observable lower fruit firmness upon arrival. This is ascribed to both ‘Fortune’ and ‘Angeleno’ showing characteristics of suppressed climacteric plum cultivars, known to show very little decrease in

fruit firmness during cold storage, and the container being able to maintain good temperature control within the container.

Keywords: Integral reefer container; single temperature; temperature variance; temperature zones; *Prunus salicina;* plum quality

1. Introduction

A refrigerated container essentially consists of 3 parts, namely an insulated box, a refrigeration system and an air circulation and distribution system (Irving, 1988). Irving (1988) stated that although the refrigeration system of the integral container has sufficient capacity to cool cargo, the air-flow system was not designed to allow efficient cooling and hence the container should not be regarded as a cooling device, but one that maintains the temperature of the cargo. Temperature variances within the integral container are influenced by a number of factors, namely poor pre-loading fruit handling procedures (Tanner and Amos, 2003a), variation in delivery air temperature brought about by differential coil frosting due to exposure to outside atmospheric conditions (Amos and Sharp, 1999; Tanner and Amos, 2003a), the heat of respiration (Irving, 1988), heat leakage into the container (Scrine, 1982a) and poor airflow (Scrine, 1982a; Tanner and Amos, 2003a).

The fruit pulp temperature is dependant on the delivery air temperature, the localised airflow past the specific fruit pallet, the heat produced by the product due to respiration and the packaging material's thermal characteristics (Billing *et al*., 1993; Billing *et al*., 1995). Tanner and Amos (2003a) showed that the pulp temperature, measured within a 40' container carrying kiwifruit at a set point temperature of -0.5°C, was always higher than the surrounding air temperature and that the fruit temperature generally increased across the width of the container, along the length of the container and up the height of the container system (Tanner and Amos, 2003a). This temperature variance pattern was attributed to variable delivery air temperatures across the width of the container due to differential coil frosting caused by non-symmetrical introduction of ambient air through ventilation.

Containers with bottom air delivery require cargo to present a uniform air resistance along the container length with no short circuits (Scrine, 1982b). Certain pallets and cartons are, however, incompatible with the container dimensions, which leads to a by pass at the door end of the container. Large gaps left between the end of the pallet rows and the door, result in poor airflow at the door of the container due to air easily short circuiting past the pallets nearest to the doors (Tanner and Amos, 2003b). Tanner and Amos (2003b) furthermore stated that the large distance from the fan at the front of the container to the door end of the container, results in lower airflow at the door end of the container due to short circuiting of air from the refrigeration end of the container along the length of the container. A lower volume of cold air is, therefore, delivered to the door end of the container resulting in higher air temperatures.

Plums are classified as climacteric fruit, showing a large increase in respiration and ethylene production rates after harvest (Holcroft *et al.*, 2002; Kader, 2002). Climacteric fruit can further be divided into climacteric and suppressed climacteric types (Holcroft *et al*., 2002). This classification is primarily based on ethylene production, where suppressed climacteric cultivars show considerably less and delayed ethylene production after harvest. ‘Pioneer’ and ‘Sapphire’ were classified as climacteric cultivars, and ‘Songold’ and ‘Angeleno’ as suppressed climacteric cultivars, due to considerably higher ethylene production rates observed in the former (Kruger, 2002). Kruger (2002) also measured higher respiration rates on climacteric plums, compared to suppressed climacteric plums, with the difference being even greater at higher temperatures. Heat generated by climacteric fruit (vital heat), as opposed to suppressed climacteric fruit, will be greater due to higher respiration rates and fruit ripening more rapidly (Holcroft *et al.*, 2002). The chance of temperatures rising rapidly during shipment is, therefore, much greater in the case of climacteric fruit.

The size and positioning of produce within a carton, the stacking arrangement of the cartons as well as the carton dimensions and total open area, influence the intensity and homogeneity of the air velocity profile throughout the packed produce (De Castro *et al.*, 2005). The ventilation openings on the carton must be designed in such a way that the holes are aligned to avoid the obstruction of air when the cartons are stacked on one another and side by side, since it plays a role in influencing the homogeneity of cooling. De Castro *et al*. (2005) also stated that the smaller the total open area on a carton, the higher the restriction to air circulation through the packed produce.

Temperature uniformity within a container is important, especially with chilling sensitive crops or crops that require temperatures to remain above freezing point (Harvey, 1981). Severe injury can occur in the coldest positions within the container if large variances occur or if a chilling sensitive crop is transported at unfavourable temperatures for prolonged periods. Heap (1989) stated that “however good a container and however well cooled, packed and stowed the cargo may be, there is of necessity a temperature gradient within the container dependent on outside conditions, thus an awareness of what a normal and reasonable temperature distribution is, is needed.” The main objective of this study was, therefore, to identify any variable temperature conditions within an integral container shipping plums using a single temperature regime, with a set point of -0.5°C, and to determine to what extent the fruit quality on arrival at the destination market is influenced by the possible variable temperature conditions.

2. Materials and methods

2.1. Plant material

‘Fortune’ and ‘Angeleno’ (*Prunus salicina Lindl.*) were sourced from a commercial stone fruit farm in the Wellington, Western Cape region in South Africa. Trial fruit were harvested and packed during the second (peak) commercial harvesting week in the case of each cultivar. Only A-size (50-55 mm) and AA-size (55-60 mm) plums were used.

Harvested plums were placed in a hydro-cooler for approximately 20 minutes. The water temperature was set at 3°C to enable cooling of the fruit to approximately 15°C, whereupon the bins were moved to a holding room with a set-point temperature of 15°C. Packing took place in a temperature controlled pack house with the air temperature set at 20°C within the packing area and 15°C within the palletization area. The wrapping of the pallets (packed fruit units) with perforated plastic wrapping (perforations stretch to large open areas), instead of using straps and corner pieces, is commercially preferred and widely used to stabilize the pallet. All pallets used for trial purposes were, therefore, also wrapped. After packing and palletization, the fruit pallets were forced-air cooled for eight hours or until the fruit pulp temperature in the centre of the pallet reached -0.5°C, whereupon the pallets were moved to the holding room with a set-point temperature of -0.5°C. The pallets were cold stored in the holding room until loading of the respective integral containers took place.

‘Fortune’ plum

‘Fortune’ was harvested at an optimum maturity and packed according to export standards on 3 January 2005 (week 1). The average maturity at harvest of the A-size and AA-size plums were 7.6 kg and 7.4 kg fruit firmness (all fruit firmness measurements were obtained using an 11.2 mm penetrometer probe) and 13.8°Brix and 13.6°Brix total soluble solids (TSS), respectively (Table 1).

‘Angeleno’ plum

‘Angeleno’ was harvested at optimum maturity and packed according to export standards on 24 February 2005 (week 8). The average fruit firmness at harvest of the A-size and AA-size plums was 7.2 kg and 7.3 kg, respectively, and the TSS for the A-size plums was 14.2°Brix and 14.1°Brix in the case of the AA-size plums (Table 1).

2.2. Treatments

Randomized packing and palletizing

The plums were sorted onto packing tables according to fruit size with an AWETA high speed (four lane) packing machine, with a number of tables packing a specific fruit size simultaneously. Packers randomly selected fruit from the table in front of them and packed it into either the 104 mm X 300 mm X 400 mm double layer carton (for the A-size fruit) or the 76 mm X 400 mm X 600 mm single layer carton (for the AA-size fruit). Once a carton was filled, it was placed on the rotating track running through the packing area to the palletizing area located in a separate room. Several pallets, each containing a different packing type as determined by the fruit size, were constructed simultaneously by a team of palletizers. Several pallets of the same packing type were also constructed simultaneously depending on the volume of fruit coming through the pack house and the fruit size distribution. Each person would randomly select a carton from the rotating track and place it on any of the corresponding pallets being constructed. Ten pallets containing only A-size fruit and ten pallets containing only AA-size fruit were randomly constructed for each integral container.

Packing material

A-size plums were packed into a 104 mm X 300 mm X 400 mm double layer carton. The first layer of plums was packed onto a pulp tray, placed at the bottom of the carton, and covered with an interleaf paper sheet to absorb any excess moisture. Another pulp tray with a second layer of fruit was placed on top of the first layer. The top layer was protected from additional moisture loss, due to exposure to fast moving cold air, with a perforated plastic shrivel sheet (perforation holes 1cm in diameter) and a corrugated paper sheet on top. Each carton contained approximately 60 fruit. AA-size plums were packed into 76 mm X 400 mm X 600 mm single layer cartons. The plums were packed onto a plastic 'llip' tray containing holes at the bottom of the fruit cups. The fruit was protected from additional moisture loss with a perforated plastic shrivel sheet (perforation holes 1cm in diameter). Each carton contained approximately 52 fruit.

Temperature recording

A digital temperature logger, namely the 'Thermocron® iButton®' (DS1921Z-F5) (Dallas Semiconductor, iButton Product Group, Dallas, Texas) with a temperature range of -5°C to +26°C, was used to log temperature data. The iButton® is a computer chip enclosed in a

16 mm diameter stainless-steel, waterproof case which enabled the measurement of both pulp- and the air temperatures.

The iButtons® were placed in 60 positions throughout each integral container. Air- and pulp temperatures were measured on three layers within each of the 20 pallets shipped within each integral container. The iButtons® were placed on the 4th, 10th and 16th layer of a pallet containing A-size plums (104 mm X 300 mm X 400 mm cartons; Figure 1) and on the 4th, 12th and 22nd layer of a pallet containing AA-size plums (76 mm X 400 mm X 600 mm; Figure 1). Hence, air- and pulp temperatures were measured at a similar height in the bottom-, middle- and top section of each of the 20 pallets. Temperature was logged throughout the palletizing process, forced-air cooling, cold storage, loading of the containers, single temperature shipment, transport to the inspection point, and until the doors of the containers were opened for unloading and logger retrieval.

Only one air temperature logger was placed in the centre of each assigned pallet layer by taping the logger to the fruit tray in the carton (Figure 2 and 3). The logger was always placed in the upper fruit layer, in between the fruit and slightly off centre towards the top right hand corner of the carton so that the logger was placed in the centre of the specific pallet layer. The pulp temperature of three fruit per layer was measured by pushing the iButton® into a slit in the fruit made with a knife and taping closed the opening. The pulp temperature loggers were placed in one fruit in the centre of the pallet layer, next to the air temperature logger and in two fruit on the opposite outside perimeters of the pallet layer (Figure 2 and 3).

Loading plan

Each integral reefer container can transport 20 pallets with dimensions 1 m X 1.2 m. Eleven pallets were loaded on the left hand side of the container by loading the pallets along the 1.0 m-width of the pallet and 9 pallets were loaded on the right hand side of the container by loading the pallets along the 1.2 m-length of the pallet. The container was loaded in such a pattern to prevent the formation of 'chimneys' or open areas on the container floor through which air can short circuit and cause poor airflow within the container (De Castro *et al*., 2005; Irving, 1988). Void plugs were also placed at the door end of the container to cover the open area between the last pallet loaded and the end of the T-bar floor. Ten pallets containing A-size fruit and ten pallets containing AA-size fruit were assigned to positions within the container in such a manner that the effect of the carton dimensions and characteristics would not influence the airflow pattern within the container; i.e., the A/AA pallets were evenly distributed (Figure 4). This loading plan was consistent for both containers loaded. Only one container was loaded per cultivar.

'Fortune' logistics

The 'Fortune' trial was packed on 3 January 2005 (week 1). After packing, inspection of the fruit by PPECB and palletization, the pallets were forced-air cooled and moved to a holding room with a set-point temperature of -0.5°C. The fruit was cold stored for six days until the morning of 9 January 2005, whereupon the pallets were loaded into the container, according to the pre-determined loading plan (Figure 4), once the core pulp temperature for each pallet had been verified to be less than 1°C as specified by the PPECB (PPECB, 2006b). The 'Fortune' container, with serial number MWCU6732215, was loaded and transported without generator power to the terminal in Cape Town, South Africa and plugged into the plug point for refrigeration to continue over the next three days. The 'City of Cape Town' (voyage A684) vessel departed three days late on 12 January 2005 and arrived in Antwerp as port of delivery after 19 days on 30 January 2005. The container was shipped at a PD1 single temperature shipment regime. The set-point temperature of the integral container was, therefore, set at -0.5°C for the full shipment period (PPECB, 2006a).

'Angeleno' logistics

The 'Angeleno' trial was packed on 24 February 2005 (week 8). After packing, inspection of the fruit by PPECB and palletization, the pallets were forced-air cooled and moved to a holding room with a set-point temperature of -0.5°C. The fruit was cold stored for one day until the morning of 25 February 2005, whereupon the pallets were loaded into the container, according to the pre-determined loading plan (Figure 4), once the core pulp temperature for each pallet had been verified to be less than 1°C as specified by the PPECB (PPECB, 2006b). The 'Angeleno' container, with serial number MWCU6733802, was loaded and transported without generator power to the terminal in Cape Town, South Africa and plugged into the plug point for refrigeration to continue over the following seven days. The 'City of Cape Town' (voyage A698) vessel departed six days late on 4 March 2005 and arrived in Antwerp as port of delivery after 17 days on 21 March 2005. The voyage period was one day longer than estimated. The container was shipped at a PD1 single temperature shipment regime. The set-point temperature of the container was, therefore, set at -0.5°C for the full shipment period (PPECB, 2006a).

2.2. Analyses

Fruit quality variables and pulp- and air temperature were evaluated. The fruit quality variables were evaluated prior to shipment on the day of harvest, and after the commercial shipping period had been completed. The occurrence of internal defects was evaluated after shelf life, seven days after the consignment arrived in the destination market, only in the case of the ‘Angeleno’ trial. Pulp- and air temperature were measured from packing until the integral containers arrived in the destination markets and were unloaded.

Pre-shipment analysis

One carton was randomly selected from every pallet shipped in each trial. The fruit firmness and TSS were measured for 52 fruit in each sampled carton. Fruit firmness was measured with an electronic penetrometer fitted with an 11.2 mm tip (FTA - Fruit Texture Analyser) on both cheeks of each of the 52 fruit measured prior to shipment. Total soluble solids was determined by extracted juice from each fruit by cutting off one randomly chosen cheek and squeezing the juice out onto the calibrated, digital refractometer (Atago, PAL-1). The presence of internal defects was evaluated pre-shipment.

Post-shipment analysis

Upon arrival of the integral containers at the point of inspection, the pallets were unloaded and broken down layer by layer to retrieve the ‘iButtons®’ and perform the sampling procedure for the post-shipment quality analysis. Eight fruit were randomly sampled from each of the three cartons containing the ‘iButtons®’, in each of the assigned pallet layers. Twenty-four fruit were, therefore, sampled per layer and pooled for post-shipment- and shelf life quality analysis. Twelve of the 24 fruit were selected for shelf life analysis and the fruit firmness was evaluated on the remaining 12 sampled. A hand-held penetrometer was used for post–shipment measurement of fruit firmness, due to the lack of available equipment at the inspection site. TSS was not evaluated after shipment.

Shelf life analysis

The occurrence of internal defects was evaluated seven days after arrival at the destination market for the ‘Angeleno’ trial. Twelve of the 24 fruit sampled upon arrival were held under ambient conditions for seven days and the occurrence of internal defects, namely gel breakdown, internal browning, aerated flesh and over ripeness was evaluated. The occurrence of internal defects was expressed as a percentage of the total number of fruit evaluated, even though the defects were classified. The shelf life evaluation was performed by Marine Management Surveys Ltd.

Temperature recording

The ‘Thermocron® iButton®’ logged pulp- and air temperature data every 30 minutes from packing until arrival in the destination market.

2.4. Data analyses

Temperature data

Approximately 1, 700 measurements were logged for each of the 60 positions within each integral container. The initial objective of the study was to explore the data through multivariate analysis techniques and to identify temperature zones within each container with similar pulp temperature conditions. Data analysis concentrated on the fruit pulp temperature data from loading to unloading since it was important to ultimately understand the effect of the container's performance on fruit quality. A set of 17 variables was created from the pulp temperature data, where each variable described a number of hours within a certain temperature range for each of the 60 positions (Table 2).

Fruit quality data

The initial objective was to perform an analysis of variance on the fruit quality data collected prior to shipment relative to position and to examine the effect of fruit size on the average fruit firmness and TSS.

Data analysis

Where data was analysed, the one-way analysis of variance procedure in the Statistica program (Statistica Release 7) was used.

3. Results and discussion

3.1. Results

Temperature data

Upon evaluation of the 17 variables (Figure 5A, 5B, 6A, 6B and 6C), it was found that only one variable, namely FR ($-0.5°C \leq x \leq 0°C$) showed enough variation to enable statistical analysis in both the 'Fortune' and the 'Angeleno' trials (Figure 5B and 6B). No observations were found in six of the 17 variables for 'Fortune' and in four of the 17 variables for 'Angeleno'. Data for only 11 and 13 variables, respectively, are therefore shown (Figure 5 and 6). According to Johnson (1998), the importance and usefulness of multivariate methods increase with the number of variables and the number of experimental units evaluated. It was furthermore found that the cluster analysis procedure, an individual-directed analysis technique where relationships between the experimental units are analysed, could not be performed with only one variable measured for each of the 60 positions within the container

(Johnson, 1998). It was, therefore, clear that temperature zones could not be identified within integral containers that shipped plum fruit at a single temperature regime.

The second approach was to examine the possible variable temperature conditions by performing an analysis of variance. It, however, became apparent that differences found along the length of the container could possibly be influenced by differences found between the left and right hand side of the container, and by differences found between the bottom, middle and top positions within the pallet. This applied regardless of the approach taken. Performing an analysis of variance according to position from the front to the door end of the container could, therefore, possibly give an incorrect account of the differences found within the container.

Therefore, since no statistical analysis could be performed on the 'Fortune' and 'Angeleno' trials, it was decided to evaluate the average voyage pulp temperature as calculated for each of the 60 positions (Figure 7A and 7B) and the proportion of time spent at temperature ranges FR (-1.0°C≤ x ≤-0.5°C), FR (-0.5°C≤ x ≤0°C), FR (0°C≤ x ≤0.5°C), FR (0.5°C≤ x ≤1.0°C), FR (1.0°C≤ x ≤1.5°C) and FR (1.5°C≤ x ≤2.0°C), as described in Table 2 (Figure 8 and 9).

Fruit quality data

An analysis of variance could not be performed on the fruit quality data pre- or post-shipment where positions situated from the front to door end of the container, from the left to the right hand side of the container and from the bottom to the top of the pallet, could be compared, since an incorrect account of the differences found within the container could possibly be given.

Therefore, since no statistical analysis could be performed on the 'Fortune' and 'Angeleno' fruit quality data according to position within the container, it was decided to evaluate the average fruit firmness, as measured post-shipment, and the percentage internal defects, as measured after a shelf life period of seven days post-shipment (only for the 'Angeleno' trial), for each of the 60 positions within each container trial.

'Fortune'

The average pulp temperature for the full voyage was calculated for each of the 60 positions within the 'Fortune' container (Figure 7A). It was found that the pulp temperature increased slightly along the length of the container and that more positions at the door end of the container showed average pulp temperatures greater than 0.4°C. It was also clear that the area occupied by positions showing temperatures greater than 0.4°C, was larger on the right hand side of the container than the left (facing from the door end; Figure 7A).

Positions six to nine, located at the door end on the right hand side of the container, spent proportionately more time at temperatures between 0.5°C and 1.0°C than corresponding positions on the left hand side of the container (Figure 8A, 8B and 8C). Positions ten and 11 on the left hand side of the container spent proportionately less time at temperatures between 0.5°C and 1.0°C, compared to corresponding positions on the right hand side of the container (Figure 8A, 8B and 8C). The left hand side of the container spent proportionately more time at temperatures between 0°C and 0.5°C, compared to the right hand side of the container (Figure 8). It is furthermore clear that positions located in the middle of the pallet on both the left (Figure 8Bi) and right (Figure 8Bii) hand side of the container spent proportionately more time at temperatures between -0.5°C and 0°C and proportionately less time at temperatures between 0.5°C and 1.0°C (Figure 8).

Fruit size significantly influenced average fruit firmness and TSS measured at harvest, where larger fruit (AA-size) had significantly lower average fruit firmness and significantly lower TSS levels (Table 1). No internal defects were observed prior to shipment. Upon comparing the average fruit firmness on arrival for each of the 60 positions with the pulp temperature data, no relationship could be observed (Figure 7A and 10A). It could, therefore, not be concluded that the higher average temperatures found towards the door end of the container, and predominantly on the right hand side, resulted in lower average fruit firmness levels on arrival.

'Angeleno'

The average pulp temperature for the full voyage was calculated for each of the 60 positions within the 'Angeleno' container (Figure 7B). Less temperature variance occurred within the 'Angeleno' container and the pulp temperatures measured were on average lower compared to the 'Fortune' container (Figure 7A and 7B). It was found that positions located at the top of the pallet, on predominantly the left hand side of the container and nearest to the door end, showed average pulp temperatures greater than 0.3°C (Figure 7B).

Upon comparing the proportion of time spent within certain temperature ranges, it was clear that the fruit in the 'Angeleno' container spent on average more time at temperatures between -0.5°C and 0°C and temperatures between 0°C and 0.5°C, than fruit in the 'Fortune' container (Figure 8 and 9). Position 11, situated near the door end, on the left hand side of the container (Figure 9Ai, 9Bi and 9Ci) spent some time at temperatures greater than 1°C and proved to have the highest average voyage temperature (Figure 7B). It was, furthermore clear that fruit located at the top of the pallets in positions eight to 11 on the left hand side of the container (Figure 9Ci), proved to represent the warmest area within the container, spending proportionately more time at temperatures between 0.5°C and 1°C (Figure 9). Similar to the 'Fortune' container, fruit located in the middle of the pallet on both the left and right hand side of the container, spent proportionately more time at temperatures between -0.5°C and 0°C and proportionately less time at temperatures between 0.5°C and 1.0°C and greater (Figure 9).

Fruit size had no significant influence on average fruit firmness and TSS measured at harvest (Table 1). Upon comparing the average fruit firmness on arrival for each of the 60 positions with the pulp temperature data no relationship could not be observed (Figure 7B and 10B). It could, therefore, not be concluded that the higher average temperatures found towards the door end of the container, and predominantly on the left hand side, resulted in lower fruit firmness levels on arrival.

No internal defects were observed prior to shipment. The average percentage defects for each of the 60 positions were evaluated post-shipment, after a shelf life period of seven days (Figure 10C). The internal defects were observed predominantly towards the front and on the left hand side of the container (Figure 10C). Defects were limited to one or two fruit per sample.

3.2. Discussion

Temperature variance pattern

Fruit pulp temperature is dependant on the delivery air temperature (DAT), the localised airflow past the specific fruit pallet, the heat produced by the product due to respiration and the packaging material's thermal characteristics (Billing *et al*., 1993; Billing *et al*., 1995). Tanner and Amos (2003a) showed that the pulp temperature, within a 40' container carrying kiwifruit with a set point temperature of -0.5°C, was always higher than the surrounding air temperature and that the pulp temperature generally increased across the width of the container, along the length of the container and up the height of the container system.

The average voyage pulp temperature for the 'Fortune' container, as calculated for each of the 60 positions within the container, showed a fairly similar temperature variance pattern as found by Tanner and Amos (2003a). The average voyage pulp temperature increased from the front to the door end of the container and a larger area on the right hand side of the container, compared to the left, showed higher average voyage pulp temperatures (Figure 7A and 8). It, therefore, appears that the pulp temperature also increased from the left to the right hand side of the container. The ‘Angeleno’ container showed less temperature variance and the average voyage temperatures were also lower, when compared with the ‘Fortune’ container (Figure 7B and 9). However, the highest average voyage pulp temperatures were still found at the door end of the container, while the rest of the container was stable.

Amos and Sharp (1999) and Tanner and Amos (2003a) showed that air ventilation, the rate of ventilation and outside atmospheric conditions had a significant influence on the delivery air temperature. The PPECB (Perishable Products Export Control Board) of South Africa has set the rate of air circulation in a container at 60 changes per hour when carrying fruit, compared to the standard minimum requirement of 30 to 40 changes per hour of the empty volume of the container when carried in an insulated hold (Scrine, 1982a). An increase in the moisture load of fresh air can lead to differential coil frosting due to the fresh air vent being situated on only the one side of the container (Tanner and Amos, 2003a). The fresh air vent was situated on the right hand side for both our integral container trials. Tanner and Amos (2003a) further explained that differential coil frosting results in an increased resistance, and therefore reduced airflow, resulting in higher delivery air temperatures on the right hand side of the container, if the fresh air vent is situated on the right hand side of the container. As a result the refrigeration unit attempts to maintain temperature control and delivers lower air temperatures on the left hand side of the container. As a result a temperature variance pattern develops in the container. Since the average voyage pulp temperatures showed a similar distribution pattern as found by Tanner and Amos (2003a), it is possible that a variation in delivery air temperature also caused the variable temperature conditions found in our container trials.

It is furthermore clear that the two containers did not show the same amount of temperature variance, possibly due to the inherent characteristics of the cultivars shipped (Figure 7A, 7B, 8 and 9). In work done by Kruger (2002) it was shown that ‘Angeleno’ plum had the lowest respiration and ethylene production rates, compared to ‘Pioneer’, ‘Sapphire’ and ‘Songold’ plum cultivars. Kruger *et al*. (2003) classified ‘Angeleno’ as a true climacteric plum, where suppressed climacteric fruit show a delayed and considerably lower ethylene production after harvest. ‘Angeleno’ was very unique in that it ripened very slowly, with a small reduction in firmness after shelf life and no internal disorders evident even after five weeks cold storage at -0.5°C. Since the respiration rate of ‘Angeleno’ is so much slower, much less heat of respiration is produced, resulting in more easily maintainable temperature conditions within the integral container (Holcroft *et al*., 2002). It is observable in our 'Angeleno' container trial that very little temperature variance occurred within the container and that the pulp temperatures were on average lower than found with the 'Fortune' container trial (Figure 7B and 9). In work done by Punt (2001), it was found that 'Fortune' plum could be cold stored successfully under either a 42-day single temperature or a 42-day dual temperature storage period with no internal defects visible after shelf life. It was also shown in our work done on commercial dual temperature storage of plums in integral containers, as discussed in the previous chapter, that over-heating was not an important characteristic of the 'Fortune' temperature data, suggesting that the respiration and ethylene production rates of 'Fortune' are substantially lower. However, it is clear from studying the average voyage pulp temperatures, as calculated for each of the 60 positions within the container, that either variable delivery air conditions or a higher production of vital heat resulted in the more prominent temperature variance pattern visible in the 'Fortune' container (Figure 7A).

Since it is evident that higher average voyage pulp temperatures were also found in the 'Angeleno' container, predominantly at the door end, another factor could possibly have played a role in causing the difference found (Figure 7B and 9). Tanner and Amos (2003b) stated that the large distance from the fan at the front of the container to the door end of the container, results in lower airflow at the door end due to short circuiting of air from the refrigeration end along the length of the container. A lower volume of cold air is, therefore, delivered to the door end resulting in higher air temperatures. According to Irving (1988), although the refrigeration system of the container has sufficient capacity to cool cargo, the air-flow system was not designed to allow efficient cooling and the containers should not be regarded as cooling devices, but devices that maintain the temperature of the cargo. It is, therefore, possible that insufficient airflow to the door end of the container resulted in the higher average voyage pulp temperatures measured.

Fruit quality

Fruit size had no significant influence on the fruit firmness and TSS levels observed at harvest for 'Angeleno' plum (Table 1). However, larger 'Fortune' plums were significantly softer with lower sugar levels (Table 1). Taylor *et al*. (1993) found that 'Songold' plums harvested from the bottom of the trees had significantly lower soluble solids contents and fruit firmness levels, compared to fruit harvested from the top of the trees and that the lower soluble solids levels were probably due to shading resulting in decreased rates of photosynthesis. The lower fruit firmness levels were attributed to earlier flowering in the bottom part of the tree resulting in the fruit maturity being more advanced compared to the top fruit.

Upon evaluating the average fruit firmness for each of the 60 positions within both the ‘Fortune’ and ‘Angeleno’ container trials, it was found that the higher average voyage pulp temperatures measured did not result in lower fruit firmness levels (Figure 10B and 10C). Kruger *et al*. (2003) found that ‘Angeleno’, being classified as a suppressed climacteric plum fruit, was very unique in that it ripened very slowly, with a small reduction in firmness after shelf life and no internal disorders evident even after five weeks cold storage at -0.5°C. ‘Fortune’ similarly showed a very small reduction in fruit firmness and ‘Angeleno’ a tendency for the fruit firmness levels to increase during shipment (Figure 10A and 10B).

Total percentage internal defects were evaluated after a shelf life period of seven days (only for the ‘Angeleno’ trial) without classification of the internal defect observed. Internal defects were observed in fruit predominantly located near the front, on the left hand side of the container (Figure 10C). Comments in the shelf life report suggest that the defect observed was aerated flesh. The occurrence of aerated flesh and causal factors are not well documented. Aerated flesh is often observed prior to harvest (personal observation) and it can, therefore, not be described as a true chilling disorder.

4. Conclusion

Temperature zones could not be identified within the integral containers that shipped plum fruit under a single temperature regime, suggesting that the refrigerated integral container can maintain temperature well during single temperature shipment. Fruit pulp temperature showed a limited increase from the front to the door end of the container, and from the left to the right hand side of the container in the ‘Fortune’ trial. Little temperature variance was found in the ‘Angeleno’ trial. The limited temperature variances found could possibly be due to changing outside atmospheric conditions resulting in a variation in delivery air temperature across the width of the container, insufficient airflow to the door end of the container or the effect of the varying production of vital heat by either plum cultivars, where an elevated fruit respiration and an increased production of vital heat is known to accentuate the effects of poor airflow (Oosthuyse, 1997).

Higher average voyage pulp temperatures did not result in observable lower fruit firmness levels measured upon arrival. This was true for both ‘Fortune’ and ‘Angeleno’, both showing characteristics of suppressed climacteric plum cultivars, known to exhibit limited declines in fruit firmness levels during cold storage, and the refrigerated integral container showing good temperature maintenance throughout the container area.

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Table 1

Average fruit firmness and soluble solids content of ‘Fortune’ and ‘Angeleno’ fruit of two sizes, measured prior to shipment.

	‘Fortune’		‘Angeleno’	
	Fruit firmness (kg)	TSS (°Brix)	Fruit firmness (kg)	TSS (°Brix)
Fruit size A	7.56 a	13.79 a	7.21 a	14.21 a
Fruit size AA	7.37 b	13.64 b	7.28 a	14.13 a
Pr > F	0.0339	0.0245	0.2360	0.3688

z Mean separation within columns followed by different letters according to Bonferroni (5% level).

Table 2

Seventeen variables were created and the variable values calculated for each of the 60 positions to test whether data analysis, through multivariate exploratory techniques, could be performed. Each variable describes a number of hours within a certain temperature range.

Variable	Description
< -0.5°C FR	Hours at temperatures below -0.5°C, calculated over the full temperature range (FR)
> -0.5°C FR	Hours at temperatures above -0.5°C, calculated over the full temperature range
= -0.5°C FR	Hours at -0.5°C, calculated over the full temperature range
± 1°C outside FR	Hours at temperatures 1°C and more above or below the set point temperature, calculated over the full temperature range, i.e. $x \leq -1.5$°C and $x \geq 0.5$°C when the set point temperature is -0.5°C
± 2°C outside FR	Hours at temperatures 2°C and more above or below the set point temperature, calculated over the full temperature range, i.e. $x \leq -2.5$°C and $x \geq 1.5$°C when the set point temperature is -0.5°C
≥ 1°C outside FR	Hours at temperatures 1°C and more above the set point temperature, calculated over the full temperature range, i.e. $x \geq 0.5$°C when the set point temperature is -0.5°C
≥ 2°C outside FR	Hours at temperatures 2°C and more above the set point temperature, calculated over the full temperature range, i.e. $x \geq 1.5$°C when the set point temperature is -0.5°C
≤ 1°C outside FR	Hours at temperatures 1°C or more below the set point temperature, calculated over the full temperature range, i.e. $x \leq -1.5$°C when the set point temperature is -0.5°
≤ 2°C outside FR	Hours at temperatures 2°C and more below the set point temperature, calculated over the full temperature range, i.e. $x \leq -2.5$°C when the set point temperature is -0.5°C
FR (-2.0°C≤ x ≤-1.5°C)	Hours at temperatures greater than/or equal to -2°C and less than/or equal to -1.5°C, calculated over the full temperature range
FR (-1.5°C≤ x ≤-1.0°C)	Hours at temperatures greater than/or equal to -1.5°C and less than/or equal to -1.0°C, calculated over the full temperature range
FR (-1.0°C≤ x ≤-0.5°C)	Hours at temperatures greater than/or equal to -1.0°C and less than/or equal to -0.5°C, calculated over the full temperature range
FR (-0.5°C≤ x ≤0°C)	Hours at temperatures greater than/or equal to -0.5°C and less than/or equal to 0°C, calculated over the full temperature range
FR (0°C≤ x ≤0.5°C)	Hours at temperatures greater than/or equal to 0°C and less than/or equal to 0.5°C, calculated over the full temperature range
FR (0.5°C≤ x ≤1.0°C)	Hours at temperatures greater than/or equal to 0.5°C and less than/or equal to 1.0°C, calculated over the full temperature range
FR (1.0°C≤ x ≤1.5°C)	Hours at temperatures greater and equal to 1.0°C and less and equal to 1.5°C, calculated over the full temperature range
FR (1.5°C≤ x ≤2.0°C)	Hours at temperatures greater than/or equal to 1.5°C and less than/or equal to 2.0°C, calculated over the full temperature range

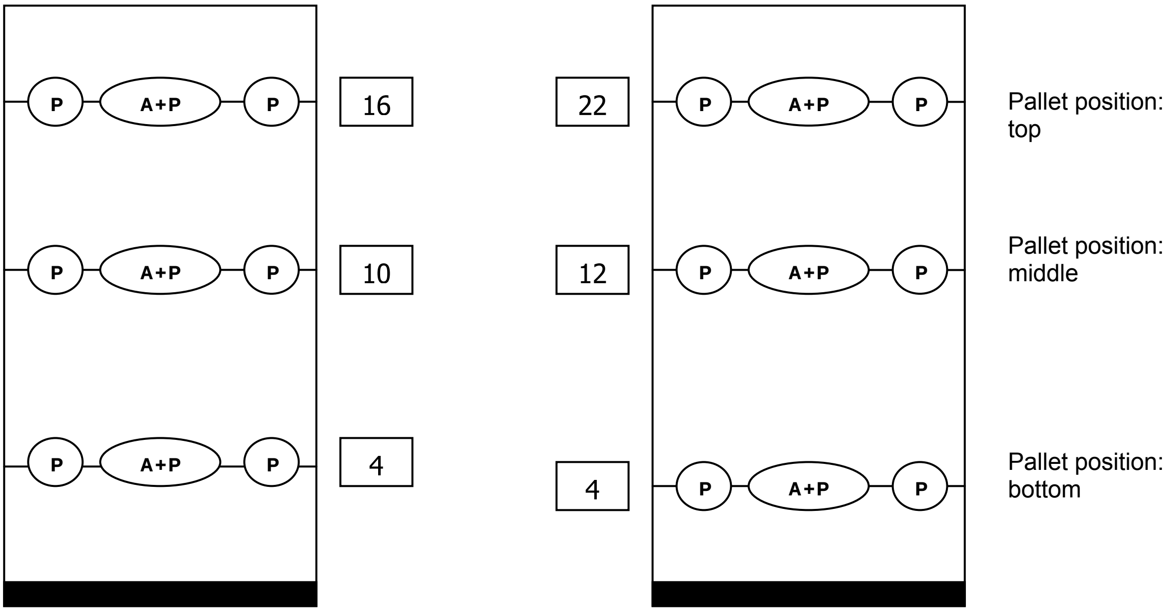

Figure 1: Positioning of one air temperature logger (A) and three pulp temperature loggers (P) on the 4th, 10th and 16th layers of a pallet containing A-size plums packed in 104 mm X 300 mm X 400 mm double layer cartons and on the 4th, 12th and 22nd layer of a pallet containing AA-size plums packed in 76 mm X 400 mm X 600 mm single layer cartons.

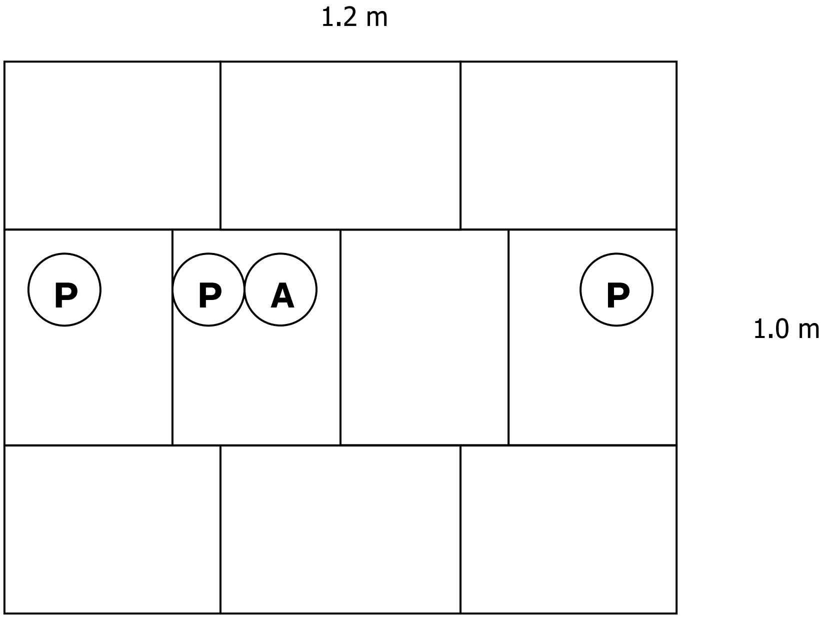

Figure 2: Positioning of the one air temperature logger (A) and the three pulp temperature loggers (P) on each of the assigned layers of a pallet containing A-size plums packed in 104 mm X 300 mm X 400 mm cartons.

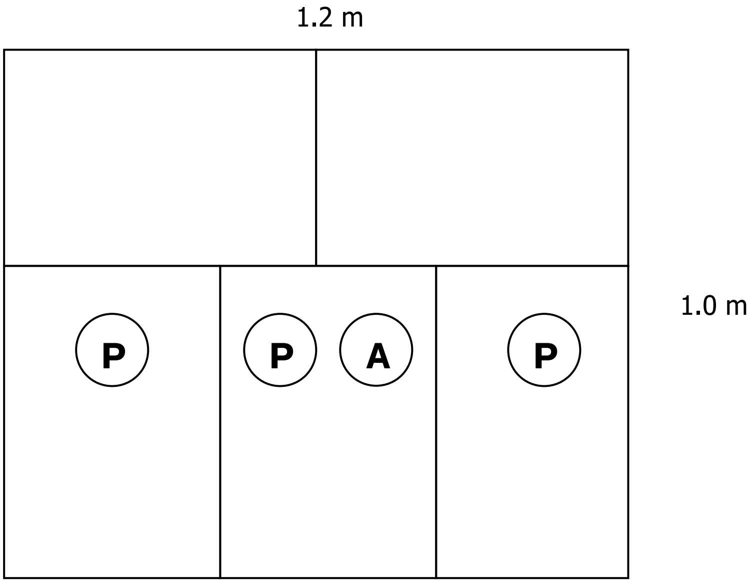

Figure 3: Positioning of the one air temperature logger (A) and the three pulp temperature loggers (P) on each of the assigned layers of a pallet containing AA-size plums packed in 76 mm X 300 mm X 400 mm cartons.

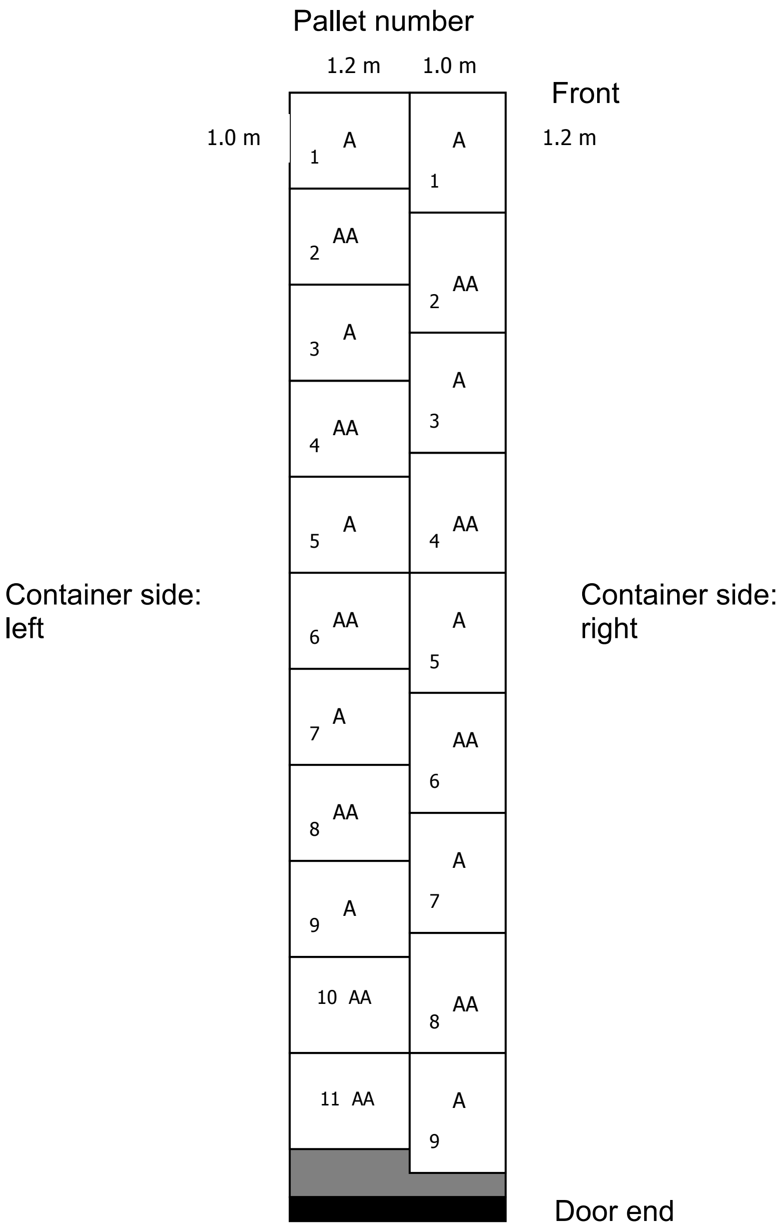

Figure 4: Ten pallets of A-size fruit and ten pallets of AA-size fruit were loaded and randomly distributed throughout each integral reefer container.

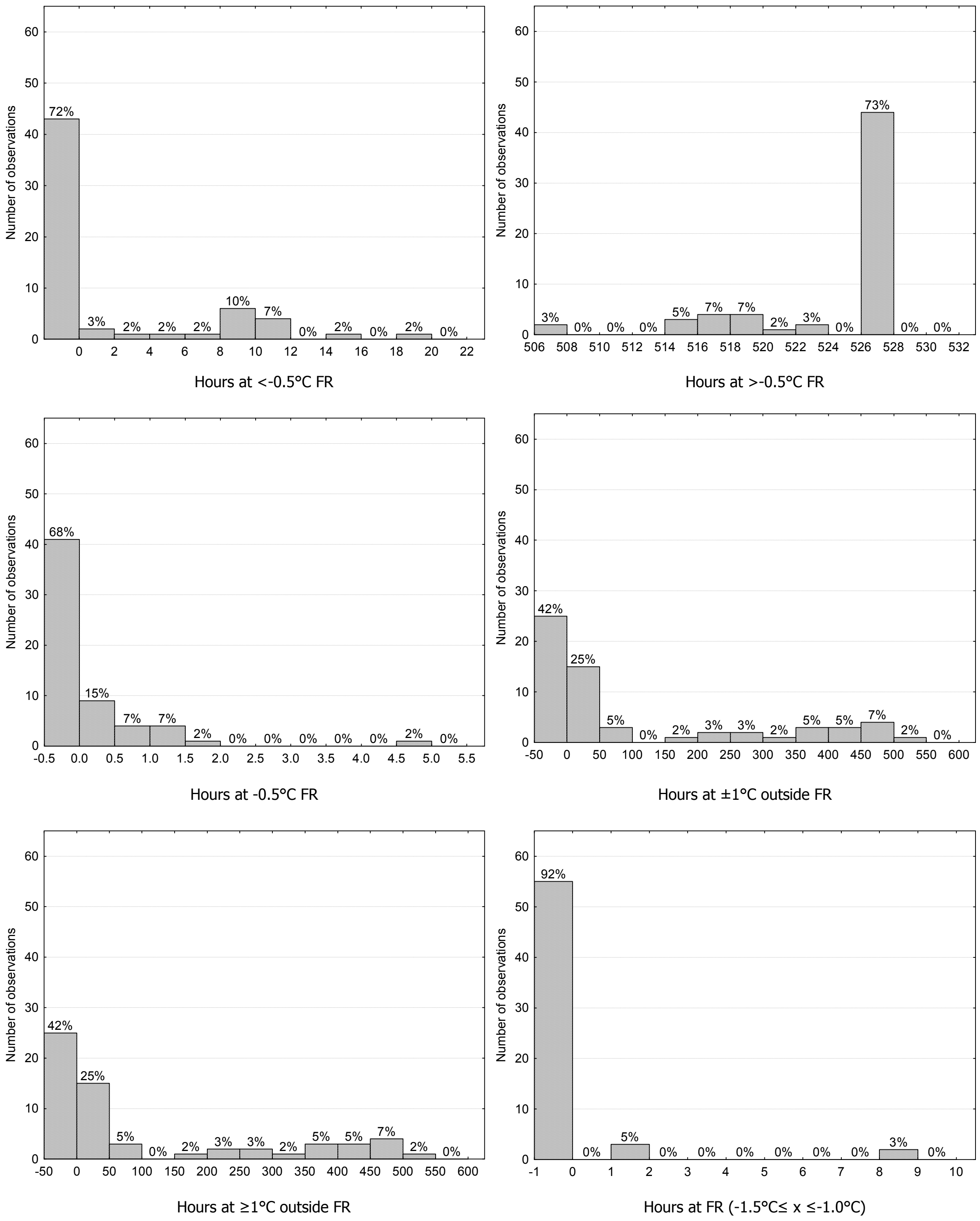

Figure 5 (A): Histograms representing number of observations per calculated value for each created variable in the 'Fortune' trial, as described in Table 2. Observations left of zero hours indicate the number of observations where the observed temperature fell outside the specific temperature range evaluated.

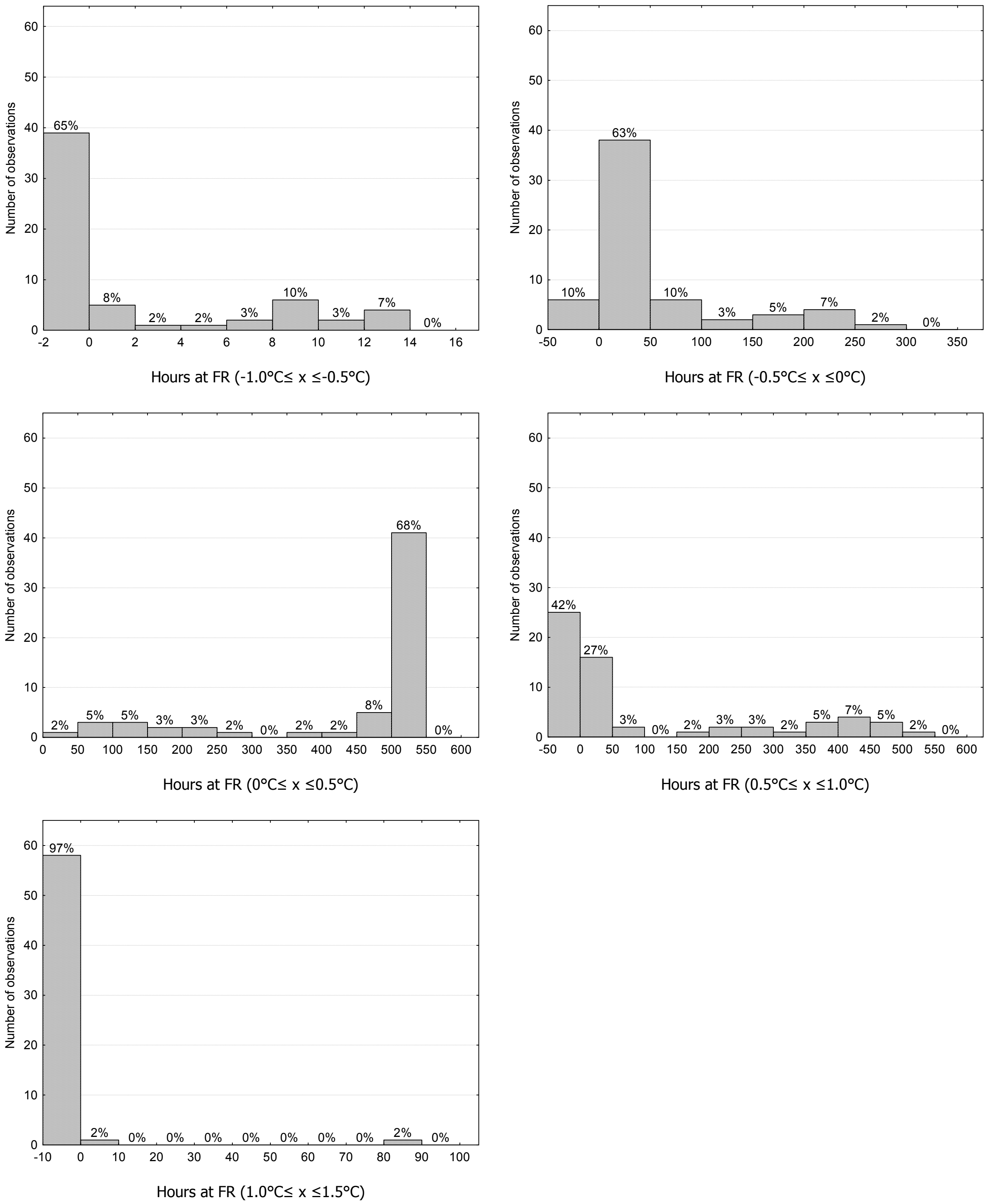

Figure 5 (B): Histograms representing number of observations per calculated value for each created variable in the ‘Fortune’ trial, as described in Table 2. Observations left of zero hours indicate the number of observations where the observed temperature fell outside the specific temperature range evaluated.

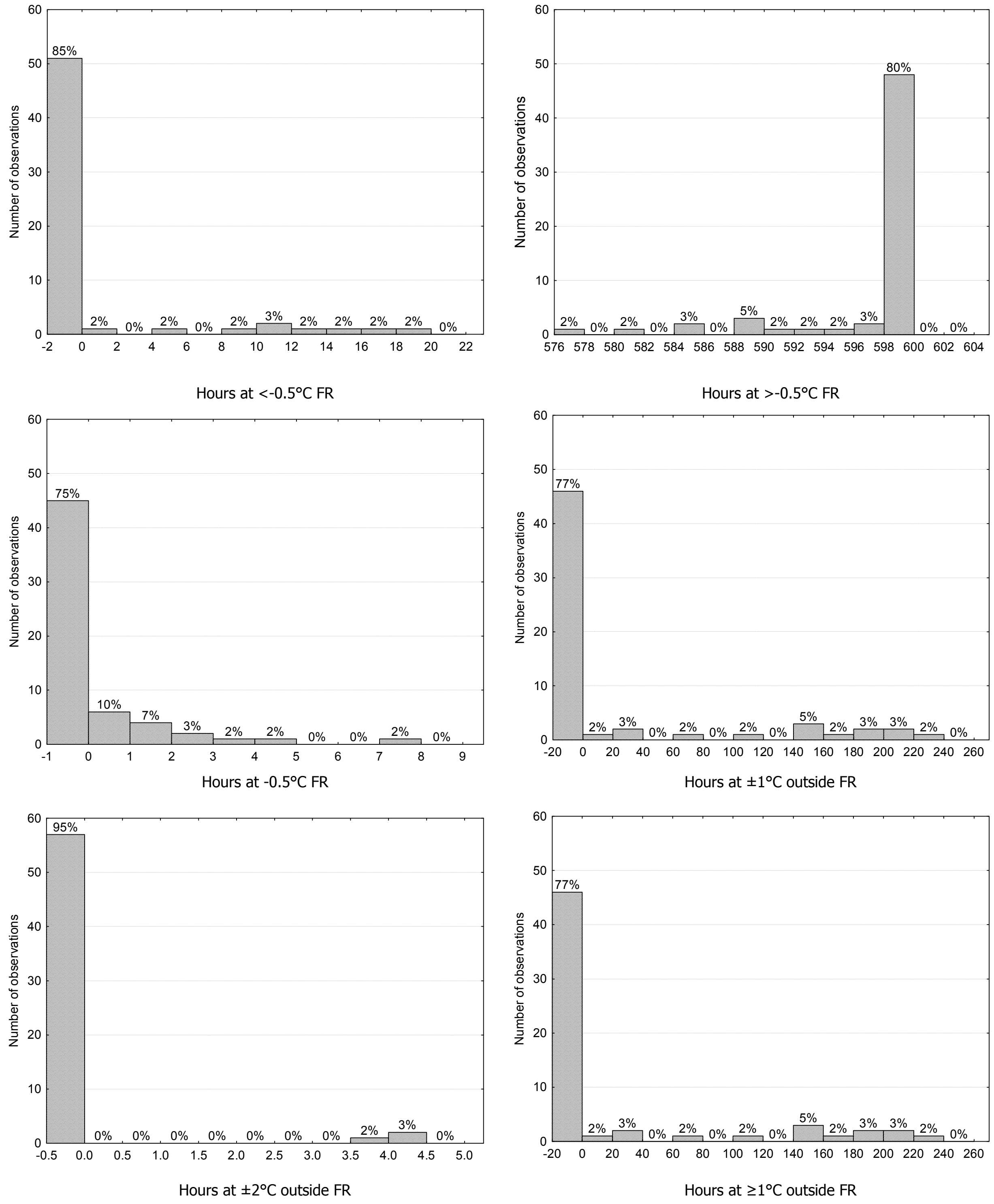

Figure 6 (A): Histograms representing number of observations per calculated value for each created variable in the ‘Angeleno’ trial, as described in Table 2. Observations left of zero hours indicate the number of observations where the observed temperature fell outside the specific temperature range evaluated.

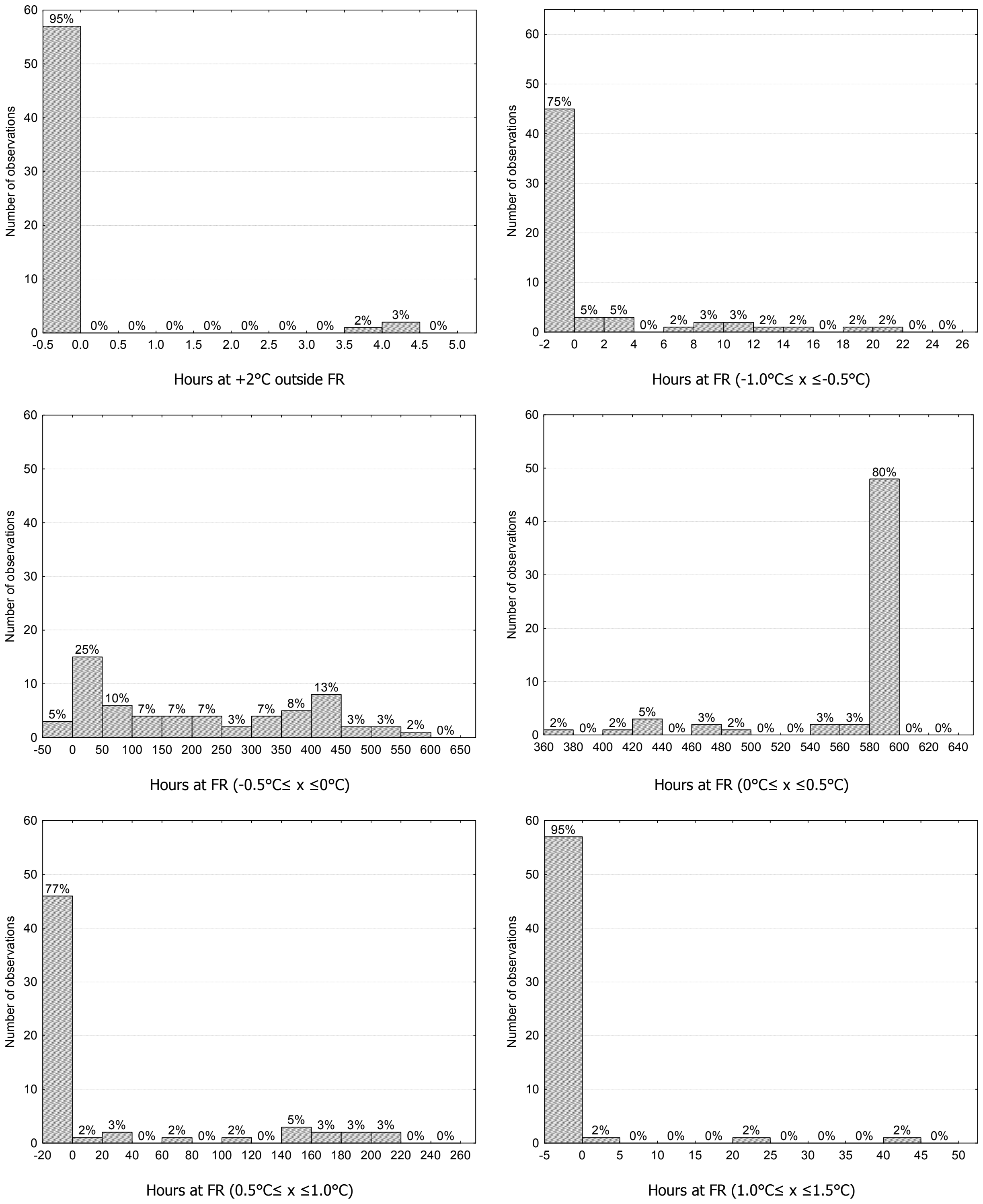

Figure 6 (B): Histograms representing number of observations per calculated value for each created variable in the 'Angeleno' trial, as described in Table 2. Observations left of zero hours indicate the number of observations where the observed temperature fell outside the specific temperature range evaluated.

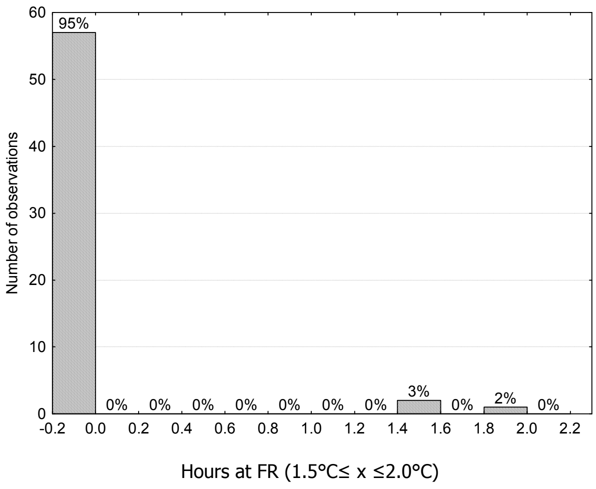

Figure 6 (C): Histograms representing number of observations per calculated value for each created variable in the 'Angeleno' trial, as described in Table 2. Observations left of zero hours indicate the number of observations where the observed temperature fell outside the specific temperature range evaluated.

FRONT OF CONTAINER DOOR END OF CONTAINER

PALLET:	1	2	3	4	5	6	7	8	9
Top	0.24	-0.01	0.18	**0.63**	0.29	0.02	**0.66**	**0.68**	**0.62**
Middle	-0.02	-0.03	0.23	0.32	0.24	**0.51**	0.39	**0.62**	0.15
Bottom	0.25	0.22	0.05	**0.42**	0.16	**0.52**	**0.46**	**0.60**	**0.57**

RIGHT

PALLET:	1	2	3	4	5	6	7	8	9	10	11
Top	0.30	0.15	0.08	0.31	0.17	0.09	0.38	0.36	0.37	0.25	**0.79**
Middle	0.05	0.07	0.15	0.12	0.23	0.19	0.24	0.23	0.22	**0.41**	**0.42**
Bottom	0.28	0.05	0.12	0.11	0.13	0.31	0.10	0.26	0.20	**0.49**	**0.53**

LEFT

A

FRONT OF CONTAINER DOOR END OF CONTAINER

PALLET:	1	2	3	4	5	6	7	8	9
Top	-0.04	0.12	0.12	0.11	0.18	-0.05	0.15	**0.34**	0.16
Middle	-0.06	-0.17	0.06	0.11	-0.03	0.26	0.04	0.15	0.10
Bottom	0.05	0.02	0.07	0.11	0.20	-0.01	0.10	**0.35**	0.12

RIGHT

PALLET:	1	2	3	4	5	6	7	8	9	10	11
Top	-0.02	0.05	0.03	0.19	-0.03	0.01	-0.09	**0.38**	**0.33**	**0.40**	**0.52**
Middle	-0.04	-0.19	**0.45**	-0.17	0.13	0.05	-0.19	0.21	0.11	-0.05	0.12
Bottom	-0.35	0.24	0.06	0.15	0.23	0.18	0.13	0.06	-0.09	**0.32**	**0.43**

LEFT

B

Figure 7 (A): The average voyage pulp temperature (°C) as measured at each of the 60 positions within the ‘Fortune’ container. Figures in bold represent average pulp temperatures greater than 0.4°C.

Figure 7 (B): The average voyage pulp temperature (°C) as measured at each of the 60 positions within the ‘Angeleno’ container. Figures in bold represent average pulp temperatures greater than 0.3°C.

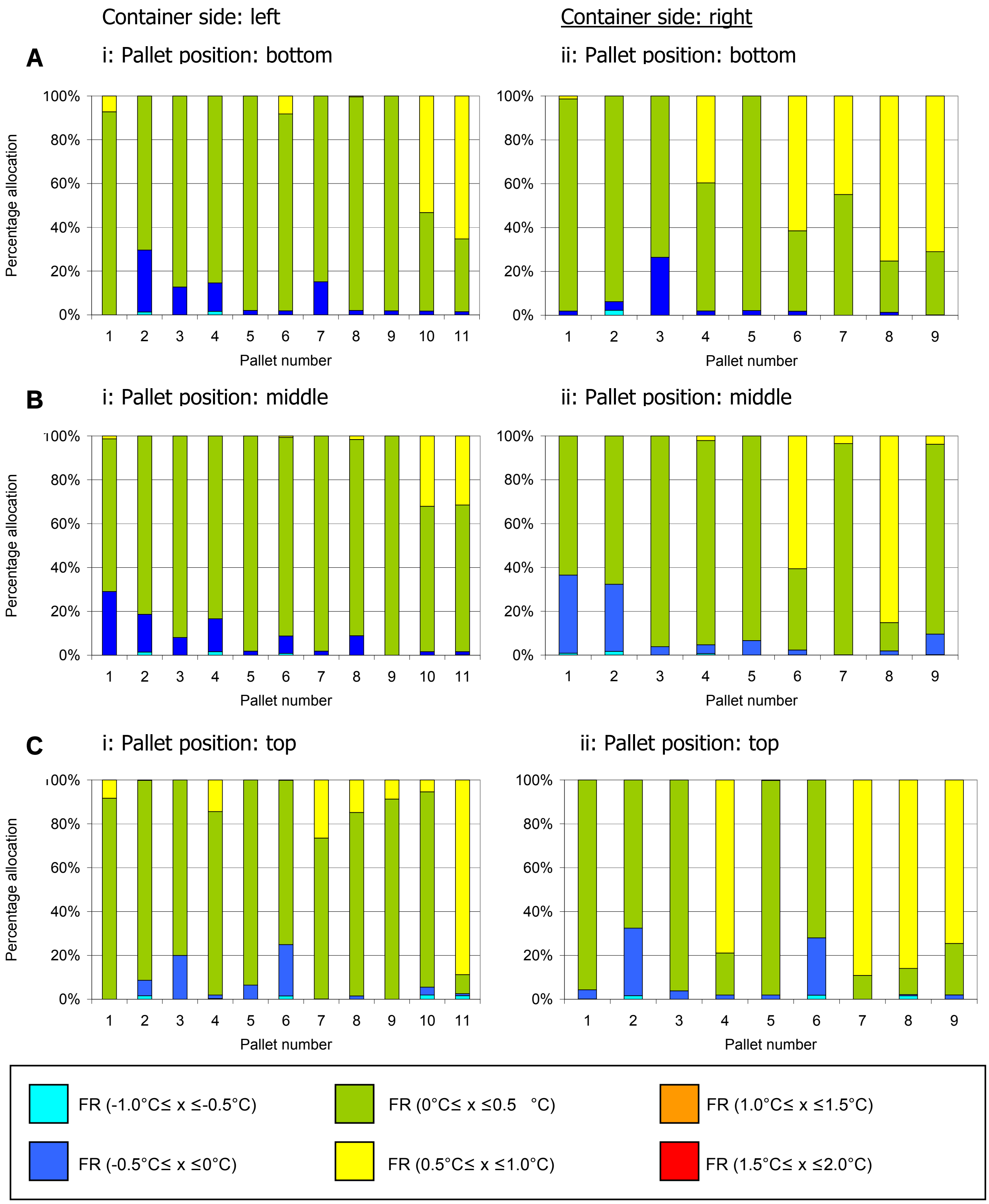

Figure 8: Proportion of time spent (in percentage) at temperature ranges FR (-1.0°C≤ x ≤-0.5°C), FR (-0.5°C≤ x ≤0°C), FR (0°C≤ x ≤0.5°C), FR (0.5°C≤ x ≤1.0°C), FR (1.0°C≤ x ≤1.5°C) and FR (1.5°C≤ x ≤2.0°C) on either the left (i) or the right (ii) hand side of the container, for pallet positions bottom (A), middle (B) or top (C) as calculated for the 'Fortune' container.

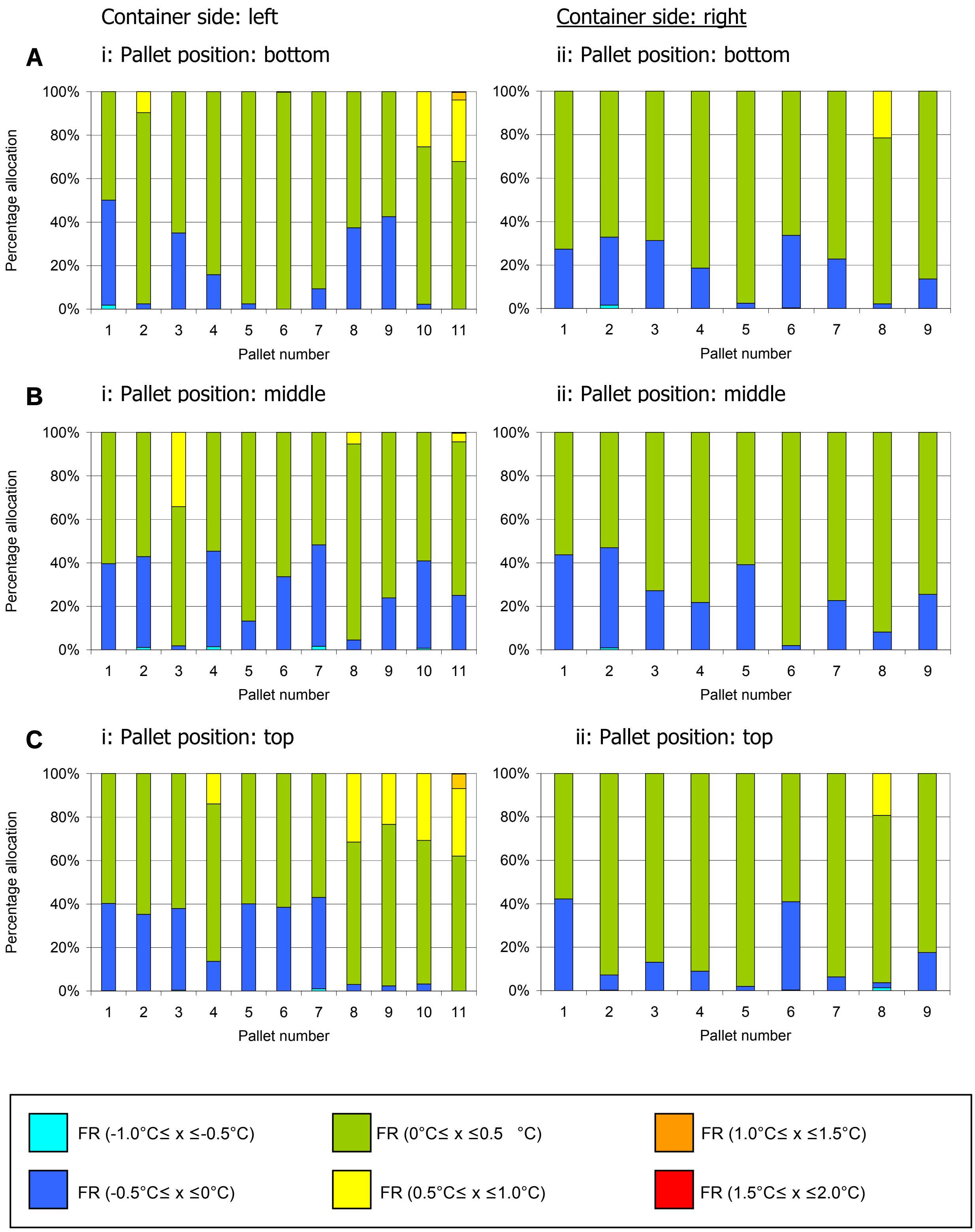

Figure 9: Proportion of time spent (in percentage) at temperature ranges FR (-1.0°C≤ x ≤-0.5°C), FR (-0.5°C≤ x ≤0°C), FR (0°C≤ x ≤0.5°C), FR (0.5°C≤ x ≤1.0°C), FR (1.0°C≤ x ≤1.5°C) and FR (1.5°C≤ x ≤2.0°C) on either the left (i) or the right (ii) hand side of the container, for pallet positions bottom (A), middle (B) or top (C) as calculated for the ‘Angeleno’ container.

FRONT OF CONTAINER DOOR END OF CONTAINER

PALLET:	1	2	3	4	5	6	7	8	9
Top	7.3	7.2	7.6	7.0	7.7	6.8	8.3	6.7	8.4
Middle	7.2	6.9	7.1	6.3	6.9	6.5	7.6	7.1	8.1
Bottom	7.6	7.0	6.7	6.6	7.1	6.7	7.4	7.0	6.4

RIGHT

PALLET:	1	2	3	4	5	6	7	8	9	10	11
Top	6.4	6.9	7.6	6.0	6.2	6.8	7.2	7.1	6.8	7.4	7.0
Middle	6.8	6.2	7.0	7.3	6.5	7.1	6.7	6.8	7.2	7.1	7.2
Bottom	7.1	6.3	7.8	7.7	7.0	6.9	7.1	7.4	7.2	7.2	7.5

LEFT

A

FRONT OF CONTAINER DOOR END OF CONTAINER

PALLET:	1	2	3	4	5	6	7	8	9
Top	7.2	7.6	8.8	7.9	7.5	7.6	7.7	7.5	7.8
Middle	7.8	7.5	8.5	7.6	7.8	7.5	7.8	7.4	7.6
Bottom	7.4	7.9	7.8	8.1	8.4	7.0	8.0	7.7	7.3

RIGHT

PALLET:	1	2	3	4	5	6	7	8	9	10	11
Top	7.1	7.4	7.7	8.3	7.7	7.3	7.6	7.6	7.3	7.7	8.4
Middle	8.1	7.1	8.0	8.4	8.5	7.6	8.4	7.6	8.1	7.4	8.2
Bottom	7.4	7.9	8.3	8.4	6.6	7.2	7.8	7.5	7.6	7.3	7.8

LEFT

B

FRONT OF CONTAINER DOOR END OF CONTAINER

PALLET:	1	2	3	4	5	6	7	8	9
Top	16.7	0	0	8.3	8.3	0	0	0	0
Middle	0	0	0	0	0	0	0	8.3	16.7
Bottom	8.3	8.3	0	0	0	0	0	8.3	0

RIGHT

PALLET:	1	2	3	4	5	6	7	8	9	10	11
Top	8.3	8.3	8.3	8.3	16.7	0	0	0	0	0	0
Middle	0	0	0	8.3	0	0	0	0	0	0	0
Bottom	0	0	8.3	0	8.3	16.7	0	0	0	0	0

LEFT

C

Figure 10: The average fruit firmness (kg) post-shipment for ‘Fortune’ (A), the average fruit firmness (kg) post-shipment for ‘Angeleno’ (B) and the average percentage internal defects after a seven day shelf life period for ‘Angeleno’ (C), as measured for each of the 60 positions within the respective containers.

Evaluation of electrolyte leakage and fruit quality of 'Pioneer' plums (*Prunus salicina* Lindl.) stored at various temperatures

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Abstract

'Pioneer' plums (*Prunus salicina Lindl.*) were harvested at an optimum maturity of 8.3 kg (11.2 mm penetrometer probe) fruit firmness. Fruit was stored for 27 days under the commercially applied dual temperature (DT) storage regime (ten days at -0.5°C, followed by seven days at 7.5°C and ten days at -0.5°C), or at -0.5°C, 2°C, 5°C or 7.5°C. Percentage electrolyte leakage, internal defects (gel breakdown, internal browning and aerated flesh), colour (hue angle), fruit firmness, total soluble solids, titratable acidity and the occurrence of decay and shrivel were evaluated after a 27-day storage period and a seven day shelf life period at 10°C. The different temperature treatments had a significant effect on electrolyte leakage and fruit quality. Stone fruit is susceptible to low temperature injury (gel breakdown and internal browning) and the most internal quality problems were found in plums ripened following storage under die DT regime (control), 5°C and at 7.5°C treatments. These treatments operate at temperatures within the so called 'killing zone' (between 2°C and 7°C) which possibly contributed to the occurrence of chilling injury symptoms. Membrane permeability increases as a result of ripening and senescence, especially in the case of climacteric fruit. Increased ripening due to higher storage temperatures could have resulted in higher levels of electrolyte leakage in the control, 5°C and 7.5°C treatments. There seems to be a positive correlation between the occurrence of gel breakdown and an increase in electrolyte leakage, suggesting that the development of gel breakdown is closely associated with membrane integrity. The 2°C treatment could possibly replace the commercial DT in the case of 'Pioneer' plum due to improved fruit firmness after ripening in combination with similar colour development to that of the control. 'Pioneer' plum has a very high respiration rate and it would be beneficial if fruit could be stored at temperatures below 3°C to ensure lower sensitivity to ethylene, control of ripening (hence, the occurrence of gel breakdown and over ripeness) and the loss of soluble solids.

Keywords: Electrolyte leakage; chilling injury; temperature storage regimes; gel breakdown; internal browning

1. Introduction

The loss of membrane permeability and consequent increase in electrolyte leakage has been shown to be closely associated with the occurrence of gel breakdown in ‘Songold’ plums stored at different temperature regimes (Taylor *et al*., 1994a). Furmanski *et al*. (1979) and Von Mollendorff *et al.* (1992) established that the loss of membrane integrity enhances the leakage of cell fluids and solutes out of the cells into the cell wall area where binding with pectins takes place, resulting in the occurrence of woolliness in peaches and nectarines. Electrolyte leakage has been widely used as an indirect indicator of membrane permeability (Murata, 1990; Murata and Tatsumi, 1979; Saltveit, 2002) and expressed as a percentage of the total electrolyte leakage.

Murata (1990) stated in his review that membrane permeability demonstrated an increased rate of solute leakage as a result of chilling stress. Chilling increased membrane permeability, possibly due to physical phase transition of membranes from a flexible liquid-crystalline to a solid-gel structure at a critical temperature resulting in the development of membrane cracks (Wang, 1982). Healthy cell membranes have the ability to regenerate if exposed to chilling temperatures for only short periods before actual injury occurs, resulting in a decrease of electrolyte leakage (Lyons *et al*., 1979; Taylor, 1993; Taylor *et al.*, 1993a). Prolonged exposure of ‘Songold’ plums to chilling temperatures, however, led to irreversible degeneration of membranes, and a loss of regulatory ability (Taylor, 1993; Taylor *et al.*, 1993a). Membrane permeability, of climacteric fruit especially, shows an increasing trend during ripening and senescence (Murata, 1990). Electrolyte leakage is, therefore, not only an indirect indicator of membrane permeability due to chilling injury, but also due to the ripening and senescence process.

Plums are shipped at various temperature regimes from South Africa with variable results. Dual temperature shipping regimes (two days at -0.5°C followed by either five, seven or nine days at 7.5°C, with the remainder of the voyage at -0.5°C) are commonly used as a means to control the levels of internal browning of plums (Hartmann *et al*., 1988). The conditions created by the dual temperature regime, however, resulted in an increase of previously unseen gel breakdown (Taylor *et al*., 1993a). Low temperature injury is similar to the chilling injury of tropical fruit and most stone fruit cultivars show the greatest internal breakdown problems at temperatures between 2°C and 7°C (Mitchell, 1986b). This temperature range is often referred to as the ‘killing zone’ in stone fruit cold storage. The objective of this trial was to indirectly evaluate the effect of different storage regimes on membrane functionality and subsequent fruit quality.

2. Materials and methods

2.1. Plant material

‘Pioneer’ plums were harvested on 15 November 2005 (week 46) at an optimum average maturity of 8.33 kg fruit firmness (measured with an 11.2 mm penetrometer probe) and 10.1°Brix, on a commercial farm in the Franschhoek, Western Cape region in South Africa. The fruit was transported from the farm to the pack house immediately after harvest and packed according to export standards with no refrigeration having taken place prior to packing. The fruit was packed without ‘shrivel sheets’. Twenty-six double layer cartons containing approximately 72 A-size (50 – 55 mm) plums were sampled for trial purposes after packing. The packed fruit was transported (30 minute drive in a non-refrigerated vehicle) to the cold storage facilities at the University of Stellenbosch. One carton of plums was used for pre-treatment measurements and the remaining 25 cartons were placed in a cold room at -0.5°C.

2.2. Treatments

The following five temperature treatments were applied over four weeks and variables measured and evaluated directly following storage as well as after ripening for seven days at 10°C:

a) 10 days at -0.5°C, 7 days at 7.5°C and 10 days at -0.5°C (commercial control),
b) 27 days at -0.5°C (-0.5°C regime),
c) 3 days at -0.5°C and 24 days at 2°C (2°C regime),
d) 3 days at -0.5°C and 24 days at 5°C (5°C regime) and
e) 3 days at -0.5°C and 24 days at 7.5°C (7.5°C regime).

Each of the five treatments consisted of five single carton replicates of approximately 72 fruit per carton.

2.3. Analyses

Evaluation of the following variables took place prior to treatment on the day of harvest, after a cold storage period of 27 days and after shelf life (seven days storage at 10°C).

Pre treatment analysis

Four fruit were randomly selected from the carton for measurement of electrolyte leakage. Eighteen fruit were used to classify and measure the occurrence of internal defects, measurement of the total soluble solids and titratable acidity. Skin colour (hue angle), the occurrence of shrivel and decay, and fruit firmness were evaluated and measured on the remaining 50 fruit.

Post storage and shelf life analysis

The plums were removed from cold storage and shelf life storage on the morning of evaluation. Analysis commenced 90 minutes later.

Fifty four fruit per replicate were randomly selected and the following variables evaluated: four fruit were selected for measurement of electrolyte leakage, 30 fruit were used to evaluate skin colour (hue angle) and the occurrence of shrivel and decay, ten fruit were selected to measure fruit firmness and to measure the total soluble solids and titratable acidity and ten fruit were selected to classify and measure the occurrence of internal defects.

Skin colour (hue angle)

The skin colour (hue angle) was measured with a colorimeter (Nippon Denshoku, NR – 3000). Measurement took place on the equatorial axis of the fruit on the side with the more advanced (redder) colour development, where a lower hue angle value indicates redder colour development.

Fruit firmness

Fruit firmness was measured with an electronic penetrometer (Fruit Texture Analyser (FTA), GS-14) on one cheek of each fruit. An 11.2 mm probe was used and measurement expressed in kg. The measurement side was randomly selected.

Total soluble solids (TSS)

Juice was extracted with a standard food processor and pooled as a single juice sample for each replicate. The juice was extracted from cut fruit sectors consisting of skin and mesocarp flesh. The total soluble solids contents were measured with a digital refractometer (Atago, PR-32).

Titratable acidity

An aliquot of the same juice used for TSS determination was used. Ten grams of the pooled juice sample were titrated with 0.1 N NaOH to an end point of pH 8.2 using an automated titrator (Metrohm, 719 S Titrino). Results were expressed as percentage malic acid equivalents.

Internal defects

Fruit was randomly selected and cut in half along the equatorial axis. The occurrence of internal defects was classified, measured and expressed as a percentage of the total number of fruit evaluated. The most common plum internal defects were evaluated, namely gel breakdown, internal browning and aerated flesh. Gel breakdown was recorded as a translucent, gelatinous appearance, occurring between the stone and the centre of the mesocarp (Taylor *et al*., 1993a). Internal browning was recorded as browning of the mesocarp tissue (Hartmann *et al*., 1988; Taylor, 1996; Taylor *et al*., 1993a) and aerated flesh as a white, aerated area found in the mesocarp of the fruit.

Shrivel and decay

The occurrence of shrivel and decay were evaluated and expressed as a percentage of the total number of fruit evaluated per replicate.

Electrolyte leakage

Disc cylinders were cut with a cork borer from the mesocarp on the equatorial axis of each of four fruit selected per replicate. Approximately three disc cylinders per fruit were cut. One disc, 3 mm thick and 8 mm in diameter, was cut from each disc cylinder at 5 mm depth below the skin. Each treatment-replicate sample weighed approximately 2 g and consisted of approximately 11 discs.

The discs were rinsed three times in de-ionised water and carefully dried on paper towel prior to incubation (Saltveit, 2002). Discs samples were placed in the incubation solution (0.6 M mannitol) for five hours at ambient temperature according to the method of Lurie *et al.* (1987). The temperature was controlled by placing the tubes in a water bath at 25°C.

Calibration of the Orion Aplus 145A+ basic conductivity meter was performed using a 1,413 uS conductivity calibration standard (0.692 M NaCl solution).

Following incubation the samples were shaken for 30 minutes at 200 cycles per minute prior to measurement of the fluid conductivity to ensure accuracy of reading without damaging the cells. The discs were removed from the incubation solution and the conductivity measured on the remaining solution. The solution was mixed with a small magnetic stirrer bar during measurement of conductivity to ensure accurate measurement. Once the measurement was completed, the discs were placed back into the incubation solution and were frozen in a -18°C freezer for a minimum period of 12 hours.

The frozen samples were removed from the freezer, thawed and filtered to enable measurement of electrolyte conductivity of the solution. Whatman no.2 (diameter 12.5 cm) filter paper was used. The Orion Aplus 145A+ basic conductivity meter was again calibrated and conductivity measured. This value was taken as total conductivity. Electrolyte leakage was expressed as a percentage of the conductivity value measured after the samples had been frozen and thawed (Saltveit, 2002).

2.4. Data analyses

Data were analysed using the GLM procedure in the SAS program (SAS 9.1, 2003). Where applicable single degree of freedom, orthogonal polynomial contrasts were fitted to the data. Arcsine transformation was performed on data not normally distributed prior to statistical analysis. Where the transformation did not normalise the data only standard deviations were presented.

3. Results and discussion

3.1. Results

Electrolyte leakage

Electrolyte leakage was measured as 24.9% on the day of harvest, prior to treatment.

Upon measurement after the 27-day cold storage period, no significant difference in average percentage electrolyte leakage between treatments was found (Table 1). The average percentages increased slightly from the initial measurement in all treatments except the 5°C regime.

Electrolyte leakage measured after the shelf life period, showed a significant difference between treatments before (Pr>F: p=0.0008) and following (Pr>F: p=0.0278) freezing and thawing. The percentage electrolyte leakage also differed significantly between treatments (Table 2). A highly significant contrast in percentage electrolyte leakage between the ‘high temperature’ treatments, namely the 5°C and 7.5°C treatments, and the ‘low temperature’ treatments, namely the -0.5°C and 2°C treatments, was observed (Pr>F: p=0.0001). The ‘low temperature’ treatments resulted in the lowest average percentage electrolyte leakage, where the ‘high temperature’ treatments had the highest average percentage conductivity (Table 2).

The linear contrast in percentage electrolyte leakage was highly significant (Pr>F: p=0.0004; Table 2). A linear increase in average percentage electrolyte leakage could be observed from the -0.5°C (38.1%) and the 2°C (37.1%) treatments, to the 5°C (46.7%) and the 7.5°C treatment which had the highest average percentage electrolyte leakage (47.8%).

Internal Defects

No internal defects were found prior to cold storage. The occurrence of internal defects following cold storage was influenced by the temperature treatments with gel breakdown and aerated flesh occurring at the high temperature treatments, namely the 5°C and 7.5°C treatments (Table 1).

No significant differences in total percentage internal defects between treatments were found after the shelf life period had been completed (Table 2). The contrast of ‘high temperature treatments’ versus ‘low temperature treatments’ was, however, significant, with the -0.5°C and 2°C regimes having the lowest percentage of internal defects (28% in both cases) and the 5°C and 7.5°C regimes the highest percentage of internal defects (66% in both cases).

Internal defect: Gel breakdown

No gel breakdown was present prior to cold storage. The occurrence of gel breakdown was influenced by the temperature treatments after cold storage and evident at the high temperature treatments, namely the 5°C and 7.5°C treatments (Table 1).

Gel breakdown levels increased considerably during the shelf life period in all treatments. No significant differences in gel breakdown were found between treatments after shelf life (Table 2). However, the ‘high versus low temperature treatment’ contrast proved to be significant, where the ‘low temperature treatments’ (-0.5°C and 2°C treatments) resulted in the lowest percentage of gel breakdown.

Internal defect: Internal browning

No internal browning was detected after cold storage (data not shown) and it only became evident after shelf life (Table 2). There were, however, no significant differences between treatments.

Internal defect: Aerated flesh

The occurrence of aerated flesh following storage proved to be similar to that found in the case of gel breakdown (Table 1). Temperature treatments influenced the occurrence of aerated flesh, evident only at the high temperature treatments (5°C and 7.5°C treatments). In contrast to gel breakdown, aerated flesh completely disappeared during the shelf life period (data not shown).

Colour

Average hue angle prior to storage was 112 ±4.2°. The treatments proved to have a highly significant influence on colour development during cold storage (Pr>F: $p<0.0001$; Table 3). The -0.5°C regime resulted in the worst average colour development (59.79°) significantly different to all other treatments, followed by 2°C treatment (34.25°), control (28.08°), 5°C treatment (19.79°) and finally the 7.5°C treatment (14.37°) with the best colour development (most red; Table 3). The ‘high versus low temperature treatment’ contrast proved to be highly significant (Pr>F: $p<0.0001$), where the ‘high temperature treatments’ resulted in the best colour development and the ‘low temperature treatments’ resulted in poorer levels of colour development. The quadratic contrast was significant with the colour development improving from the -0.5°C treatment to the 2°C, 5°C and 7.5°C treatment which had the best colour development.

Temperature treatment also had a highly significant influence on colour development following the shelf life period (Pr>F: $p<0.0001$; Table 4). The colour of plums stored at -0.5°C improved most markedly from 59.79° to 22.21° (62.9% improvement). In contrast, plums stored at 7.5°C improved least from 14.37° to 12.25° (14.8% improvement). Although the colour of the plums stored at -0.5°C showed the greatest improvement, the specific storage regime resulted in significantly the worst colour development. The 2°C treatment followed in level of colour development, and was not significantly different to that of the control. The 5°C and 7.5°C treatments resulted in the highest level of colour development, with no significant difference to one another.

The ‘high versus low temperature treatment’ contrast after shelf life proved to be highly significant (Pr>F: $p<0.0001$), where the ‘high temperature treatments’ resulted in the best colour development and the ‘low temperature treatments’ resulted in poorer levels of colour development (Table 4). The quadratic trend in colour development was significant, with the colour development improving from the -0.5° treatment to the 2°C, 5°C and the 7.5°C treatment having the best colour development, as also previously found during the post storage evaluation (Table 3).

Fruit firmness

Average fruit firmness was determined as 8 ±2.1 kg on the day of harvest. Firmness levels decreased during cold storage and the various treatments differed significantly (Pr>F: p=0.0002). Treatments -0.5°C, 2°C and 5°C did not result in significantly different firmness levels to the control. Treatment 7.5°C resulted in the lowest fruit firmness, significantly lower than to all other treatments except the 5°C treatment (Table 3).

The ‘high versus low temperature treatment’ contrast after storage was highly significant (Pr>F: p<0.0001), where the ‘high temperature treatments’ resulted in the lowest fruit firmness levels and the ‘low temperature treatments’ resulted in higher fruit firmness levels (Table 3). The quadratic trend was significant.

Shelf life storage resulted in highly significant differences in fruit firmness trends between treatments compared to levels measured previously after cold storage (Pr>F: p<0.0001; Table 4). Significantly the highest average fruit firmness levels were measured on plums stored at the -0.5°C treatment and 2°C treatment. The control performed similarly to the 5°C treatment. No significant difference could be found between the 5°C treatment and the 7.5°C treatment. The control did, however, result in a significantly higher fruit firmness level than the 7.5°C treatment.

Similar results were obtained when the contrasts after shelf life were evaluated. The ‘high versus low temperature’ contrast was highly significant (Pr>F: p<0.0001), where the ‘high temperature treatments’ resulted in the lowest fruit firmness levels and the ‘low temperature treatments’ resulted in higher fruit firmness levels (Table 4). The quadratic trend was significant.

Total soluble solids (TSS) and titratable acidity

The average percentages TSS and malic acid were, respectively, determined as 10.1% and 2.15% on the day of harvest. The different cold storage treatments had a significant influence on the average percentage TSS, but not on malic acid levels (Table 3). Similar results were found after the shelf life period (Table 4).

The high temperature treatments (5°C and 7.5°C treatments) resulted in significantly lower TSS averages, compared to the low temperature regime treatments (-0.5°C and 2°C treatments) after cold storage (Table 3). This was not the case, however, after the shelf life period had been completed (Table 4). An almost significant quadratic trend could be observed after storage, with the TSS decreasing as the storage temperature increased (Table 3). This trend changed to a linear trend after shelf life (Table 4).

Shrivel

No shrivel was evident prior to treatment on the day of harvest. The occurrence of shrivelling of plums after storage was influenced by the temperature treatments where the high temperature treatments (5°C and 7.5°C treatments) resulted in the occurrence of shrivelling (Table 3). Upon evaluation after the shelf life period, the influence of storage treatments was significant with the 2°C treatments resulting in the highest levels of shrivel (Table 4). The ‘high versus low temperature’ contrast also proved to be significant, where the ‘low temperature treatments’ resulted in the higher occurrence of shrivelling.

3.2. Discussion

Electrolyte leakage

No significant difference in average percentage electrolyte leakage was found between treatments after the 27-day cold storage period (Table 1). A very small increase in percentage electrolyte leakage from the day of the harvest until the 27-day storage period had been completed was observed.

Furmanski *et al*. (1979) found similar results on peaches where the electrolyte leakage remained low and unchanged while the peaches were stored at 1°C for 5 weeks. Salveit (2002) found with tomatoes that chilling did not immediately cause an increase in permeability of membranes, but rather resulted in a progressive increase in permeability over time. Taylor *et al*. (1993a) found that electrolyte leakage measured on ‘Songold’ plums remained constant during the first 30 days of storage at -0.5°C and thereafter permeability increased during storage, possibly due to membrane cracking as a result of physical phase transition from a flexible to a solid gel state in membrane lipids (Wang, 1982).

The effect of the different temperature treatments could not be observed after cold storage and ripening during shelf life was needed to reveal the significant differences in percentage electrolyte leakage (Table 2). An increase in membrane permeability, and therefore electrolyte leakage, is an expected result of ripening and senescence (Lurie *et al*., 1987;

Murata, 1990; Taylor *et al*., 1993a), and was the increase in percentage electrolyte leakage after shelf life, therefore, expected.

The 5°C and 7.5°C treatments resulted in significantly the highest levels of percentage electrolyte leakage after shelf life (Pr>F: p=0.0001; Table 2). Three evident aspects need to be taken into consideration to enable evaluation of the significant high- versus low storage temperature contrast.

The higher storage temperatures possibly resulted in an increased respiration rate, since respiration and the production of ethylene is temperature dependant (Mitchell, 1986b). ACC (1-aminocyclopropane-1-carboxylic acid), ACC synthase activity and ethylene production are inhibited at low storage temperatures and only increase rapidly when temperature is increased (Wang, 1982). Therefore, the cell membranes of fruit stored at these higher temperature treatments possibly became more permeable due to ripening (Lurie *et al*., 1987), resulting in higher electrolyte leakage levels.

Secondly, the extent of low temperature damage in stone fruit is the greatest at temperatures between 2°C and 7°C (Mitchell, 1986b). Membrane permeability increase at chilling temperatures due to the effect of phase separation of the membrane lipids, since solute permeability is maximal where the bi-layers undergo a gel to liquid-crystalline phase transition (Murata, 1990). Our results show that electrolyte leakage levels are lower in the case of the -0.5°C and 2°C regimes, which fall just outside the ‘killing zone’. The highest electrolyte leakage levels were measured in the 5°C and 7.5°C treatments, which do fall within the range of the ‘killing’ zone. A much more extensive trial will, however, need to be performed where 3°C and 4°C regimes are investigated to give a more clear picture of the role of the ‘killing zone’ and significant linear trends that exists between electrolyte leakage and increasing temperatures (Table 2).

The third aspect which needs to be considered is to what extent exposure of ‘Pioneer’ plum to chilling damage conditions is reversible at various temperatures. Taylor *et al.* (1993a) found that when ‘Songold’ plums were ripened at 15°C after ten and 20 days of cold storage at -0.5°C, the membranes still had the ability to regenerate and permeability (measured as electrolyte leakage) decreased. Membranes were, therefore, still healthy and uninjured. This was, however, not possible after 30 days of cold storage at -0.5°C and electrolyte leakage increased during cold storage and subsequent ripening. It is, therefore, possible that the breakpoint had not yet been reached in our trials where storage of fruit was only over a 27-

day storage period. A considerable, further increase in electrolyte leakage in the low temperature treatments could, therefore, still have been possible.

Internal defects

The internal defects gel breakdown (GB) and aerated flesh was evident after cold storage, with the 5°C and 7.5°C treatments showing the highest percentage of total internal defects, GB and aerated flesh (Table 1). According to Mitchell (1986b) the rate of physiological activity and development of internal quality problems are delayed and less severe at lower temperatures. Internal browning (IBR) only became evident after the shelf life period had been completed (Table 2). No significant difference in percentage total internal defects, GB, and IBR, between treatments were found after shelf life (Table 3).

Both GB and aerated flesh were visible after cold storage. Taylor *et al.* (1994a) found that GB was evident in 10% of the 'Songold' plums evaluated on the day of harvest and that GB could therefore not be classified as a true cold storage chilling disorder although the symptoms were similar to that of chilling disorders (Morris, 1982). Similarly, it is speculated that aerated flesh develops prior to harvest and is therefore not a chilling disorder.

Low levels of GB was evident in only the 5°C and 7.5°C treatments after the 27-day storage period (Table 1). Taylor *et al*. (1994a) found a significant 22% increase in GB during a 28-day storage period at -0.5°C and a 46% increase in the case of a 28-day dual temperature treatment. In our trial, no GB was observed in the -0.5° treatment and control (commercial dual temperature regime). Possible reasons for the contradicting results could be the difference in susceptibility to chilling temperatures of 'Songold' and 'Pioneer' plums and an initial difference in maturity of material used. Taylor and De Kock (1992) and Taylor *et al*. (1993b) found that advanced harvest maturity promotes the development of GB in cold stored apricots and plums.

Gel breakdown levels increased considerably in all treatments during the shelf life period, but no significant differences between treatments were found (Table 2). Taylor *et al.* (1994a) found no significant increase in percentage GB in the case of dual temperature cold stored fruit once ripened. The GB levels, however, increased with 67% in the case of fruit stored at -0.5°C for 28 days after ripening, resulting in the -0.5°C regime showing the highest levels of GB.

The high temperature treatments (5°C and 7.5°C treatments) resulted in the greatest increase and significantly highest levels of GB after shelf life compared to the lower levels of

GB found in the plums stored at -0.5°C and 2°C (Table 2). The development of GB is possibly due to changes which occur during ripening and senescence (Taylor, 1993). It was clear that the 5°C and 7.5°C treatments resulted in the most mature 'Pioneer' plums according to fruit firmness, except for the control (Table 4). Gel breakdown is identified as a "flesh breakdown with a translucent, gelatinous appearance occurring between the stone and the centre of the mesocarp" (Taylor *et al*., 1993a). Taylor *et al.* (1993a) furthermore defined over ripeness (OR) as "softening of the mesocarp tissue directly below the epidermis, characterised by slippery, juicy tissue". Gel breakdown and OR are difficult to distinguish and is it possible that the GB figures also include OR. This could explain the high levels of GB found in the treatments stored at high temperatures where over ripe fruit are more likely to occur.

Membrane permeability of fruit exhibits an increasing trend during ripening and senescence, especially in the case of climacteric fruit (Murata, 1990). Taylor *et al.* (1993a) found that the transition from OR to GB, and therefore the occurrence of chilling injury, in 'Songold' plums is associated with a significant increase in electrolyte leakage and internal conductivity when the viscosities of water soluble pectins were high. In harvest maturity trials performed on 'Songold' plums by Taylor *et al*. (1994b), it was shown that plums harvested at both optimum maturity and post-optimum maturity, lost their membrane integrity towards the end of the dual temperature storage period, and that it was however the plums harvested post-optimum that showed more than 22% GB. A significant contrast between the high temperature treatments (5°C and 7.5°C treatments) and the low temperature treatments (-0.5°C and 2°C treatments) was found after shelf life in percentage conductivity (Pr>F: p=0.0001) and in GB (Pr>F: p=0.0496; Table 2), where the high temperature treatments (5°C and 7.5°C treatments) resulted in the highest occurrence of gel breakdown and in the highest percentage conductivity averages measured.

Similar to the results of Taylor *et al.* (1994a), there seems to be a positive correlation between the occurrence of GB and an increase in percentage electrolyte leakage, suggesting that the development of GB was closely associated with membrane integrity and therefore membrane functionality and permeability. It is, therefore, possible that highly permeable membranes, due to ripening and senescence, resulted in a release of cell fluids leaking through the cell membranes, bounding to pectic substances when viscosities of water soluble pectins were high (Taylor *et al*., 1993a).

Low levels of aerated flesh were evident after storage in the 5°C and 7.5°C treatments (Table 1), but completely disappeared during shelf life (data not shown). Although it is speculated that aerated flesh develops prior to harvest and is not a chilling disorder, no aerated flesh was evident on the day of harvest.

Internal browning was recorded as browning of the tissue (Hartmann *et al.*, 1988; Taylor *et al*., 1993a) and only became evident after shelf life. Taylor (1996) defined internal browning as a disorder where “plums with a normal external appearance, exhibit a brown discolouration of the mesocarp tissue, which with increasing severity, changes from light to dark brown and is associated with a loss of juiciness”.

Internal discolouration or browning of the tissue is, amongst others, a symptom of chilling injury and associated with a change in membrane permeability (Morris, 1982; Murata, 1990). It is expected that membrane permeability would increase at chilling temperatures due to the effect of phase separation of membrane lipids, since the solute permeability is maximal where the bi-layers undergo gel to liquid-crystalline phase transition (Murata, 1990). An increase in membrane permeability, specifically for phenol substances, may cause the promotion of an enzyme-substrate interaction, resulting in the occurrence of browning of the tissue (Murata, 1990). Browning of the mesocarp became evident after prolonged (more than 30 days) exposure to low temperature (-0.5°C treatment) and this was probably due to the enzyme, polyphenoloxidase, catalysing the oxidation of phenolic compounds when the enzyme has unrestricted access to the phenols due to membrane damage (Taylor *et al.,* 1993a). Similar results were found by Punt (2001) when ‘Pioneer’ plums were stored at -0.5°C for 29 days.

Although no significant differences between treatments were found in our trial, the low temperature treatments (-0.5° and 2°C treatments) resulted in a slightly higher level of internal browning evident after the shelf life period, similar to the results of Taylor *et al*. (1993a) and Punt (2001) (Table 2). Taylor *et al.* (1993a) furthermore found that a transition from over ripeness to internal browning during prolonged storage at chilling temperatures was associated with a significant increase in electrolyte leakage. Our results show that the low temperature treatments (-0.5°C and 2°C treatments) resulted in significantly lower levels of electrolyte leakage, which is contrary to what Taylor *et al*. (1993a) found. As previously mentioned, it is possible that the breakpoint in terms of chilling injury had not yet been reached in our trials where fruit was cold stored only for a 27-day period. A considerable, further increase in electrolyte leakage in the low temperature treatments could, therefore, still have been possible, also resulting in significant differences in the occurrence of internal browning. It can, however, also be speculated that the significantly lower electrolyte leakage levels are due to the loss of juiciness associated with internal browning (Taylor, 1996).

Colour (hue angle)

The rate of ripening of stone fruit is temperature dependant and ethylene gas functions as the ripening hormone (Mitchell, 1986b). ACC (1-aminocyclopropane-1-carboxylic acid), ACC synthase activity and ethylene production are inhibited at low storage temperatures and only increase rapidly when temperature is increased (Wang, 1982). The normal range of ethylene sensitivity of most species and cultivars is between 4°C and 38°C (Mitchell, 1986b).

The different temperature treatments had a highly significant effect on colour development of ‘Pioneer’ plums during storage (Pr>F: $p<0.0001$) and after shelf life (Pr>F: $p<0.0001$; Tables 3 and 4, respectively). The development of colour is a ripening response, being highly temperature dependant, and did the high temperature treatments (5°C and 7.5°C treatments), therefore, result in the best colour development after storage (Table 3) and after shelf life (Table 4). Both the high- versus low storage temperature contrast and linear contrast proved to be highly significant after storage and again after shelf life (Tables 3 and 4).

It was interesting to observe to what extent the commercially applied dual temperature regime differ from temperature treatments evaluated in this trial (Tables 3 and 4). The -0.5°C regime resulted in the worst colour development after 27 days cold storage and shelf life. There was, furthermore, no significant difference in colour development between the 2°C treatment and the commercially applied dual temperature treatment after the 27-day cold storage period and shelf life period. The 2°C regime could, therefore, possibly be a good alternative to the commercially applied dual temperature storage regime in the case of ‘Pioneer’ plum, since similar colour development can be achieved. The 5°C and 7.5° treatments resulted in the best colour development (more red) with no significant difference evident after cold storage and shelf life.

Fruit firmness

Peaches and nectarines show a dramatic change in rate of flesh softening at temperatures below 3°C due to inactivity of ethylene gas as ripening hormone at these temperatures (Mitchell, 1986b). According to Mitchell (1986b), ‘Sungrand’ nectarines lost 17% of initial firmness measured when stored at 2.2°C in comparison to 78% when stored at 5°C and was it recommended that stone fruit should be cold stored at lower temperatures to ensure the retention of firmness.

The individual temperature treatments had a highly significant influence in loss of fruit firmness during the 27-day cold storage period (Pr>F: $p=0.0002$; Table 3) and during the shelf life period (Pr>F: p<0.0001; Table 4). It was clear that the -0.5°C and 2°C treatments resulted in similar firmness levels to the control upon evaluation after 27 days (Table 3). Only the -0.5°C and 2°C treatments retained fruit firmness at an acceptable level (5.1 kg and 6.3 kg respectively) after the shelf life period. The control, 5°C and 7.5°C treatments responded fairly similarly with a sudden decrease in fruit firmness after shelf life (Table 4). Taylor (1993) showed that fruit firmness in ‘Songold’ plum was significantly lower in dual temperature shipment (similar to our control) than in single temperature shipment (-0.5°C regime) and this was mainly due to a more advanced state of ripeness.

Total soluble solids (TSS) and titratable acidity

Taylor (1993) found significant differences in soluble solids and titratable acidity between the inner and outer regiments of ‘Songold’ plums throughout storage. It was, therefore, suggested that the plums were riper on the inside than the outside from harvest throughout storage. No significant differences in soluble solids and titratable acids were, however, found over time. In contradiction to the results found by Taylor (1993) on ‘Songold’ plums stored at dual temperature, the different temperature treatments in this trial resulted in a significant influence on soluble solids levels measured after storage (Table 3) and after shelf life (Table 4).

The TSS dropped significantly at higher storage temperatures suggesting that respiration might have played a role in the drop in soluble solids levels. A significant contrast between the high temperature treatments and the low temperature treatments were observed only after storage (Table 3). A significant linear trend was observed after shelf life where the -0.5°C treatment resulted in the highest average TSS, decreasing as the storage temperature increased (Table 4). In studies performed by Kruger (2002), it was shown that ‘Pioneer’ plum had a higher respiration rate and ethylene production than ‘Sapphire’, ‘Songold’ and ‘Angeleno’. It is, therefore, possible that the significant difference in TSS due to increased respiration rate at higher storage temperatures might have caused the decrease in soluble solids levels in the 5°C and the 7.5°C treatments. No significant difference in malic acid levels were observed at either evaluation time.

Shrivel

According to Mitchell (1986b) plums lose water more slowly than other stone fruits and visual shrivel only appears when water loss reaches 4 to 5% of the initial fruit weight. The cuticle forms a major barrier to the movement of water and solutes and is a non-cellular, nonliving, lipoidal membrane (Storey and Price, 1999). Major differences in the crystalline form of the epicuticular wax on the bloom and non-bloom side of ‘d’Agen’ plums was observed by Storey and Price (1999) and it was concluded that the microclimate of the fruit (temperature, light and humidity) may modify the composition and crystalline structure of epicuticular waxes. This phenomenon will contribute to the variation found in the occurrence of shrivelling. Immature fruit are also more susceptible to water loss than mature fruit due to the immature fruit's lack of fully developed cuticle surface (Mitchell, 1986a). Mitchell (1986a) furthermore stated that the maintenance of high relative humidity around the fruit in the storage atmosphere is vital for minimising water loss.

Results on the occurrence of shrivelling after the 27-day cold storage period proved that the plums stored at the highest temperatures, showed the highest level of shrivel, however, the shrivel levels were still low and within acceptable limits (Table 3). The level of shrivelling increased after shelf life in most treatments, possibly due to accelerated ripening and water loss. The low temperature treatments, however, now proved to have the highest occurrence of shrivel after the shelf life period (Table 4).

4. Conclusion

The different temperature storage regimes applied had a significant effect on percentage electrolyte leakage, an indirect measurement of membrane permeability, and fruit quality. Stone fruit is susceptible to low temperature injury and the most internal quality problems were found in plums stored at the commercially applied dual temperature regime (control), 5°C and 7.5°C temperature treatments after the fruit had been ripened. These regimes operate at temperatures within the so called 'killing zone' (temperatures between 2°C and 7°C) which possibly contribute to the occurrence of chilling injury symptoms (Mitchell, 1986b).

An increase in membrane permeability is an expected result of ripening and senescence of especially climacteric fruit (Murata, 1990). According to Taylor *et al.* (1994a), GB cannot be classified as a true chilling disorder due to the occurrence thereof sometimes already at harvest. There seems to be a positive correlation between the ripening of 'Pioneer' plums, an increase in electrolyte leakage and the occurrence of GB, suggesting that the development of GB was closely associated with membrane integrity. The higher storage temperatures (5°C and 7.5°C treatments) could, therefore, have resulted in elevated ripening and higher levels of electrolyte leakage.

It has furthermore been found that the 2°C treatment could possibly replace the commercially applied dual temperature regime (control) in the case of 'Pioneer' plum. Firstly, similar colour development is achieved through the 2°C treatment as in the case of the control. Secondly, it is known that ‘Pioneer’ plum has a very high respiration rate and it would be beneficial if fruit could be stored at temperatures below 3°C to ensure lower sensitivity to ethylene (Mitchell, 1986b), control of ripening, and indirectly therefore the occurrence of gel breakdown, and the loss of soluble solids. It is also known that ‘Pioneer’ plum is very susceptible to develop internal quality problems (Punt, 2001) and the avoidance of the ‘killing zone’ might prove to be advantageous. Thirdly, the 2°C treatment proved to result in improved fruit firmness levels after ripening in combination with similar colour development to that of the control. However, this treatment had unacceptably high internal browning and shrivel levels after shelf life.

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Table 1

Effect of temperature treatments on electrolyte leakage and occurrence of internal defects of 'Pioneer' plums after a 27-day storage period.

Treatment	Conductivity[b] (uS/m)	Total conductivity[c] (uS/m)	Conductivity[d] (%)	Total internal defects (%)	Gel breakdown (%)	Aerated flesh (%)
Control	87.6 a	351.2 a	25.2 a	0 ± 0	0 ± 0	0 ± 0
-0.5°C	90.3 a	347.4 a	26.4 a	0 ± 0	0 ± 0	0 ± 0
2°C	88.4 a	338.6 a	26.2 a	0 ± 0	0 ± 0	0 ± 0
5°C	89.2 a	373.0 a	23.9 a	4 ± 8.9	2 ± 4.5	2 ± 4.5
7.5°C	107.3 a	355.6 a	30.6 a	16 ± 15.2	8 ± 13.0	8 ± 13.0
Pr>F	0.2224	0.6425	0.2723	[f]	[f]	[f]
Contrast: High vs. low temp. treatments [a]	0.1940	0.1971	0.9350	-	-	-
Contrast: Temp. linear	0.0991	0.3919	0.4579	-	-	-
Contrast: Temp. quadratic	0.1497	0.7904	0.1412	-	-	-
Tukey (5%)	28.02	67.55	[e]	-	-	-

[a] -0.5°C and 2°C vs. 5°C and 7.5°C

[b] Conductivity of solution before freezing discs

[c] Conductivity of solution after freezing discs

[d] Percentage conductivity = (conductivity of solution before freezing / conductivity of solution after freezing) X 100

[e] Statistics performed on arcsine transformed data

f Data not normally distributed (even after performing arcsine transformation)

Table 2

Effect of temperature treatments on electrolyte leakage and the occurrence of internal defects of 'Pioneer' plums after a 27-day storage and seven day shelf life period.

Treatment	Conductivity[b] (uS/m)	Total conductivity[c] (uS/m)	Conductivity[d] (%)	Total internal defects (%)	Gel breakdown (%)	Internal browning (%)
Control	149.5 b	370.8 ab	40.3 ab	40 a	36 a	4 a
-0.5°C	131.2 b	344.0 b	38.1 a	28 a	18 a	10 a
2°C	134.7 b	363.8 ab	37.1 a	28 a	18 a	10 a
5°C	165.8 ab	354.6 ab	46.7 b	66 a	66 a	0 a
7.5°C	190.7 a	398.8 a	47.8 b	66 a	62 a	4 a
Pr>F	0.0008	0.0278	0.0033	0.2554	0.2003	0.3681
Contrast: High vs. low temp. treatments [a]	<0.0001	0.0555	0.0001	0.0529	0.0496	0.0838
Contrast: Temp. linear	<0.0001	0.0066	0.0004	0.1336	0.1484	0.1434
Contrast: Temp. quadratic	0.2515	0.2895	0.7159	0.4898	0.3584	0.3094
Tukey (5%)	38.24	47.45	[e]	[e]	[e]	[e]

[a] -0.5°C and 2°C vs. 5°C and 7.5°C

[b] Conductivity of solution before freezing discs

[c] Conductivity of solution after freezing discs

[d] Percentage conductivity = (conductivity of solution before freezing / conductivity of solution after freezing) X 100

[e] Statistics performed on arcsine transformed data

Table 3

Effect of temperature treatments on fruit quality characteristics of ‘Pioneer’ plums after a 27-day storage period.

Treatment	Colour (hue angle)	Firmness (kg)	TSS (°Brix)	Malic acid (%)	Shrivel (%)
Control	28.1 bc	6.6 a	10.7 a	1.8 a	0 ± 0
-0.5°C	59.8 a	6.9 a	10.6 a	1.8 a	0 ± 0
2°C	34.3 b	7.3 a	10.4 ab	1.8 a	0 ± 0
5°C	19.8 cd	4.9 ab	9.9 b	1.8 a	2.7 ± 2.8
7.5°C	14.4 d	2.4 b	10.3 ab	1.7 a	2.7 ± 2.8
Pr>F	<0.0001	0.0002	0.0153	0.8532	[b]
Contrast: High vs. low temp. treatments [a]	<0.0001	<0.0001	0.0205	0.5885	-
Contrast: Temp. linear	<0.0001	<0.0001	0.0660	0.4586	-
Contrast: Temp. quadratic	0.0021	0.0448	0.0591	0.7301	-
Tukey (5%)	12.03	2.75	0.66	0.25	-

[a] -0.5°C and 2°C vs. 5°C and 7.5°C

[b] Data not normally distributed (even after performing arcsine transformation)

Table 4

Effect of temperature treatments on fruit quality characteristics of ‘Pioneer’ plums after a 27-day storage and seven day shelf life period.

Treatment	Colour (hue angle)	Firmness (kg)	TSS (°Brix)	Malic acid (%)	Shrivel (%)
Control	16.9 b	3.0 b	11.0 a	1.9 a	8.0 ab
-0.5°C	22.2 a	5.1 a	10.5 ab	1.7 a	6.7 ab
2°C	17.9 b	6.3 a	10.2 ab	1.3 a	17.3 a
5°C	12.9 c	2.2 bc	10.2 ab	1.7 a	0.7 b
7.5°C	12.3 c	1.5 c	9.8 b	1.6 a	12.7 a
Pr>F	<0.0001	<0.0001	0.0052	0.1283	0.0021
Contrast: High vs. low temp. treatments [a]	<0.0001	<0.0001	0.0930	0.3617	0.0478
Contrast: Temp. linear	<0.0001	<0.0001	0.0251	0.8810	0.9784
Contrast: Temp. quadratic	0.0035	0.0078	0.7588	0.3170	0.7950
Tukey (5%)	2.31	1.33	0.82	0.73	10.71

[a] -0.5°C and 2°C vs. 5°C and 7.5°C

GENERAL DISCUSSION AND CONCLUSION

The South African fruit export industry has to overcome two major obstacles, namely the distance to the overseas markets and the time it takes to complete such voyages. Both challenges require the development of technology to ensure that the horticultural product arrives in a good condition.

The refrigerated integral container essentially consists of three parts, namely an insulated box, a refrigeration system and an air circulation and distribution system and was designed to operate independently (Irving, 1988). Therefore, power consumption and the dimensions of the refrigeration unit itself had to be minimised. As a result the integral container has a limited capacity to refrigerate and it was, therefore, designed to only maintain product temperature.

Efficient temperature control of a respiring product requires that ideally the air should be distributed in such a way that the quantity of air flowing in each section should be proportional to the amount of heat to be removed to attain such temperature uniformity (Irving, 1988). Airflow rate and -distribution, therefore, play an important role in uniform temperature maintenance throughout the container (Irving and Sheperd, 1982; Irving, 1988). Irving (1988) stated that the air-flow system of an integral container was not designed to allow efficient cooling, which further accentuates the fact that the integral container should not be regarded as a cooling device.

Outside air is introduced into the circulating airflow of an integral container through fresh air ventilation in an effort to prevent the build up of carbon dioxide and ethylene (Billing *et al*., 1998). Since the air contains moisture and the carriage temperatures are operated below freezing point, the evaporator coil is subject to frost deposition and progressive build up (Tso *et al*., 2006; Irving, 1988). Due to the positioning of the fresh air vent, differential coil frosting can result in a temporary variation in delivery air temperature, spatially and across the width of the container, contributing to temperature variation (Amos and Sharp, 1999; Tanner and Amos, 2003a).

Between seven and eight million cartons of plums are exported annually from South Africa (Anonymous, 2006). Browning of the mesocarp, referred to as internal breakdown by Dodd (1984), seriously affects the quality of plums exported from South Africa. Stone fruit is susceptible to chilling injury (CI), being genetically influenced and triggered by a combination of storage temperature and storage time (Crisosto *et al*., 1999; Lurie and Crisosto, 2005).

The harmful effect of chilling temperatures is reversible when fruit is timeously transferred to temperatures above the critical minimum threshold (Artés *et al*., 1996). However, prolonged storage at temperatures below the critical temperature leads to irreversible injury (Hakim *et al*, 1997). Intermittent warming (IW) has been shown to alleviate and/or delay CI during cold storage on a number of fruit commodities and a dual temperature storage regime was developed in South Africa for plums based on the principles of IW to alleviate the CI related defects (Hartmann *et al*., 1988; Taylor, 1993). The dual temperature shipping regime consists of an initial period at -0.5°C, a variable intermittent warming period at 7.5°C, followed by -0.5°C for the remainder of the voyage (PPECB, 2006a; Punt and Huysamer, 2005). Numerous dual temperature regimes exist and the cultivar and maturity of the fruit determine which regime is chosen (PPECB, 2006a). Taking into consideration that dual temperature shipment requires refrigeration and effective distribution of cool air to remove the sensible- and respiratory heat throughout the container, the capacity of integral containers to ship plums successfully at dual temperature is questioned.

Plums are classified as climacteric fruit, showing a peak in respiration and ethylene production during ripening, releasing vital heat to the storage environment (Holcroft *et al*, 2002). Kruger (2002) measured higher respiration rates in climacteric plums, compared to suppressed climacteric plums, which suggests that the vital heat produced by climacteric plums will also be greater. The chance of temperatures rising rapidly during shipment is, therefore, much greater in the case of climacteric fruit. It is, therefore, important to understand how the specific plum cultivar influences the container's performance.

The objectives of this study were, therefore, firstly, to generate and analyse pulp temperature data and possibly identify different temperature zones within integral containers shipping plums at dual temperature, where a number of positions within a specific zone experience similar temperature conditions. Secondly, to understand the underlying processes that differentiate the temperature zones and thirdly, to determine the effect of the container's performance and, therefore, the existence of temperature zones on fruit quality.

Three distinct processes were identified as important fundamental influences or characteristics of pulp temperature data sets of plums shipped at dual temperature, namely the cooling down process, the heating up process and the role of over heating in the container. The order of importance differed depending on the cultivar shipped and the integral container's performance. The formation of the temperature zones could be explained by considering the factors that influence pulp temperature, namely the delivery air temperature, localised airflow and the influence of the heat of respiration produced by the product (Billing *et al*., 1993; Billing, *et al*., 1995).

The average pulp temperature measured during the first and third phases of the dual temperature cycle, the time it took for the fruit to heat up and the time it took to cool down again, increased along the length of the container, across the width of the container and up the container system. Tanner and Amos (2003a) have shown that a change in atmospheric conditions can result in a variation in delivery air temperature across the width of the container, contributing to the development of similar pulp temperature variances within the container.

Significantly higher pulp temperatures near the door end of the container, and differences in temperature variance patterns in two ‘Sapphire’ containers could possibly be ascribed to poor airflow patterns. According to Tanner and Amos (2003b), the large distance from the fan, situated at the front of the container, to the door end of the container, results in lower airflow at the door end of the container due to short circuiting of air from the refrigeration end of the container along the length of the container. A lower volume of cold air is, therefore, delivered to the door end of the container resulting in higher air temperatures.

Over heating played an important role in characterising the pulp temperature data sets, depending on the plum cultivar shipped. The higher temperatures experienced during the heating up phase of dual temperature shipment, results in an increase of the respiration and ethylene production rates (Kader, 2002). ‘Sapphire’ plum fruit can be classified as climacteric, showing higher respiration rates than suppressed climacteric fruit, with the difference being even greater at higher temperatures (Holcroft *et al*., 2002; Kruger, 2002). It was found that the temperatures increased more rapidly during shipment in the case of ‘Sapphire’ plums, which can be attributed to the greater production of vital heat and fruit ripening more rapidly (Holcroft, *et al*., 2002). Over heating taking place was, therefore, an important characteristic of the ‘Sapphire’ pulp temperature data sets. ‘Laetitia’ showed a similar rapid rise in pulp temperatures. However, lower respiration rates and less vital heat produced were possible factors preventing over heating from taking place in the container. It is thought that ‘Fortune’ plum can possibly be characterised as a true suppressed climacteric fruit, similar to ‘Angeleno’ plum, showing considerably less and delayed ethylene production (Holcroft, *et al*., 2002). ‘Fortune’ plum took the longest period of time to heat up, possibly due to inherently lower respiration rates, resulting in much lower levels of vital heat and ethylene produced. This can also be observed in a much faster cooling rate than observed in the case of ‘Sapphire’ plum. Over heating was, therefore, not an important characteristic of the

‘Fortune’ pulp temperature data set. It is, therefore, evident that the different plum cultivars influenced the container’s performance differently and should be considered individually.

In work performed on ‘Pioneer’ plum, showing the highest respiration rate compared to ‘Sapphire’, ‘Songold’ and ‘Angeleno’ (Kruger, 2002), it was suggested that storage or shipping at 2°C could possibly replace the commercially applied dual temperature regime (control). Firstly, similar colour development was achieved through the 2°C treatment, as in the case of the control. Secondly, it is known that ‘Pioneer’ has a very high respiration rate and it would be beneficial if fruit could be stored at temperatures below 3°C to ensure lower sensitivity to ethylene (Mitchell, 1986), control of ripening, and indirectly therefore the occurrence of gel breakdown, and the loss of soluble solids. The chance of temperatures rising rapidly during shipment is also much greater in the case of climacteric fruit, and it could be beneficial to ship the fruit at 2°C since ripening will be suppressed to a degree. It is also known that ‘Pioneer’ is very susceptible to development of internal defects (Punt, 2002) and the avoidance of the ‘killing zone’ might prove to be advantageous. Thirdly, the 2°C treatment proved to result in improved fruit firmness levels after ripening in combination with similar colour development to that of the control. However, this treatment had unacceptably high internal browning and shrivel levels after shelf life.

The cooling down process was identified as the most important factor discriminating the temperature zones when climacteric plums were shipped.

Fruit size had a significant influence on the average fruit firmness and TSS prior to shipment in all trials performed. Larger fruit showed significantly lower fruit firmness and higher total soluble solids levels, except in the case of ‘Laetitia’.

In the ‘Sapphire’ trials it was shown that the significant difference in fruit firmness found between cluster groups post shipment was due to either temperature variation during shipment or a combination of temperature variation and differences in fruit firmness prior to shipment. It has, therefore, been shown that the initial fruit maturity can also have a determining effect on post-shipment fruit quality. The fruit firmness generally decreased from the front to the door end of the container and average pulp temperature increased along the length of the container, from the front to the door end, along the width of the container, from left to right, and up the height of the container system. It was, therefore, shown that the rate of deterioration increased from the front to the door end of the container due to an increase in pulp temperature.

The temperature variance found within the ‘Fortune’ container had no significant influence on the fruit firmness post-shipment, confirming the thought that ‘Fortune’ can be classified as a true suppressed climacteric plum cultivar. In the ‘Laetitia’ trials it could be concluded that the average fruit firmness decreased from the front of the container towards the door end of the container due to the variable temperature conditions found within the container.

Although there was a trend in all the dual temperature container trials performed that the fruit situated in the temperature zone at the door end of the container showed the highest levels of internal defects, the differences found were mostly insignificant. Gel breakdown caused widespread quality problems in a high percentage of ‘Laetitia’ plums shipped from South Africa in the 2004/2005 stone fruit season (Kapp and Jooste, 2006), and this internal defect was also evident in our trial. There was a trend that higher temperatures, as found predominantly at the door end of the container, expressed the already present gel breakdown better. Taylor *et al*., (1994) stated that gel breakdown cannot be classified as a true storage chilling disorder since it was already evident prior to harvest in more mature ‘Songold’ plums. It can, therefore, be concluded that the greatest effect the variable temperature conditions had, was on the fruit firmness levels.

Temperature zones could not be identified within the integral containers that shipped plum fruit under a single temperature regime, suggesting that the refrigerated integral container can maintain temperature well during single temperature shipment. Fruit pulp temperature showed a limited increase from the front to the door end of the container, and from the left to the right hand side of the container in the ‘Fortune’ trial. Little temperature variance was found in the ‘Angeleno’ trial. The limited temperature variances found could possibly be due to changing outside atmospheric conditions resulting in a variation in delivery air temperature across the width of the container, insufficient airflow to the door end of the container or the effect of the varying production of vital heat by ‘Fortune’ and ‘Angeleno’ cultivars, where an elevated fruit respiration and an increased production of vital heat is known to accentuate the effects of poor airflow (Oosthuyse, 1997).

Higher average voyage pulp temperatures did not result in observable lower fruit firmness levels measured upon arrival. This was true for both ‘Fortune’ and ‘Angeleno’, both showing characteristics of suppressed climacteric plum cultivars, known to exhibit limited declines in fruit firmness levels during cold storage, and the refrigerated integral container showing good temperature maintenance throughout the container area.

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