AN ABSTRACT OF THE THESIS OF

Pichaya Boonprasom for the degree of Doctor of Philosophy in Bioresource Engineering presented on September 17, 2001. Title: Extending Market Potential of Blueberries with Controlled Atmosphere Storage.

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Abstract approved: ______________________
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The goal of this research was to determine if controlled atmosphere (CA) storage could be used to extend the market period of fresh Pacific Northwest blueberries and to evaluate the effects different storage atmospheres have on fruit quality. Furthermore, this research also investigated heat and mass transfer characteristics during cooling and storage of fresh blueberries in controlled atmosphere storage "Elliott" blueberries were stored at –1 ^{0}C (30 ^{0}F) with 80-95% RH in combinations of 2% and 5% O_2 with 5% and 15% CO_2 during the 1996 storage season and in combinations of 2% and 5% O_2 with 10% and 15% CO_2 in the 1997 and 1998 storage seasons.

Fruit quality attributes were determined after 53 and 80 days of storage in 1996 and after 53 and 93 days of storage in 1997 and 1998. In the 1996 storage season, berries stored in combinations of 15% CO_2 were firmer, developed less decay, and were lower in SS/Ac after 53 and 80 days in storage than berries stored in 5% CO_2. After 80 days in storage, fruit stored in combinations of 5% CO_2 exhibited high levels of visible fungal decay. In the 1997 and 1998 seasons, storage of berries in high CO_2 concentration levels of 15% resulted in greater percentages of marketable and firm fruit, and better sensory

ratings, than storage in carbon dioxide concentration levels of 5%. Controlled atmosphere conditions of 5% O_2 and 15% CO_2 were rated as superior for blueberries stored 93 days.

A simple model was developed to determine the cooling process parameters including cooling coefficient, lag factor, half cooling times, seven-eighths cooling times, and effective heat transfer coefficients. Estimated cooling coefficient, lag factor, half cooling times, and seven-eights cooling times ranged from 0.23 hr^{-1} to 0.40 hr^{-1}; 1.01 to1.05; 1.56 hrs to 2.85 hrs; and 5.57 hrs to 8.81 hrs, respectively. The effective heat transfer coefficient varied from 10.17 W/m^2 K to 16.05 W/m^2 K depending upon berry basket position. The greater the surface area exposed to the cooling medium, the higher the heat transfer coefficients and the lower the half cooling time and the seven-eighths cooling time.

Transpiration coefficients, on per unit mass and per unit area basis, were determined for "Elliott" blueberries stored in bulk refrigerated CA environments. Fruit mass loss was greatest during the cool down period because both respiration and transpiration rates were high, then decreased exponentially. Fruit stored in controlled atmosphere conditions of 5%O_2 and 15%CO_2 (Box D) had the lowest mass loss and the lowest transpiration rate of 0.00023 mg/s•kg•kPa.

Extending Market Potential of Blueberries with Controlled Atmosphere Storage

by

Pichaya Boonprasom

A THESIS

Submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented September 17, 2001
Commencement June 2002

Doctor of Philosophy thesis of Pichaya Boonprasom presented on September 17, 2001

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ACKNOWLEDGEMENTS

At the completion of my study, I would like to acknowledge the many persons who have contributed so much to the planning and development of this thesis. Without their help, this accomplishment could not have been attained. I would like to express my deepest gratitude to those for their contribution toward succeeding in my doctoral program.

I would like to express my sincere appreciation and respect to my major advisor, Dr. Martin L. Hellickson. His never-ending patience and guidance to make this achievement possible will always be remembered. The kindness, support, and understanding he always provided were invaluable throughout my graduate programs.

I would like to thank Dr. John P. Bolte and Dr. Paul M. Chen for serving on my committee and their assistance throughout my M.S. and Ph.D. programs.

I am indebted to Dr. Frank Chaplen for providing his valuable time serving on my Ph.D. committee.

I am grateful for Dr. Thomas K. Plant for his kindness serving as my Ph.D. Graduate Council Representative.

This thesis would not have been possible without the assistance of Mr. Mark Hurst and Mr. Dan Caldwell at Hurst's Berry Farm for their continuous supplying blueberries for all my 3 years' experiments. Their support shall never been forgotten.

The financial support from The Royal Thai Government (Chiang Mai University) for both my M.S. and Ph.D. programs is highly appreciated.

Finally, I would like to express my love and heartful gratitude to my family for all of their emotional support in completing my Ph.D. program. In particular to my mother, father, and my husband who provide me with their unwavering and constant support; believing in me that I would finally succeed in my doctoral program.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF APPENDIX FIGURES

LIST OF APPENDIX FIGURES (Continued)

LIST OF APPENDIX FIGURES (Continued)

LIST OF APPENDIX TABLES

LIST OF APPENDIX TABLES (Continued)

LIST OF APPENDIX TABLES (Continued)

EXTENDING MARKET POTENTIAL OF BLUEBERRIES WITH CONTROLLED ATMOSPHERE STORAGE

CHAPTER 1

INTRODUCTION

North America is the world's leading blueberry producer, accounting for nearly 90% of total production in the year 2000. North American blueberries are harvested from mid-April through early October. Peak harvest occurs in July which is also known as National Blueberry Month. Cultivated blueberries are grown in more than 30 states in the United States as well as in British Columbia, Canada. Nearly half of the cultivated blueberries are sold as fresh product.

Blueberries were the fourth largest berry crop in Oregon with 22.5 million pounds production in 1999. Although production was down 2 percent from 1998, the value of production increased 55 percent from 1998 to 1999 to 17.9 million dollars. The average price increased from 50.2 cents per pound in 1998 to 79.7 cents per pound in 1999 (OSU, 1999-2000). Washington State produced 10.8 million pounds of blueberries in 1999 (OSU, 2000). Commercial blueberry production in the Pacific Northwest is becoming an important industry noted for high quality fruit. In 1999, Oregon lead the Pacific Northwest in acres planted (approximately 2,600 acres), while Washington state listed 1,600 acres planted (OSU, 2000).

Highbush blueberries are appreciated throughout the world. The United States per capita consumption of fresh blueberries has increased during the last decade from 7 to 10 oz per person (Hellman, 1997). Recently, blueberries have been found to benefit health in fighting cancer, improving cardiovascular activity and improving eyesight (Wyman, 1997). Cold storage volume of blueberries in the Pacific Northwest region is approximately 11.5 million pounds as of February 2001, an increase of 20% from the previous three year average (USDA, 2001).

Decay caused by fungi is the primary factor that limits postharvest acceptability. Due to the relative shortness of the harvest period, large quantities of blueberries arrive at the marketplace at one time. Significant interest has been expressed by the Pacific Northwest blueberry industry in extending the period this highly perishable commodity can be successfully marketed as fresh rather than frozen produce. Successfully delaying marketing these fruit could provide growers the ability to sell at significantly higher prices than attainable when the market is flooded.

Innovators in the industry have attempted to extend the postharvest quality of blueberries by wrapping individual flats of fruit with plastic and injecting a mixture of gases (nitrogen and carbon dioxide) to achieve a modified atmosphere package. This technology can successfully extend the marketing period of fresh blueberries up to ten days, but requires precise temperature management throughout the distribution chain. More recently, some producers have constructed controlled atmosphere (CA) rooms to store later harvested varieties (primarily Elliott) for even longer periods before marketing. The longer blueberries can be stored without significant reduction in quality, the greater the potential to command premium prices when marketed. However, many questions exist as to what are the appropriate storage conditions (temperature, carbon dioxide, oxygen and humidity levels and their combinations) that will maintain product quality at levels acceptable to the consumer.

Temperature is the most important environmental factor in maintaining storage quality of horticultural products because of its dramatic effects on respiration rates and other biological reactions (Robertson, 1993). Low temperature contributes to decrease the respiration rate, retards or prevents microorganism growth and reduces the metabolic activity of plant tissues (Riquelme et al., 1994) and moisture loss. Rapid cooling of produce immediately after harvest is very beneficial but is not sufficient to maintaining quality for extended periods. For this reason, precise temperature and atmospheric control are being investigated.

Controlled atmosphere storages actively regulate temperature, O_2 and CO_2 concentrations, and humidity levels around the fresh produce. Beneficial effects of CA conditions in prolonging the postharvest life of various commodities have been demonstrated and reviewed in many papers. This technology can extend seasonal availability and eating-quality fruit at reasonable costs. A positive return on investment in CA storage has been demonstrated for many commodities such as apples, pears, bananas, cabbages and cherries.

Harvested fresh blueberries are living tissue, and, like all agricultural commodities, continue to carry on metabolic processes during storage. Most important of these is respiration. As fresh blueberries continue to respire, water, carbon dioxide and heat are produced. Water lost from tissue through transpiration is the main factor in loss of salable weight. Water loss also adversely effects nutritional quality, appearance (witting and shriveling) and textural quality (Kader, 1992). Different experimental methods have been used to determine transpiration coefficients of some commodities, however mass loss data of fresh Elliott blueberries are not presently available.

The development of accurate moisture loss data from commodities during storage assists in the design of storage facilities. Rate of moisture loss from fruits is directly proportional to the water vapor pressure difference between the fruit surface and its environment, which is governed by temperature and relative humidity (Sastry, 1985). Designing a storage to minimize shrinkage requires knowledge of optimum storage temperatures and humidities, rate of moisture loss from fruits at various vapor pressure differences, the effects of the packaging systems on moisture loss rates and the effect of various heat sources on the cold storage (Sainsbury, 1985).

The goal of this research was to determine if controlled atmosphere (CA) storage could be used to extend the market period of fresh Pacific Northwest Elliott blueberries and to evaluate the effects different storage atmospheres have on fruit quality. Furthermore, this research also investigated heat and mass transfer characteristics during cooling and storage of fresh blueberries in controlled atmosphere environments. The specific objectives of this study were to determine:

1. Cooling process parameters including cooling coefficient, lag factor, half cooling times, seven-eighths cooling times, and effective heat transfer coefficients.
2. The transpiration rates and transpiration coefficients.
3. The effect of different CA storages on:
    3.1. Accumulated weight loss.
    3.2. Fruit soluble solids concentrations, pH, acid contents, and sugar-acid ratio

3.3. Unmarketable fruit percentage.

3.4. Fruit appearance and flavor as evaluated by consumer acceptance tests.

3.5 Losses in fruit firmness during CA storage.

3.6 Fruit color change.

CHAPTER 2

LITERATURE REVIEW

The blueberry is one of the most recent major fruit crop to be brought under cultivation, having been domesticated entirely in the twentieth century (Janick and Moore, 2000). Blueberries are members of the Ericaceae family, genus Vaccinium, subgenus Cyanococcus. The genus is very diverse, containing between 150 and 450 species, mostly found in the tropics at high elevation, but also in temperate and boreal regions (Rieger, 2000).

World production statistics of blueberries listed 178,000 acres under cultivation in the world, with 90% of this in the US and Canada (Rieger, 2000). There are a few thousand acres in Europe, particularly northern countries like Poland, Lithuania, and the Netherlands. In Japan, native blueberries are collected from the wild and processed, and plantings are expected to develop there (V. uliginosum and V. vitis idaea). In North America, over 70% of the crop is processed. Most of the Canadian production is likely lowbush ; the rest of the world produces highbush blueberries, for the most part (Rieger, 2000). This industry has continued to thrive and expand with the continuing development of newer and better cultivars. More than 61 highbush and 35 rabbiteye cultivars, which originated from controlled pollinations, have been named to date. In addition, 22 southern highbush and 7 half-highbush cultivars have also been named.

2.1. HIGHBUSH CULTIVARS

Highbush blueberries (*Vaccinium corymbosum L.*) are the most important species, based on acreage, grown in the United States. Highbush blueberries belong to the family Ericacea and are perenial, long-lived, deciduous, woody shrubs. In the Pacific Northwest, the highbush blueberry's fruiting season extends from early July to mid-September. Cultivars are classified as early, early mid-season, mid-season, late mid-season, and late. The fruit of each cultivar ripens over a two to five week period. Cultivars that ripen after mid-September are rarely grown in the Pacific Northwest because wet weather often makes harvest difficult (Strik, 1993).

Elliott is a late-season highbush blueberry cultivar grown in the Pacific Northwest. "Elliott" is vigorous, erect, and consistently productive. The fruiting season extends from mid-August to early September. Fruit clusters are loose and individual berry fruits are medium in size, light blue in color, and firm with a small stem scar. The fruit flavor is mild to good, slightly tart. Fruit ripening is concentrated. Elliott blueberry plants are moderately resistant to mummy berry and are well-suited for machine harvest.

2.2. HARVEST MATURITY AND RIPENING

2.2.1. Harvest Maturity

The important indices of fruit maturity include size, shape, pH, total acidity, soluble solids, and surface color, which is significantly related with anthocyanin content. Blueberries usually mature in 60 to 90 days after flowering (Eck, 1988).

Blueberries harvested immediately after obtaining a blue skin color (hard ripe) can be stored more satisfactorily than fruit harvested at the ripe and firm-ripe stages. Fruit for fresh market require a deep-blue color with a dusting of light-blue waxy bloom. Absence of the waxy bloom is an indication of overripe fruit or mishandling of the fruit during or after harvest (Galletta and Himelrick, 1990). Soluble solids content averaged 11, 12, and 13.5% for hard ripe, firm ripe and ripe, respectively. The last two stages were similar in taste, but hard ripe berries were markedly tart and lacking in sweetness (Bunemann et al., 1957). However, uniformity in maturity problems can arise when picking blueberries. All fruit from the same cluster do not ripen at the same time and is a particular problem when fruit are machine-harvested. After reaching final color, blueberries change little in size, although for several days continue to improve in sweetness and flavor (Eck, 1988). In addition, blueberries will continue to ripen after harvest, soluble solids content will increase gradually (Eck et al., 1990). Soluble solids in highbush blueberries increased from 6 to 7% in small deep green berries and from 10 to 12% in entirely blue berries. Blueberries that had a soluble solids to acid ratio (SS/Ac) of 40 showed increased incidence of mold even at low temperature. Berries with a SS/Ac ratio higher than 20 are not recommended for long distance shipment (Ballinger et al., 1978).

Berries ripeness associated with changes in surface color arising from pigment accumulation has been correlated with changes in sugar and acid concentrations. Ballinger et al. (1972) reported that surface color, berry sugar, and acid contents are best correlated within cultivar, since different cultivars vary in their rates of pigment formation during ripening. Kushman and Ballinger (1975) also suggested that the relationship between surface color and other ripening parameters persisted among seasons, locations, harvested dates, and berry sizes within a cultivar.

Woodruff et al. (1960) reported that the percent of total sugars in Jersey and Rubel blueberries increased the first nine days following red coloration, then remained constant. Titrable acidity in the berries decreased continuously as ripening progressed. The intensity of pigmentation increased the first six days following red coloration and then did not change. Soluble pectin decreased continually and was associated with increased pectin methylesterase activity. Organic constituents, namely starch, acid hydrolyzable polysaccharides, ether soluble materials, lignin, and cellulose changed minimally. Their studies also showed a positive linear relationship between sugar-acid ratios and fruit ripening. Ballinger and Kushman (1970) also found a close relationship between the sugar-acid ratio, stage of berry maturity, and shelf-life in Wolcott blueberries grown in North Carolina. Berry sugar content continued to increase significantly through the various stages of ripening to an overripe condition. Both total acidity and percent total acidity decreased with berry ripening, while pH increased. The investigation also found a significant increase in anthocyanins throughout the progressive phases of berry ripening.

Anthocyanins in ripening Wolcott blueberries were identified and their amounts estimated spectrophotometrially. Fifteen anthocyanins, all combinations of 5 aglycones (Cy, Dp, Mv, Pn, and Pt) with glu, gal, or arsb in the 3-position were found in unripe, red fruit. Ripe and overripe fruit contained all the identified anthocyanins except Pn-gal. Total anthocyanins in unripe fruit were comprised of about 40 % Cy-glu and Cy-gal, while Mv-glu and Mv-gal comprised about 60 % in the overripe fruit. The relative proportions of 3-glucosideds, 3-arabinosides remained essentially constant throughout fruit ripening (Donald et al., 1973).

2.2.2. Fruit Ripening

Fruits are classified, in terms of respiratory activity, as climacteric or nonclimacteric. Climacteric fruits exhibit a sharp rise in respiration activity during fruit ripening which results in increasing CO_2 and ethylene production. Climacteric fruit are most commonly harvested before the start of the climacteric respiratory rise to attain maximum postharvest life. The peak of the respiratory curve approximates the point at which fruit are considered eating ripe. Beyond that point, respiration gradually decreases as the fruit senesces. Many climacteric fruits can be maintained in a healthy condition for extended periods through lowering the respiratory rate to the minimum that still permits normal cellular function. With climacteric fruits it is also essential to minimize and delay the climacteric rise and associate ripening processes (Kader, 1992). Examples of climacteric fruits are apples, pears, bananas, avocados, and blueberries. Highbush blueberries exhibit a climacteric type of ripening pattern. Ismail and Kender (1967 and 1969) and Windus et al. (1976) showed a marked surge in both carbon dioxide and ethylene production during ripening of highbush blueberries.

Nonclimacteric fruit do not exhibit rising respiration and show no change in CO_2 and ethylene production during fruit ripening. Sweet cherries, grapes, citrus, strawberries, and pineapples are the examples of nonclimacteric fruits. Most nonclimacteric and some climacteric commodities do not ripen after harvest. Thus, the quality of those products is set at harvest, and the primary objective is to minimize quality loss prior to consumption. While most climacteric, and some nonclimacteric fruits such as pineapple, continue to ripen after separation from the plant, the primary objective is to deliver the product to the consumer at the level of optimal quality (Wiley, 1994).

2.3. FRUIT STORAGE

Blueberries continue to respire and produce heat after being harvested. Respiration is primarily governed by temperature, therefore temperature control is required to ensure postharvest quality. The respiration rate of blueberries is three times higher for fruit held at 10 °C (50 °F) compared to fruit held at less than 4 °C (40 °F), and ten times higher when held at a room temperature of 27 °C (80 °F) (Hadenburg et al., 1986). Field heat should be removed from freshly harvested fruit as soon as possible. The rapid removal of heat from berries, which may come from the field at temperatures as high as 25 to 27 °C (70 to 80 °F), can dramatically lengthen shelf life (Ballinger et al. 1976; Ballinger, 1980; Hudson and Tietjet, 1981). Research has also shown that blueberries cooled to 2 °C (35 °F), within two hours after picking had significantly less decay (37 to 46 percent) after 10 days in storage at 35 °F than fruit that was cooled to 2 °C (35 °F) within 48 hours after picking (Strik et al., 1993). Ceponis and Cappellini (1983) reported that the storage of fresh blueberries for 7-14 days at 2 °C in an atmosphere in 15% CO_2 delayed decay by 3 days after being returned to storage in air at ambient temperature. Furthermore, their results showed that storage in 2% O_2 had no added effect over the CO_2 treatment. Kader (1993) recommended 0-5 °C with 15-20% carbon dioxide and 5-10% oxygen concentrations for blueberry optimum storage. Ellis

(1995) recommended 0.5 °C, 90-95% RH with 10% O_2 and 10% CO_2 for "medium term" storage of blueberries.

2.3.1. Refrigerated Air Storage

Temperature regulation is the most effective tool for extending the storage life of fresh commodities. Low temperatures retard respiration, undesirable metabolic changes, and as well as slowing moisture loss and spoilage due to invasion of decay organisms. Salunkhe and Desai (1984) and Hardenburg et al. (1990) stated that good quality blueberries can be satisfactorily stored at –0.5 to 0 °C (31 to 32 °F) in high relative humidity (90 to 95%) air for two weeks. Some loss in quality was reported when fruit were stored 4 to 6 weeks. Maturity of blueberries affects expected refrigerated storage life and subsequent market quality. Overmature fruit deteriorate rapidly in storage while immature fruit do not generally improve in quality during refrigerated storage. Therefore, only highest quality fruit should be placed in refrigerated storage.

2.3.2. Controlled Atmosphere (CA) Storage

Controlled atmosphere storage is a system for holding produce that differs substantially from refrigerated air storage in respect to the proportions of nitrogen (N_2), oxygen (O_2), and carbon dioxide (CO_2) present (Ryall and Lipton, 1979). Controlled atmosphere storage rooms must be sufficiently gastight to limit entry of high oxygen air from outside in order to control the atmosphere within the storage room. Proper use of CA supplements temperature management. Effective temperature control helps reduce both quantitative and qualitative losses by slowing respiration and ethylene production rates. Additional benefits of CA include: less fruit softening, reduced fruit sensitivity to ethylene, ease of chilling injury of various commodities, inhibition of postharvest pathogen development and insect control (Kader, 1992).

Controlled atmosphere storage is one technique that has been examined for extending bluberry storage life. A CO_2 enriched atmosphere, averaging 10-20%, has been found effective in retarding decay (Ceponis, 1983; Ceponis and Cappellini, 1985). Ceponis and Cappellini (1985) stored freshly harvested blueberries (*Vaccinium corymbosum L.*) for 7 and 14 days at 2 °C under combinations of 10, 15, and 20% CO_2 with 2% O_2, and in 2% O_2 with 98 % N_2, and in normal atmosphere. When the berries were removed from the controlled atmospheres and held for 3 days at 21 °C, the CO_2 enriched atmospheres of 10% and 15%, and 20% had significantly inhibited decay development for 1-2 days. The higher CO_2 enriched atmospheres generally were more effective and the 2% O_2 atmosphere alone was ineffective. Further studies by Borecka and Pliszka (1985) reported that highbush blueberry cultivars "Herbert", "Lateblue", and "Goldrobe" stored in 5% CO_2 with 3% O_2 for 17 and 31 days had a better taste, less acids, and more soluble solids than those stored in 20% CO_2 and 3% O_2 at 2 °C.

Smittle and Miller (1988), reported results of storage tests using Rabbiteye blueberries (*Vaccinium ashei* Read "Climax" and "Woodard") harvested by hand in 1984 and machine in 1985. Samples of each cultivar were stored in air, 100% N_2, and in 10%, 15% or 20% CO_2 with 5% O_2. Storage of either blueberry cultivar in high CO_2 atmospheres resulted in greater percentages of marketable and firm fruit, plus better sensory ratings, than did storage in air. "Climax" berries lost less weight, were firmer, and developed less decay after 21 or 42 days of storage than "Woodard" blueberries. Fruit quality characteristics of hand-harvested "Climax" blueberries stored for 42 days and machine harvested "Climax" berries stored for 21 days in 20% CO_2 with 5% O_2 were reported to be similar to those of freshly harvested fruit. Proper use of CA can also eliminate the need for using some postharvest fungicides (Ceponis and Cappellini, 1983 and 1985). Patterson et al. (1993) stored "Bluecrop" blueberries at 0 °C in atmospheres of 0, 5, 10, and 15% CO_2 with 0.5, 1, 2, and 16.8% O_2. After 32 and 76 days storage, fruit firmness and decay were determined. Results showed that CO_2 concentration was the major factor that affected fruit firmness and decay. Firmness of blueberries decreases as the CO_2 levels increased. At low CO_2 levels (0% and 5%), decay increased as O_2 increased, but at high CO_2 levels (10% and 15%), decay decreased as O_2 increased. Percentage of decay decreased as the CO_2 levels increased from 0 to 10%. As CO_2 levels increased from 10% to 15%, decay decreased. Fruit stored in 15% CO_2 exhibited off-flavors after 76 days storage. Oxygen level had no consistent effect on percent decay or firmness. There were no significant interactions between O_2 and CO_2. According to Strik (1993), the best CA treatments consisted of 1.8% O_2 and 12% CO_2. After 46 days of storage under these conditions, 97 percent of the berries were rated as having very good quality.

Further research investigated the response of two lowbush blueberry cultivars (*Vaccinium angustifolium Ait.*), "Fundy" and "Blomidon", in CA storage in combinations of 1, 2, and 5% O_2 with 0, 5, 10, and 15% CO_2, and air storage. A second set of samples was inoculated with Botrytis-infected raspberries prior to storage to determine the effect of CA storage on decay development. The berries were held at 0 °C and samples were evaluated for percent unmarketable berries, firmness, titrable acids, and percent decayed berries. The experiment was replicated over 2 years and the results showed a positive response of both cultivars to CA storage. Increasing CO_2 in the presence of 1-5% O_2 reduced decay and the percent unmarketable berries and maintained titrable acids and berry firmness levels. After 42 days of storage, Fundy blueberries had 30.5% unmarketable berries in air storage, compared with 8.7% in 15% CO_2. Blomidon blueberries had 36% and 6.8% unmarketable berries in air and 15% CO_2, respectively. Decreasing O_2 reduced the percentage of decayed berries and maintained titrable acids. Botrytis inoculation before storage reduced berry quality, but cultivars responded differently. The quality of berries 7 days after removal from storage was influenced primary by cultivar, storage time, and shelf temperature and not by storage atmosphere (Prange et al., 1994)

Recent studies by Retamales et al. (1998) reported the influence of fruit maturity, shipping mode (plane vs boat), and storage method (refrigerated air or CA) on highbush blueberry ("Ivanhoe" and "Bluecrop") quality. Fruit picked when 60% blue had lower soluble solids, higher titrable acidity, and a lower SS/AC ratio than 100% blue fruit both before and after 15 days of storage at 2 °C. Fruit picked when 60% blue was also firmer and had better internal condition. Fruit shipped by sea to North America had poorer internal condition, were less firm, had fewer sour fruit, and lost more water than those arriving by air and stored for the duration of sea shipment. Controlled atmosphere storage (21 days in 2% O_2 with 8% CO_2 at 0 °C) of fruit shipped by air did not enhance fruit quality in comparison with RA storage except by reducing mass loss. After an additional holding period (20 °C, 3days) to simulate non-refrigerated retail conditions, CA-stored fruit had less decay than RA-stored fruit. Maintaining low temperature during the holding period after CA or RA was critical in preventing decay, especially for the "Ivanhoe", which was more susceptible to decay, softening, and internal breakdown than "Bluecrop" across all treatments.

2.3.3. Modified Atmosphere (MA) Storage

Modified atmosphere (MA) storage refers to storage of produce in an atmosphere that is different from air but not precisely controlled. The atmosphere surrounding produce packaged in plastic film is an example. Gas composition is dependent upon several factors: produce respiration rate, any addition of gas mixtures to the package prior to being sealed, permeability of the plastic film, storage temperature, and tightness of the container (Hardenburg et al., 1990). The benefits of MA storage depend upon the commodity, variety, physiological age, atmospheric composition, temperature, and duration of storage (Kader, 1985). Any Modified Atmosphere Packaging (MAP) should maintain O_2 and CO_2 at adequate levels, and not exceed tolerance limits, which may increase the risk of detrimental effects.

Lange and Beaudry (1991) investigated blueberry fruit cultivars "Bluecrop", "Elliott", and "Jersey" stored under various O_2 and CO_2 regimes using modified atmosphere packaging techniques at 0, 5, and 20 °C. The results of the studies showed that storage life was a function of both temperature and package O_2 levels. As O_2 declined and CO_2 increased, shelf life increased. Optimal O_2 concentration (defined as the lowest O_2 levels permissible without inducing anaerobic respiration) yielded an approximate doubling of storage life. In a related experiment with the same lot of fruit, the relationship between package O_2, CO_2 and flavor was examined. Flavor was detrimentally affected at O_2 concentrations below 1.0. 1.5, and 3.0% at 0, 5, and 20 °C, respectively. In a similar study, Bluecrop blueberries were sealed in low-density polyethylene packages and stored at 0, 5, 10, 15, 20, and 25 °C until O_2 and CO_2 in the package reached steady state, which was approximately 1 to 18 % O_2 (1 to 18 kPa). The experimental data indicated that MAP of blueberry fruit, designed to develop and maintain aerobic steady state O_2 partial pressures at storage temperatures ranging from 0 to 25 °C, should maintain O_2 partial pressures at or above 4% (4 kPa) at 25 °C. The data also suggested that the system should be able to maintain O_2 partial pressures at or above 1.8% O_2 (1.8 kPa) at 0 °C. The steady state O_2 partial pressure at which the fruit began to exhibit anaerobic respiration increased with increasing temperature. Lange and Beaudry concluded that this implied that blueberry fruit can be stored at lower O_2 partial pressures when stored at lower temperatures.

2.4. FRUIT PHYSIOLOGY IN CONTROLLED ATMOSPHERE STORAGE

Increases in carbon dioxide and decreases in oxygen concentrations create largely independent effects on respiration and other metabolic reactions. Generally, oxygen concentration must be reduced to less than 10 percent by volume before any retardation of respiration is achieved. Increased carbon dioxide concentrations surrounding fruit also inhibit respiration. Elevation of carbon dioxide content above 5% percent noticeably suppresses respiration (Kader, 1992). Wills et al. (1998) also reported that reduction in oxygen concentration necessary to retard respiration depends on the storage temperature. As the temperature is lowered, the minimum concentration is also reduced.

The physiological effects of low oxygen and high carbon dioxide are believed to be additive (Kader, 1992). Commonly used atmospheres of 2 to 4% O_2 with 5 to 7% CO_2 suppressed respiration and delayed ripening of fruit, which could not be achieved with modification of the atmosphere by single gasses. Kader (1992) also reported that modification of O_2 alone would likely require 1 percent O_2 or less to achieve similar effects. Carbon dioxide might require 15 to 20%, or more, to equal the combined effect. The addition of only a few percent of carbon dioxide to the storage atmosphere can have a marked effect on respiration (Kader, 1992).

The critical level of oxygen at which anaerobic respiration occurs is determined mainly by respiration rate, and is therefore greater at higher temperatures. Anaerobic or fermentation respiration is the consequence of insufficient O_2 to support aerobic respiration. The fruit first develops off-flavors of alcohols and acetaldehydes accumulate in the tissues. Finally, tissues are irreparably damaged which results in fruit injury. Tolerance to low oxygen level varies considerably among different commodities. The critical level of oxygen may vary with the time of exposure, with lower levels being tolerated for shorter periods. The critical level of oxygen may also be affected by the level of carbon dioxide, since the lower levels of oxygen often seem to be better tolerated when carbon dioxide is absent or at a low level (Wills et al., 1998).

The relationship of CO_2 concentration to fruit injury is time and temperature related. If carbon dioxide levels are too high, effects similar to those caused by anaerobiosis (lack of oxygen) can be initiated. In general, fruits tolerated very high CO_2

(more than 20%) for several days at 5 °C (38 °F to 41 °F), but few commodities can tolerate that level of CO_2 concentration for several weeks. Responses to increased carbon dioxide levels vary with variety and species, even more widely than responses to reduced oxygen. The interactions among oxygen, carbon dioxide, ethylene concentrations, temperature, and duration of storage influence the incidence and severity of physiological disorders related to atmospheric composition (Kader, 1992).

A minimum concentration of 1 to 3 per cent O_2 should be used depending on the product to avoid a shift from aerobic to anaerobic respiration (Kader, 1986). The oxygen concentrations from 2 to 5% have been suggested as having beneficial effects upon storage life. Blueberries have been found to benefit from carbon dioxide concentrations up to 20% (Kader, 1989). Carbon dioxide concentrations of more than 25% cause skin browning and off-flavors in both highbush and rabbiteye blueberries (Kader, 1989).

2.5. STORAGE QUALITY CHARACTERISTICS

Fresh fruit quality is related to appearance, color, uniformity, taste, flavor, texture, aroma, nutritive value, chemical composition, defective marks on the skin, chemical residues, additives and other parameters consumers judge to be acceptable on the basis of their experience and education (Thompson, 1998). Quality can be measured in two ways: subjective and objective. Subjective tests also called sensory evaluations, mean making an impression on sensory organs including sight, hearing, feeling, smell, and taste (Thompson, 1998). Objective tests use either the human eye or instruments. The relative importance of each quality factor depends upon the commodity and its intended use (fresh or processed). Quality factors for fresh blueberries, in the U.S. Standards for Grades are maturity, color, size, and freedom from defect and decay.

2.5.1. Color and Appearance

Blueberry color is an important quality factor that influences fresh market value. Highbush blueberry color is a complex attribute affected by distribution of individual anthocyanins, total anthocyanin content, quality and structure of surface wax, and pH, and the formation of metal complexes of anthocyanins (Albrigo et al., 1980; Kushman and Ballinger, 1975; Sapers et al., 1984). These factors are subject to genetic and environmental influences and depend on the degree of ripeness (Ballinger et al., 1979; Ballinger and Kushman, 1975; Galletta et al., 1971). Ten types of anthocyanins have been documented in Elliott blueberries (Sapers et al., 1984). Sapers et al. (1984) identified the anthocyanins in Elliott blueberries and found 2-3 times as much pigment as in "Bluecrop" and Collins".

Fruit pH is the most important factor influencing anthocyanin color. Anthocyanins are red in acid solutions, violet or purple in neutral solutions and blue in alkaline solutions. Enhanced color strength of anthocyanins is expected in blueberries that contain high acidity. The correlation between surface color, sugar, and titrable acid contents was strong in Highbush blueberries (Kushman and Ballinger 1975a). Light blue color for blueberries is highly desirable since they appear fresher after several days in the market (Eck, 1966). However, the color expression in fresh blueberries is determined primarily by waxy bloom rather than by total anthocyanin content, distribution of individual anthocyanins, or pH (Ballinger et al., 1979; Sapers et al., 1984). Surface waxes are also important to blueberries as they affect fruit color and retard fruit desiccation and deterioration (Albrigo, 1977; Bain and MacBean, 1967; Reicosky and Hanover, 1978). Cultivars differ in the surface structure of wax responsible for bloom (Albrigo, 1977; Sapers et al., 1984; Tulloch, 1973. Albrigo et al. (1980) reported that wax bloom contributed significantly to prevention of water loss. Although some differences in color intensity may be due to variations in internal concentration of pigments, wax bloom was responsible for blue to black variations (Sapers et al., 1984). Waxy bloom can be characterized by Tristimulus reflectance. Measurements made on fresh blueberries showed a closed relationship between the "L" values (higher L-values indicate lighter colored samples) and visual assessments of waxy bloom (Sapers et al., 1984).

Blueberry appearance is not only determined by color, but also by size, and condition of the fruit including shriveling and wilting. Mechanical damage includes punctures, cuts, deep scratches, splitting and crushing, skin abrasion and scuffing, deformation by compression, bruising, and fungal infection. Stem scar or point of attachment of the fruit to the pedicel is also an important appearance factor in blueberries. A small dry, clearly abscised scar is desirable to avoid fungal infections and shriveling (Eck, 1966).

2.5.2. Flavor

Flavor is comprised of taste and aroma. Taste is due to sensations felt on the tongue. Aroma is due to stimulation of the olfactory senses by volatile organic compounds (Wills et al., 1998). Although consumers buy fruit on the basis of appearance and feel, satisfaction is dependent upon good eating quality. In blueberries, the balance of sugars, acids, astringency, bitterness components, and aromatic volatiles mainly determines flavor. Fructose and glucose are the main sugars in blueberries (Eck, 1988; Kushman and Ballinger, 1968) and contribute the major soluble solids component of the juice. These sugars were normally found to increase during blueberry development (Kushman and Ballinger, 1968; Woodruff et. al., 1960) and remained constant when the fruit was fully ripe (Woodruff et al., 1960).

Nelson (1927) reported that the predominate organic acid of highbush blueberries is citric acid, with a small amount of malic acid. Markakis et al. (1963) identified 16 organic acids in highbush blueberry fruit ("Rubel" and "Jersey") and found the predominate acids to be citric, malic, quinic, and chlorogenic (a phenolic acid) at percentages averaging 70%, 7%, 4%, and 16%, respectively. Ballinger(1968) found, on average, 95% citric acid and 1% to 2% each of quinic and malic acids in ripe "Wolcott" fruit. Although the total quantity of acid declines during ripening in highbush blueberries most changes are the result of decreased citric acid. Approximately 30% to 40% decreases in the level of citric acid between ripe and overripe fruit was reported by Kushman and Ballinger (1968). No major changes in the other acids were reported. Unlike previous studies, Ehlenfeldt et al. (1994) identified quntities of succinic acid in both highbush and rabbiteye cultivars. Previously, succinic acid had been noted only as a minor component by Markakis et al. (1963). Citric acid was the predominat organic acid in the highbush cultivars, having an average value of 75%. The next most common acid was succinic acid, which was present at an average level of 17%. In contrast, succinic and malic acids were the predominate acids in rabbiteye cultivars, averaging 50% and 33%, respectively (Ehlenfeldt et al., 1994).

Sugars and acids are important components of flavor in fruits since they determine the acceptable balance between sourness and sweetness (Sistrunk and Moore, 1983). Soluble solids to acids ratio (SS/Ac) has been one of the criteria for determining maturity of fruits. However, a high SS/Ac does not always signify superior fruit quality and neither does a low ratio (Basiouny, 1994). Ballinger et al. (1978) and Woodruff et al. (1960) found a close relationship between SS/Ac, stage of maturity, and shelf-life in blueberries. Berries with high SS/Ac ratio were prone to be affected by mold. The soluble solids to acids ratio was found to increase significantly as the berry ripened (Eck, 1988). Basiouny (1994) found that SS/Ac ratio continued to increase after harvest and during storage.

2.5.3. Texture

The quality components of texture include firmness, hardness, softness, crispness, manliness, juiciness, grittiness, toughness, and fibrousness (Kader, 1992). All fruit properties apprehended by the eyes, touch or muscle senses of the mouth are considered texture (Arther, 1975).

Texture serves as an important determinant of quality in fruit. The texture of blueberries is largely affected by maturity and cultivar (Arther, 1975; Eck, 1988; Miller and McDonald, 1988). Fruit softening as a result of over maturity or bruising has a major influence on the postharvest shelf-life of berries (Ballinger et al., 1973; Mainland et al., 1975). Consumer response to the presence of soft blueberries in fresh packs has been overwhelmingly negative (Rohrbach and Mainland 1978; Morris 1990). However, the degree of fruit resistance to cracking has been associated with fruit species (Ballinger and Kushman, 1970; Ballinger et al., 1973). Ballinger et al. (1973) observed that berries picked later in the season are less firm than berries picked earlier season, regardless of cultivar or stage of ripeness. Ballinger et al. (1973) also reported that at a given stage of ripeness smaller blueberries tend to be firmer than larger berries. Furthermore, berries soften appreciably as they ripen from the green to red stage, but very little from red-purple to overripe stage. Fruit softening has also been reported in blueberries as storage time increased (Miller and McDonald, 1988). Basiouny (1994) correlated calcium applications with fruit firmness. The results showed that "Tifblue" blueberry fruits harvested from calcium treated bushes tended to be firmer than fruit obtained from untreated bushes for fruit at harvest and after two weeks in storage.

2.5.4. Storage Diseases

Disease is the major factor limiting shelf-life of fresh marketed blueberries (Cappellini and Ceponis, 1976). Pathological defects, including decay caused by fungi, bacteria or viruses can also influence the appearance quality of horticulture crops (Kader, 1985). The principal postharvest disease causing organisms include grey *mold (Botrytis Cinerea)*, ripe rot or anthracnose (*Colletotrichum gloeo-sporoides*), and soft rot (*Rhizops nigrans*) Grey mold is the most important postharvest disease for blueberries from all major producing regions in North America (Strik et al., 1993). Infection produces a soft, watery decay followed by the development of grayish-white mycelium on the berry surface. Grey mold is more of a problem if harvest occurs during cool, rainy weather.

Decay is not evident until after the berries are placed in cold storage. Ripe rot, sometimes referred to as anthracnose fruit rot, only occurs in the Pacific Northwest if an extended period of rain occurs during harvest (Strik et al., 1993). As fruit begins to ripen and turn blue, the first indication of infection is a softening and puckering of the blossom end of the fruit.

Rhizopus soft rot is a potential problem if blueberries have not received prompt cooling after harvest. *Rhizupus nigrans* has been reported to not grow at temperatures below 10 °C (50 °F). Infections are characterized by the presence of leaking berries, white mycelial growth, and emergence of spore-bearing heads, which are white at first but later change to dull black. Infections require the presence of free water on the fruit surface, as well as a break in the fruit surface (Strik et al., 1993). Most postharvest infections occur at the stem scar (Ceponis and Cappellini, 1979; Lang and Tao, 1992; Cline, 1996). Cline (1996) found that stem scar wetness increased the likelyhood of infection. Keeping the stem scar and berry surface dry aid prevention of postharvest decay.

Fruit softening as a result of over maturity or bruising has a major influence on postharvest shelf-life (Ballinger et al., 1973, Mainland et al., 1975) since soft fruit is prone to decay and deteriorates rapidly (Ballinger et al., 1978; Miller et al., 1984).

Many studies have shown that rapid cooling freshly harvested blueberries to 2 °C (36 °F) and storing them at 0-2 °C (32-36 °F) with carbon dioxide significantly reduced postharvest disease development, and extended shelf-life (Ceponis and Cappellini, 1979 and 1983; Cappellini et al., 1983). A two percent oxygen atmosphere can suppress *Botrytis Cinerea* growth rate about 15% below the growth rate in air (21% O_2).

Significant growth reductions result if the O_2 level is lowered to 1%, but that is generally considered too low for commodity safety (Kader, 1992).

The physical attributes of the berries themselves can influence the degree of postharvest decay development. Strik et al. (1993) reported that fruit with a 16:1 sugar-acid ratio experienced an 8 percent breakdown when held at 4 °C (40 °F) for 18 days, while fruit with a sugar-acid ratio of 32:1 had a 28 percent breakdown under the same conditions.

2.5.5. Nutritional Value

In the past, nutrition was probably the least important consideration in determining whether a consumer purchased a commodity, since most essential nutrients can neither be seen nor tasted. However, present-day consumers may decide to buy a particular fruit because of its nutritional properties.

Blueberries have been reported to have health benefits since they contain a number of substances including sugar, vitamins A and C, carotenoids, anthocyanosides, ellagic acid, folic acid, antioxidants, bacteria inhibitors and dietary fiber. The USDA Human Nutrition Center (1998) has shown blueberries are one of the richest sources of antioxidant phytonutrients of all fresh fruits and vegetables. Scientists at the USDA have demonstrated that blueberries have the highest antioxidant capacity of the 40 different fruits and vegetables tested (Prior and Cao, 1998). The antioxidant characteristics in blueberries appear to be due largely to anthocyanins. Antioxidants are found to delay cancer, heart disease, and aging process (Toufexis, 1992; Prior, 1998). Ellagic acids may inhibit cancer initation. Folic acid may help guard against cervical cancer (Toufexis, 1992). Dried blueberries are used to treat childhood diarrhea in Sweden (Kowalchuk, 1976). In addition, antioxidant capacity of both highbush and lowbush blueberries remains unchanged during storage (Kalt et al., 1998).

2.6. COOLING PROCESS PARAMETERS

The goal of produce cooing is to slow deterioration without predisposing the commodity to abnormal ripening or other undesirable changes, thereby maintaining the product in a condition acceptable to the consumer for as long as possible (Wills et al., 1998) The phenomena involved in food processing and preservation are closely tied to thermodynamic heat transfer (Dincer, 1992; 1993; 1995). Factors that influence practical fruit cooling applications include temperature and flow rate of the cooling medium, thermal properties, and the shape of fruit. Regardless of the cooling technique, knowledge and determination of the cooling process parameters are essential to provide efficient and effective fruit cooling at the micro and macro scales. Some of the major design process factors for a food cooling process include: cooling process condition in terms of temperature, flow rate and relative humidity, arrangement of the individual products or product batches, depth of the product load in the cooling medium, and initial and final product temperatures (Dincer, 1997). In cooling processes, parameters such as cooling coefficient, lag factor, half cooling time, and seven-eighths cooling time are used to evaluate and present the cooling rate data and cooling behavior of commodities.

From Fourier's law, heat conduction in the absence of a temperature gradient implies the existence of infinite thermal conductivity. Such a condition is clearly impossible. Although the condition is never exactly satisfied, it is closely approximated if the resistance to conduction within the solid is small compared with the resistance to heat transfer between the solid and its surroundings (Incropera and Dewitt, 1990). Alvarez and Flick (1999) and Dincer (1995) used the Lumped Heat Capacity analysis method to determine the cooling rate of spherical products. According to the principles of transient heat conduction, if an object is placed in surroundings at a constant lower temperature, the following equation can be solved to evaluate the transient heat transfer in a bulk commodity:

$$hA_s(T - T_\infty) = -\rho Vc\frac{dT}{dt} \tag{2.1}$$

or

$$hA_s(T - T_\infty) = -mc\frac{dT}{dt} \tag{2.2}$$

where

t = time (hr)

T = temperature of the object at time t >0 (K)

T_∞ = temperature of the surroundings (K)

h = convective heat transfer coefficient (W/m^2 K)

V = volume of container (m^3)

A_s = surface area of the container (m^2)

ρ = fruit bulk density (kg/m^3)

c = fruit specific heat (J/kg K)

m = fruit mass (kg)

Equation 2.1 may then be integrated with the condition that $t = 0$ at initial product temperature T_i. Thus the solution to equation 2.1 becomes:

$$\frac{T-T_{\infty}}{T_i-T_{\infty}}=\mathrm{e}^{\left[-\left(\frac{hA_S}{\rho Vc}\right)t\right]} \tag{2.3}$$

The dimensionless temperature can be defined in terms of product and medium temperature as:

$$\theta=\frac{T-T_{\infty}}{T_i-T_{\infty}} \tag{2.4}$$

then, equation (2.4) can be rewritten as:

$$\theta=Je^{(-at)} \tag{2.5}$$

where

T_i = initial temperature of fruit (K)

a = cooling coefficient (1/hr)

J = thermal lag factor

The parameter 'a' represents $\left(\frac{hA_S}{\rho Vc}\right)$, which is the cooling coefficient of the cooling process. Cooling coefficient is an indicator of the cooling capability of a food product subjected to cooling. The cooling coefficient is expressed as the change in the product temperature per unit cooling time for each degree temperature difference between the product and its surroundings (Dincer, 1997). Cooling coefficient is also related to the Biot number ($B_i=\frac{hL}{k}$), thermal nature, and size of the product.

where

L = significant length (m)

k = thermal conductivity (W/m K)

The parameter '*J*' represents thermal lag factor. Lag factor is a function of size, shape, and the thermal properties of the product, such as the effective heat transfer coefficient, thermal conductivity, and thermal diffusivity. The lag factor quantifies the resistance to heat transfer from the product to its surroundings. With this definition it is clear that the lag factor is directly related to Biot number.

By substituting θ = 0.5 into equation (2.5), the produce half cooling time can be founded as:

$$0.5 = Je^{(-at)} \tag{2.6}$$

Half cooling time is one of the most meaningful parameters in practical fruit cooling. Half cooling time is the time required to reduce the product temperature by one-half of the difference between the initial product temperature and the temperature of the cooling medium. The cooling time of commodities is mainly influenced by heat transfer characteristics of the product, physical dimensions and properties of the commodities, heat transfer characteristics of cooling medium, and geometric details and heat transfer characteristics of packaging or containers, when used (Dincer, 1997).

Also by substituting θ = 0.125 (1/8) into equation (2.5), the seven-eighths cooling time can be determined as:

$$0.125 = Je^{(-at)} \tag{2.7}$$

The effective heat transfer coefficient is defined as a proportionally constant, relating the heat flux from a surface to the temperature difference between that surface and the fluid stream moving past the surface (Dincer, 1997). It is mainly dependent upon the velocity and fluid properties of the cooling medium and shape, size, and surface texture of the product, as well as the temperature difference between the surface and the cooling medium.

There are three main methods of determining effective heat transfer coefficients:

1. The steady-state measurement of surface temperature for a given amount of heat dissipation of the product.
2. The measurement of the transient temperature of the product during cooling.
3. The measurement of heat flux at the surface of the product.

The steady-state method gives good estimates of heat transfer coefficients if the experimental conditions of velocity, temperature, and heat flux can be held constant. However, it is very difficult to obtain such conditions in practice, therefore it is difficult to calculate accurate heat transfer coefficients for food products using this method (Dincer, 1997). Many studies on determining the effective heat transfer coefficients for food-cooling applications using transient temperature measurement methods have been reported. These studies focus on the development of mathematical models that predict effective heat transfer coefficients.

Pentima et al. (1988) determined heat transfer characteristics during air precooling of strawberries. Effective surface heat transfer coefficients were determined and a Nusselt-Reynolds correlation, which included the effect of moisture evaporation, was developed. Dincer (1995) also presented three equations to estimate heat transfer coeffficients by using a Nusselt-Reynolds correlation, where: $h = h_c$, $h = h_c + h_r$, and $h = h_c + h_r + h_e$. The first equation was used to estimate the convective heat transfer coefficient based on convection only and was derived by following Nusselt-Reynolds correlation for the flow of gases past single spheres:

$$h = h_c = \left(\frac{k_w}{d}\right)(2 + 0.552\,\mathrm{Re}^{0.53}\,\mathrm{Pr}^{0.33}) \qquad \text{for } (1<\mathrm{Re}<48000) \qquad (2.8)$$

where

h	=	effective heat transfer coefficient (W/m^2 K)
h_c	=	convective heat transfer coefficient (W/m^2 K)
k_w	=	thermal conductivity of water (W/m K)
d	=	sphere diameter (m)
Re	=	Reynolds number
Pr	=	Prandtl number

In the second equation, Dincer included the radiative heat transfer coefficient h_r. Then equation (2.8) can be rewritten as:

$$h = h_c + h_r \qquad (2.9)$$

where

$$h_r = \left[\sigma\varepsilon\left(T_s + T_\infty\right)\left(T_s^2 + T_\infty^2\right)\right] \qquad (2.10)$$

where

h_r	=	radiation heat transfer coefficient (W/m^2 K)
σ	=	Stefan-Boltzmann constant (W/m^2 K^4)
ε	=	surface emissivity

T_s = surface temperature of the fruit (K)

T_∞ = surrounding air temperature (K)

The evaporation of moisture on the surface of cooling products has a significant influence on the heat transfer rate which also affects the convective heat transfer coefficient. The effect of evaporation in a convective heat transfer situation, h_e, was defined by Suntur (1982) as:

$$h_e = h_c\left[\frac{h_{fg}(W_i - W_e)}{(c_p)(T_i - T_e)\cdot 100}\right] \tag{2.11}$$

In the third equation, Dincer included the effects of both radiation and evaporation heat transfer. Equation (2.9) can be then rewritten as:

$$h = h_c + h_r + h_e \tag{2.12}$$

where

h_e = an increase in h_c due to evaporation (W/m^2 K)

h_{fg} = latent heat of vaporization of water (J/kg)

W_i = initial water content of fruit (decimal units)

W_e = final water content of fruit (decimal units)

c_p = specific heat of fruit (J/ kg °C)

T_i = initial surface temperature of fruit (°C)

T_e = final surface temperature of fruit (°C)

Results from Dincer's study (1995) results showed that predictions from the first and second equations were in good agreement with experimental observations. Predictions from the third equation were the most realistic case, and were in very good agreement with experiment observations that included moisture loss.

The Lumped Heat Capacity method, also known as the low Biot number ($Bi < 0.1$) method, considers that the temperature gradient in the product is uniform and there is negligible internal resistance to heat transfer in the product. Flick and Alvarea (1999) performed an experiment to characterize heat transfer intensity for spherical objects packed in stacked bins and cooled by forced convection. The heat transfer coefficient was measured for each sphere in a test bin using instrumented spheres (spherical sensors). Each object was exposed to local airflow conditions (mean velocity and turbulence). A correlation was established between the local heat transfer coefficients and local airflow parameters. Alvarez and Flick (1999) used the Lumped Heat Capacity Method to evaluate the heat transfer coefficient as follows:

$$\ln \frac{T - T_{\infty}}{T_i - T_{\infty}} = \frac{6h(t - t_i)}{\rho c_p D} \tag{2.13}$$

c_p = specific heat (J/ kg $^{\circ}$C)

ρ = fruit density (kg/m^3)

D = fruit diameter (m)

t = time (hr)

t_i = initial time (hr)

T = temperature of the object at time t ($^{\circ}$C)

T_i = initial value of T ($^{\circ}$C)

T_{∞} = temperature of the surroundings ($^{\circ}$C)

To apply these results to food products, Alvarez and Flick included the effects of radiation and evaporation to obtain an effective heat transfer coefficient which was defined by Kuitche, Daudin, and Letang (1996) as:

$$h = h_c\left(1 + \frac{h_r}{h_c} + \frac{k_m h_{fg}}{h}\frac{P_s - P_h}{T_s - T_h}\right) \tag{2.14}$$

where

k_m = mass transfer coefficient (mg/s m^2 kPa)

P_s = water vapor pressure at product surface (kPa)

P_h = saturated water vapor pressure at wet bulb temperature T_h (kPa)

T_s = fruit surface temperature ($^\circ$C)

T_h = wet bulb temperature of surrounding air ($^\circ$C)

From this study, the measurements correlated well with data obtained from the instrumented spheres for the same positions in the bins.

The heat flux measurement measures rate of heat flow per unit area and surface temperature as a function of time. However, the mere presence of the measuring device alters the surface of the product, making readings approximate (Dincer, 1997).

2.7. MASS TRANSFER

Water is the most abundant compound in fruits and vegetable and forms a continuous liquid phase throughout the product. The skin of fruits and vegetables is permeable to water vapor (transpiration) and skin permeability varies greatly for different products. Moisture transpires continuously from fruits and vegetables during handling and storage. When the partial pressure of the water vapor of the surrounding air is lower than the partial pressure of the water vapor beneath the skin of the commodity, transpiration from the product to its surrounding occurs. The rate of moisture loss from the product is one of the main factors that affect keeping quality of the product. Excessive water loss adversely affects appearance, texture, and salable weight of fruit and vegetables (Gaffney et al., 1985).

Sastry et al. (1978) stated that fruits contain approximately 80 to 90 percent water, depending on variety. The atmosphere inside the fruit is considered saturated due to high water content. Water vapor pressure inside fruit is considered to be a function of temperature at the product surface. However, both temperature and relative humidity affect water vapor pressure of the air surrounding the fruit. Water vapor pressure difference between fruit and surrounding air is the driving force for transpiration (Sastry, 1985).

The transpiration rate of fruit is defined as the mass of moisture transpired per unit mass of commodity per unit time (Sastry, 1978). The transpiration coefficient of fruit is defined as the mass of moisture transpired per unit mass of commodity per unit environmental water vapor pressure deficit per unit time (Sastry, 1978). The transpiration rate and coefficient can also be expressed on a unit surface area basis.

CHAPTER 3

EFFECTS OF CONTROLLED ATMOSHPHERE STORAGE ON FRESH ELLIOTT BLUEBERRY (*Vaccinium corybosum L.*) QUALITY

Key index Words: *Vaccinium corybosum L.,* Elliott blueberries, Controlled Atmosphere (CA) storage, fruit quality.

3.1. ABSTRACT

Commercially harvested "Elliott" blueberries (*Vaccinium Corybosum L.*) were stored at –1 ^{0}C (30 ^{0}F) with 90-95% RH in combinations of 2% and 5% O_2 with 5% and 15% CO_2 during the 1996 storage season and in combinations of 2% and 5% O_2 with 10% and 15% CO_2 in the 1997 and 1998 storage seasons. Fruit quality attributes were determined after 53 and 80 days of storage in 1996 and after 53 and 93 days of storage in 1997 and 1998.

In the 1996 storage season, berries stored in combinations of 15% CO_2 were firmer, developed less decay, and were lower in SS/Ac after 53 and 80 days in storage than berries stored in 5% CO_2. After 80 days in storage, fruit stored in combinations of 5% CO_2 exhibited high levels of visible fungal decay. In the 1997 and 1998 seasons, storage of berries in high CO_2 concentration levels of 15% resulted in greater percentages of marketable and firm fruit, and better sensory ratings, than storage in carbon dioxide concentration levels of 10%. Controlled atmosphere conditions of 5% O_2 and 15% CO_2 were rated as superior for Elliott blueberries stored 93 days.

3.2. INTRODUCTION

World blueberry production and consumption has increased steadily in recent years. New plantings would indicate further increases in production are likely over the next decade. Unlike many horticultural crops, blueberries are a long-term investment. The investment required is substantial and pay back may take many years. A significant proportion of the world's production is sold fresh. As a fresh highly perishable fruit, blueberry prices are subject to the effects of supply and demand. Most northern hemisphere production comes in June, July, August, and September, and southern hemisphere production comes in December, January, and February. The remaining months (October and November) provide a good opportunity for those who, due to climate or to a lesser extent variatal factors, can supply the markets with high quality of fresh blueberry fruit by use of storage technologies.

Commercial technologies to extend the postharvest life of fresh blueberries include: rapid cooling and storage in cold rooms, modified atmosphere packaging of flats of blueberries followed by cold storage, and storage in refrigerated controlled atmosphere rooms. Controlled atmosphere storage, in addition to refrigeration, has been demonstrated to further extend fruit postharvest quality. The combined affects of reduced oxygen and elevated carbon dioxide atmospheres on postharvest responses of fruit and vegetables include: reduced respiration and delayed development of physiological disorders (Thompson, 1996). The most profound beneficial effect of elevation of CO_2 on blueberry crop was the preservation of dessert quality as well as the reduction of decay spoilage after a prolonged CA storage (Thompson, 1996).

The lower oxygen limit which commodities can tolerate has been the central issue of numerous inquiries over the past several decades. If oxygen levels decline below the tolerance level of a particular plant organ, fermentation, tissue browning, and off flavors occur (Beaudry and Gran, 1993; and Richardson and Kosittrakun, 1995). Beaudry and Gran, 1993 found that the lower CO_2 partial pressure limit for Bluecrop blueberry fruit (Vaccinium Corybosum L.) increased with temperature. Raising the temperature from 0 to 25 ^{0}C caused the lower O_2 limit to increase from about 1.8 to approximately 4 kPa. Raising CO_2 level from 5 to 60 kPa increased the lower O_2 limit for Bluecrop blueberries from approximately 4.5 to over 16 kPa. A number of factors can potentially impact the lower O_2 limit of fruits in storage. Cultivar, temperature and CO_2 level are three very commonly altered factors and each are known to interact with storage temperature (Beaudry and Gran, 1993). Smittle and Miller (1988) reported results of storage tests using Rabbiteye blueberries (*Vaccinium ashei* Read cvs. Climax and Woodard) harvested by hand in 1984 and by machine in 1985. Samples of each cultivar were stored in air, 100% N_2, and in 10%, 15% or 20% CO_2 with 5% O_2. Storage of either blueberry cultivar in high CO_2 atmospheres resulted in greater percentages of marketable and firm fruit, plus better sensory ratings, than did storage in air. Climax berries lost less weight, were firmer, and developed less decay after 21 or 42 days of storage than Woodard blueberries. Quality characteristics of hand-harvested Climax blueberries stored for 42 days and machine harvested Climax berries stored for 21 days in 20% CO_2 with 5% O_2 were reported to be similar to those of freshly harvested fruit. Proper use of CA can also eliminate the need for using some postharvest fungicides (Ceponis and Cappellini, 1983 and 1985). However, further research is needed to develop controlled atmosphere conditions which can provide the best results for blueberries grown in the Pacific Northwest.

Food quality can be defined as "the combination of attributes or characteristics of a product that have significance in determining the degree of acceptability of the product to the user" (Gould, 1951). Another definition of food quality has been presented by Cardello (1995) as "the acceptance of the perceived characteristics of a product by consumers who are the regular users of the product category or those who comprise the market segment."

Fruit quality is very important to consumers. However, the word quality is used in various ways in reference to fresh fruits such as; market quality, edible quality, shipping quality, and appearance quality (Kader, 1992). Various components of quality including appearance, texture, flavor, nutritive value, and safety (free of disease causing by organisms) are used to evaluate commodities in relation to specifications for grades and standards. The absence of decay is a major component of high quality fresh fruit. Although consumers prefer good looking fruit, their satisfaction and repeat purchases also depend on good edible qualities such as flavor, texture and fresh color (Kader, 1992).

Loss of food quality may be influenced by foreign organisms (e.g., microorganisms, parasites, insects) as well as the intrinsic physiology of the food itself. Intrinsic factors include ingredient, processing, and storage variables. These variables, by their nature, control the sensory characteristics of the product, which, in turn, are the most important variables determining both the acceptability and perceived quality of the produce by consumers (Taub and Singh, 1998).

Galletta , Monroe, and Kushman (1971), reported that the degree of blueberry ripeness is difficult to visually estimate after the fruit turns blue, and acidity and soluble solids content vary with degree of ripeness. Their study used 2 or 3 weekly samplings per selection of fruit just before it turned entirely blue (i.e., reddish-tint still existed at the stem end). This maturity is also expressed as"purple" stage. Their results showed that soluble solids and acidity are important measures and thus reflect culinary quality of the fruit. However, the upper level of acidity acceptable to most tastes should be determined if low soluble solids to acid ratio (SS/Ac) or high acid berries were selected for good keeping quality. Furthermore, various fruit acidity and soluble solids measurements accounted for almost 80% of the decay variability. This indicated that clonal field sampling of acids and soluble solids of fruit of comparable stages of ripeness and soundness should give a reasonable estimate of their potential for developing decay. Differences in ripening season, temperature, fruit to leaf ratio and moisture supply may all affect the SS/Ac ratio. Seasonal fluctuations in rot organism species and populations, differences in fruit pedicel scar area, moisture content, and fruit firmness may contribute another 20% of the decay variability.

Color and appearance are the primary basis for market acceptance of most fruits (Sistrunk and Moore, 1983). Color is often an indication of maturity and consequently quality. The characteristic color of berries is due to the presence of various anthocyanin pigments (Eck, 1988; Sapers et al., 1986; and Spanos and Wrolstad, 1987). However, the color expression in fresh blueberries is determined primarily by extent of waxy bloom on the berry rather than by total anthocyanin content. Total anthocyanin contents of blueberries generally increase with fruit ripening (Eck, 1988). Fruit pH is probably the most important factor influencing anthocyanin color. Anthocyanins are chemical indicators that are red in acid solution, violet or purple in neutral solutions and blue in alkaline solutions (Jennings, 1988). Fruit appearance is not only determined by color but also by condition of the fruit, which includes bruises, shrivel and shape. Most commodities exhibit visual shriveling after losing about 3 to 5% of their weight (Mitchell, 1985 and 1987). Maturity and cultivar (Eck, 1988 and Miller and McDonald, 1988) largely affect the texture of blueberries. Berry firmness is also affected by duration in storage. The effects of storage time on Rabbiteye blueberry softening have been reported by Miller and McDonald, 1988. The flavor of berries is determined by sugar content, acids and volatile compounds. Fructose and glucose are the main sugars of blueberries (Eck, 1988 and Kushman and Ballinger, 1968), which contribute the major soluble component of the juice. These sugars are normally found to increase during fruit development in blueberries (Kushman and Ballinger, 1968 and Woodruff et al., 1960) and then remain constant when fruit is fully ripe (Woodruff et al., 1960). The main acid of blueberries is citric acid with a small amount of malic acid present (Kushman and Ballinger, 1968). Soluble solids to acids ratio was found to increase significantly as the berry ripens (Eck, 1988). The soluble solids to acids ratio rises with increasing ripeness. Sugars and acids are important components of flavor in fruits since they determine the acceptable balance between sweetness and sourness (Sistrunk and Moore, 1983).

Earlier studies indicated that the levels and ratio of the sugar and acid fractions were related to keeping quality (Kushman and Ballinger, 1963). Ballinger and Kushman (1970) reported that sugar content and berry weight increased as berries developed from small-green to ripe and overripe. The trend for accumulation of berry acid during early development followed by a decrease in acid from ripe to overripe, was probably due to the rapid increase in overall berry weight which diluted the acid and accentuated the increase in pH. In culture solutions prepared with acid and sugar levels paralleling those of blueberries at three degrees of ripeness, growth of the two most prevalent fruit-rotting fungi affecting blueberries (*Alternaria and Botrytis spp.*) decreased as the acid level of the solution increased. Sugar levels had relatively little influence upon growth of these fungi. The acid composition of blueberry fruit appears to afford a mechanism of resistance to decay-producing organisms. As blueberries ripen total sugar and the soluble solids content of the fruit increase, and titrable acidity (as percent citric acid) decreases (Ballinger and Kushman, 1970; Kushman and Ballinger, 1963). Other indications of the losses of fruit acidity during blueberry ripening are increases in berry pH and in the SS/Ac ratio. Low SS/Ac ratio have been associated with good keeping quality and a high ratio with poor keeping quality. When the SS/Ac ratios exceeds 30, the fruit should not be sold for fresh market (Ballinger et al., 1978).

Scaling and ranking methods of measuring or comparing the sensory attributes of food and drinks, and of measuring attitudes or liking, are widely used in industry as quality control procedures for product development or research (Muller, 1997). The methods, in their many varied forms, are almost certainly the most important element of the practical application of sensory measurement techniques. However, they cover a wide range, from the almost totally arbitrary to the sophisticated and complex. Hedonic scaling relates to pleasant and unpleasant states of an organism, and in hedonic scaling, affective ratings of preference or liking and disliking are measured. The nine-point hedonic scale is the most well known scale in food research developed by the US Army in the 1940s (Piggott, 1988). Additional to the use of sensory techniques to evaluate quality, there are three other general approaches to the study of the textural properties of foods. The most common involves the use of instruments to evaluate the physical properties of the samples. Instrumental texture measurement uses a probe to come into contact with the sample. The sample is deformed and the extent of the deformation and/or the resistance offered by the sample is recorded and used as an index of the texture of the product. The type of test performed with these instruments may be purely empirical in nature. Empirical methods usually involve the sample being subjected to a complex pattern of force. However, often one type of action predominates and this provides a basis for classifying such tests. In a puncture or penetration test, the probe is made to penetrate the sample and the force necessary to achieve a certain depth of penetration or the penetration depth achieved in a specified time under defined conditions is measured and used as an index of hardness, firmness or toughness of the food. An example of a commercial instrument featuring puncture is the Fruit Pressure Tester (Piggott, 1988). Tests that measure the extent of compression achieved under a specified load in a given time, or the force required to achieved a specified load in a given time, or the load required to achieve a specified degree of compression are used as texture indicators.

"Elliott" blueberry crop grown in Oregon is a late-mature cultivar, which usually harvested in early September each year. The objective of this study was to identify the optimum CA regime (O_2 and CO_2 combination) for extending the postharvest life and quality of "Elliott" Blueberry fruits until Thanksgiving and Christmas season.

3.3. MATERIALS AND METHODS

3.3.1. Pre-Storage Treatment

Experiments were conducted in 1996, 1997, and 1998. In the 1996 preliminary experiment, Elliott blueberries *(Vaccinium corybosum)* were harvested by hand at the commercial maturity stage. All fruits were pre-cooled at the picking site, Hurst's Berry Farm, then transported to the Postharvest Engineering Research Laboratory (PERL) at the Bioresource Department, Oregon State University. Defective berries (berries that were split, shriveled, or exhibited decay) were removed. The remaining samples were stored at $-1\ ^0C$ ($30\ ^0F$) under four controlled atmosphere conditions: 15% CO_2 with 2% O_2 (Box A); 5% CO_2 with 2% O_2 (Box B); 5% CO_2 with 5% O_2 (Box C); 15%CO_2 with 5% O_2 (Box D) as shown in Figure 3.1. Blueberries harvested in 1997 and 1998 were transported directly to the Postharvest Engineering Research Laboratory (PERL) at the Bioresource Department, Oregon State University without being precooled and defective berries were removed. The remaining samples were stored at $-1\ ^0C$ ($30\ ^0F$) under four controlled atmosphere conditions: 15% CO_2

with 2% O_2 (Box A); 10% CO_2 with 5% O_2 (Box B); 10% CO_2 with 2% O_2 (Box C); 15% CO_2 with 5% O_2 (Box D).

Each controlled atmosphere chamber was equipped with a strain gauge load cell and thermistors to measure mass loss and temperature, respectively. Berry bulk temperature and chamber air temperatures were recorded every ten minutes to obtain cooling characteristics of the blueberries. Dew point temperatures were measured in Box A and Box B, and relative humidity was measured in Box C and Box D. The required gas mixture for each test chamber was controlled with precise flowmeter. Humidity levels were controlled by bubbling the mixtured gases through a water chamber as illustrated in Figure 3.2.

The statistical treatment structure for the experiment was a 2^4 factorial design and the design structure was a split plot design. The CA treatments were arranged in a Randomized Complete Block Design (RCBD) with two replications (years). The second factor, days in storage, was arranged at a subplot level. The resulting split-plot design had the whole-plot treatment factor of CA in a complete block design with days in storage as a subplot treatment factor. One hundred and twenty pints (pulpboard containers) of blueberries were randomly separated into 4 groups of 30 pints. Each of the 4 storage units held only 24 pints, therefore twenty-four pints were randomly removed from each group of 30. In 1996 and 1997, the samples in five pints were combined to measure initial values of fruit quality including: percent decay and firmness. Appearance and flavor evaluations were taken on sub-samples of the combined sample. The remaining berries were frozen (-20 ^{0}C) for the later measurements of pH, soluble solids, and acid content. In 1998, there was no fruit

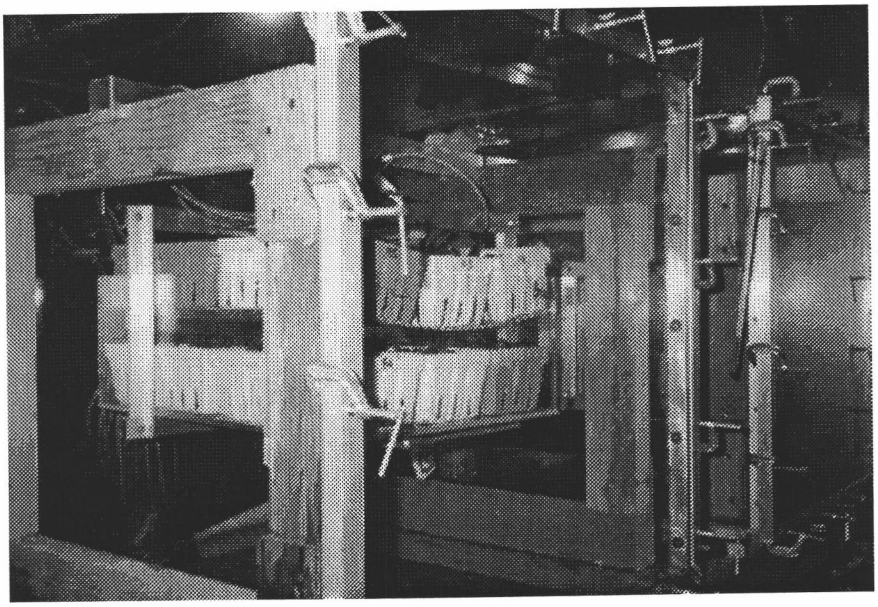

Figure 3.1. Controlled atmosphere chamber layout inside the walk-in refrigerator.

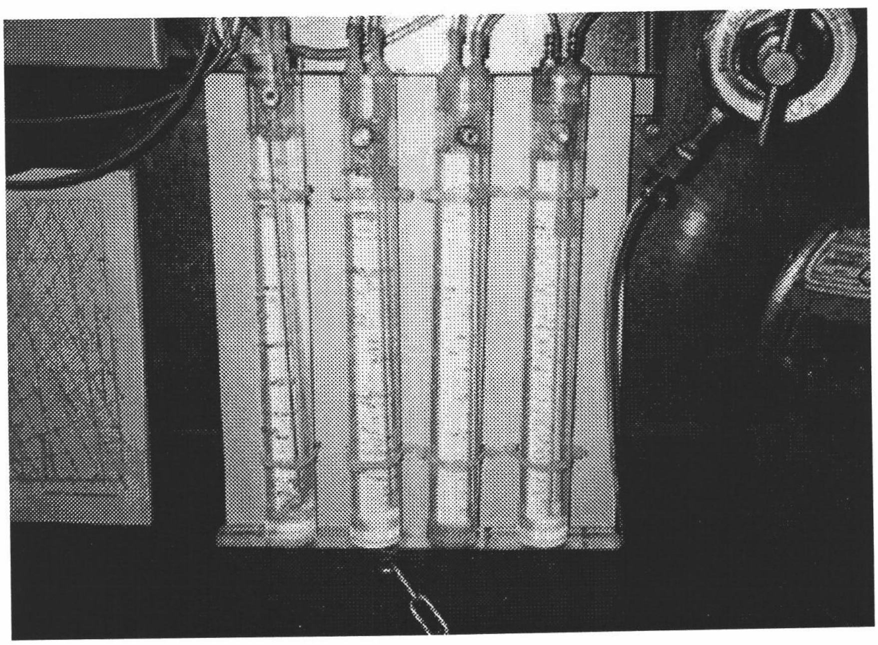

Figure 3.2. Relative Humidity control for the controlled atmosphere test chambers.

mixing. Sub-samples from each pint were analyzed separately at the beginning of the study and after 52 and 93 days of storage. Measurements included weight loss, % decay, firmness, color, and appearance and flavor. A random sample of berries was frozen (-20 ^{0}C) for the later measurements of pH, soluble solids, and acid content. Twenty-four pints of berries were placed in each CA chamber. After each chamber was closed, nitrogen, carbon dioxide, and oxygen levels were established.

3.3.2. Post-Storage Analyses

After 53 days in 1996 and 52 days in 1997, five pints were picked at random for testing, and similarly after 80 days in 1996 and 93 days in 1997. At each time, the five pints were mixed together and measurements of % decay, firmness, and appearance and flavor were immediately taken on sub-samples. The remaining berries were frozen (-20 ^{0}C) for the later measurements of pH, soluble solids, and acid content. There was no mixing of each pint, after 52 days and 93 days of storage in 1998. Sub samples from each pint were analyzed separately, and the measurements of weight loss, % decay, firmness, color, and appearance and flavor were immediately performed, while the remaining berries were frozen (-20 ^{0}C) for the later measurements of pH, soluble solids, and acid content.

3.3.2.1. Cumulative Weight Loss

At each time point after storage in 1996, 1997, and 1998, five pints of fruit from each controlled atmosphere treatment were removed for evaluation. Each pint was weighted to determine percent weight loss during storage. Furthermore, Box A, B, C, and D were each equipped with a strain gauge load cell apparatus to continuously measure fruit mass loss throughout the storage periods. Fruit mass data was recorded every 10 minutes by a microprocessor. Data were imported to a spreadsheet from which mass loss curves were plotted.

3.3.2.2. Unmarketable Fruit Percentage

Unmarketable fruit percentage was rated according to the presence of mold or juice leaking at the stem scar or a split, or whether the berries were extremely soft and shriveled. The percentage of fruit that exhibited decay in each treatment category was determined on a fresh weight basis.

3.3.2.3. Soluble Solids Concentration

Approximately 10 grams of berries were squeezed and the resulting juice measured for soluble solids concentration (percent) using a hand-held refractometer (Atago Model ATC-1, Japan).

3.3.2.4. Titratable Acidity

Five grams of the fruit homogenate (samples were macerated with a blender) were mixed with 50 ml of distilled water and, while stirring constantly, titrated with 0.1N NaOH to an end point of pH 8.1, as indicated by a glass-electrode, Orion Research pH meter. The pH of the homogenate was measured directly by use of the glass-electrode meter. Titratable acidity was expressed as percent citric acid since citric acid is the dominant acid in blueberries.

3.3.2.5. ***Fruit Firmness***

Berry firmness was measured as individual fruit resistance to compression. The force, expressed in grams, required to compress individual berries to one-half of its freestanding height was used as an index. Compression tests were conducted using a TX-XT2 Texture Analyzer. Average firmness for each treatment was determined by testing 50 berries. Tests of individual berries were conducted with a 25.5 mm diameter probe controlled as follows: a pre-test speed (the speed at which the probe traveled from a starting point to the "trigger point") of 4 mm/second; a test speed of 2 mm/second; a post-test speed (the speed at which the probe returned to the starting point and the test is finished) of 4 mm/second. The vertically operated probe compressed each berry to one-half of its free-standing height (50% strain). The "trigger point" for probe speed control was when the probe detected 10 grams of force on a berry's surface. All of the individually tested berries were pre-selected for uniformity of size

3.3.2.6. ***Sensory Evaluations***

Blueberries from each treatment were used for sensory evaluation. Test rating was done on a hedonic scale of 1 to 9; with 9 = like extremely, 8 = like very much, 7 = like moderately, 6 = like slightly, 5 = neither like nor dislike, 4 = dislike slightly, 3 =

dislike moderately, 2 = dislike very much, 1 = dislike extremely. Five berries from each sample were presented to 25 consumers. Two fruit quality attributes, overall appearance and overall flavor, were evaluated by the panel. The evaluation ballot is shown in Appendix A.

3.3.2.7. Color Change

Colorimetric measurements were made before packing and at two period storage intervals thereafter using a Minolta Chroma Meter CR-300. The instument was calibrated with a white tile before use (L=97.78, a=-0.69, b=23). The L* a* b* color space has been used successfully in quantifying color change of many other fruits and vegetables. Value of tristimulus L* a* and b* were measured at the surface of each blueberry fruit. The L* value represents the lightness index ranging from 0 for black to 100 for white. The a* value represents red-green (+ to -) and the b* value represents yellow-blue (+ to -). The L* a* b* readings were used to calculate the hue angle (arc tan b*/ a*) and chroma $(a^{*2} + b^{*2})^{1/2}$. In blueberries, the tristimulus b* value was less than 0, therefore the hue angle was calculated by $360 + \tan^{-1} b^* / a^*$ (minolta, 1988). An increase in hue angle indicated a color change from blue to red in blueberries. A hue angle of 270^0 would correspond to a blue sample while an angle of 360^0 (0^0) would correspond to a red sample.

3.3.2. Data Analysis

Data obtained in 1996 were statistically analyzed using Analysis of Variance (ANOVA) models in SAS System for Windows version 8.0, software. Significant differences between samples were identified by use of the Multiple Range Test.

Data obtained in 1997 and 1998 were statistically analyzed using the generalized linear models in SAS System for Windows version 8.0, software. The model consisted of whole plot (CA treatment) and subplot (days in storage) arranged as a split plot design with a Randomized Complete Block Design (RCBD). Analysis of variance was used to evaluate the effects of independent variables on weight loss, decay, soluble solids, titratable acidity, SS/AC, fruit firmness, and, color. Sensory evaluation data were analyzed separately by using Analysis of Variance (ANOVA). Two sensory quality attributes, overall appearance and overall flavor, were evaluated by the panel. Significant differences between samples were identified by use of Multiple Range Test.

3.4. RESULTS AND DISCUSSION

3.4.1. 1996 Preliminary Experiment

3.4.1.1. Cumulative Weight Loss

Cumulative weight loss increased as the length of time in storage increased (Figure 3.3). Weight loss did not differ between Box A (15%CO_2 with 2%O_2), Box B

($5\%CO_2$ with 2% O_2), and Box D (15% CO_2 with $5\%O_2$) during the first 53 days of storage. Fruit weight loss averaged approximately 3.25%, 3.41%, and 3.34%, respectively, during the first 53 days of storage (Table 3.1). However, during the second storage period (the following 27 days), Box D had the highest weight loss per day (4.28%) compared to Box A (1.26%) and Box B (0.89%), as illustrated in Table 3.1.

3.4.1.2. Unmarketable Fruit Percentage

The percentage of unmarketable fruit increased with length of time in storage (Figure 3.4). The mean percentage of unmarketable fruit was highest in Box C (12.48%) and lowest in Box D during the first 53-day storage period (Table 3.1). However, the result was slightly different for the second period storage (from day 53 to day 80). Based on analysis of variance, results obtained after the 53 day storage period indicated that at least one sample was significantly ($p<0.01$) different from the others (Table 3.1). Data obtained after 80 days in storage also indicated that at least one sample was significantly ($p<0.05$) different from the others (Table 3.1). Berries from Box B and Box C had relatively high average unmarketable fruit percentages of 27.08% and 26.86%, respectively. There were high levels of visible fungal decay in Box B and Box C. Similar to the first storage period, Box D had the lowest (14.80%) average percentage of unmarketable fruit.

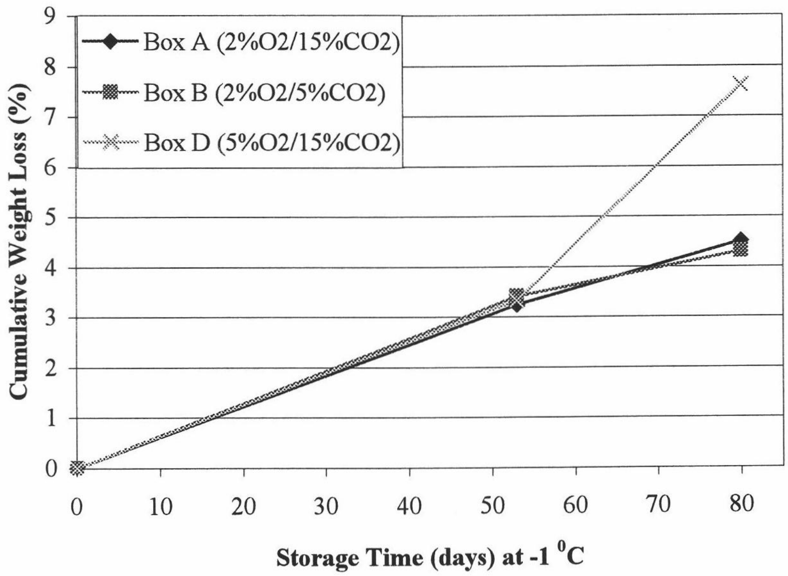

Figure 3.3. Cumulative weight loss of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1996 storage season.

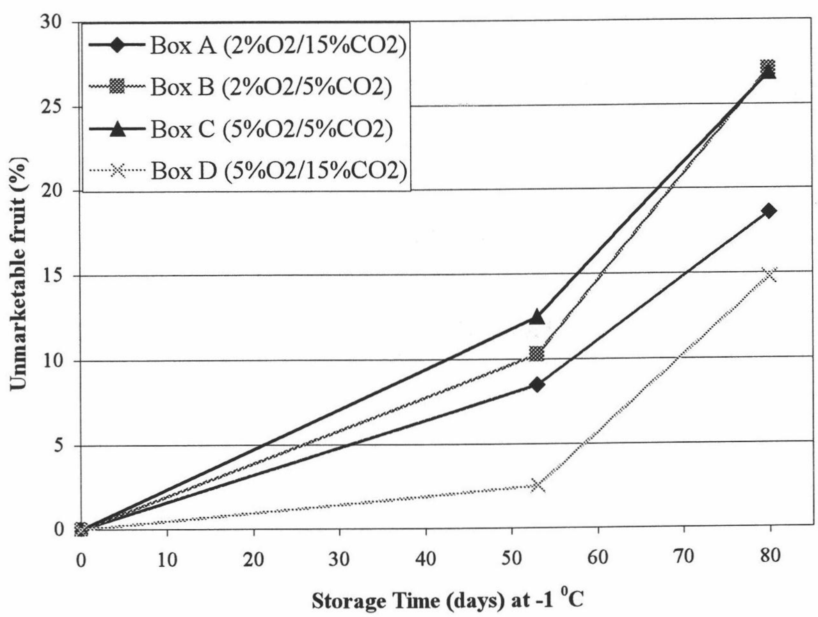

Figure 3.4. Percentages of mean unmarketable fruit of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1996 storage season.

Table 3.1. Effect of different atmospheric conditions and storage duration on percent weight loss, percent unmarketable fruit, pH, soluble solids, titrable acids, sugar-acid ratio, sensory score, and firmness of "Elliott" blueberries after removal from storage at -1 °C in 1996 preliminary experiment.

Treatment	Weight Loss (%)	Unmarketable fruit (%)	pH	Soluble Solids (%)	Titrable acidity (as % Citric Acid)	Sugar-acid ratio	Sensory Score 1-9		Firmness (gm)
							Overall Appearance	Overall Flavor	
53 days storage									
BOX A ($2\%O_2/15\%CO_2$)	3.25%	8.47	3.53	16.4	0.68	24.12	6.2	4.9	781.92
BOX B ($2\%O_2/5\%CO_2$)	3.41%	10.25	3.62	17.3	0.60	28.83	6.2	5.5	863.88
BOX C ($5\%O_2/5\%CO_2$)	N/A	12.48	3.59	17.5	0.63	27.78	5.7	4.6	680.08
BOX D ($5\%O_2/15\%CO_2$)	3.34%	2.52	3.58	16.6	0.65	25.54	6.7	5.6	1225.82
Samples from Warehouse ($5\%O_2/15\%CO_2$)	N/A	5.89	3.53	15.0	0.68	22.06	5.6	6.5	1230.26
		**	***	***	*	***	n.s.	*	***
80 days storage									
BOX A ($2\%O_2/15\%CO_2$)	1.26%	18.56	3.60	16.0	0.63	25.40	N/A	N/A	716.24
BOX B ($2\%O_2/5\%CO_2$)	0.89%	27.08	3.71	15.5	0.48	32.29	N/A	N/A	618.72
BOX C ($5\%O_2/5\%CO_2$)	N/A	26.86	3.75	14.4	0.45	32.00	N/A	N/A	361.02
BOX D ($5\%O_2/15\%CO_2$)	4.28%	14.80	3.65	16.2	0.58	27.93	N/A	N/A	982.94
		*	***	***	***	**			***

n.s. = non significant; * = significant at 5% level; ** = significant at 1% level; *** = significant 0.1% level

3.4.1.3. Fruit pH

Fruit pH increased as storage time increased (Figure 3.5). Mean fruit pH was highest in Box B (3.62) and lowest in Box A and samples from the warehouse of Hurst's Berry Farm (3.53) during the first 53 days storage period (Table 3.1). After 80 days storage, mean fruit pH was highest in Box C (3.75) and lowest in Box A (3.60) as listed in Table 3.1). Analysis of variance of the results obtained after 53 and 80 days storage period indicated that at least one sample was significantly ($p<0.001$) different from the others (Table 3.1).

3.4.1.4. Soluble Solids Concentration

Length of time in storage appeared to have an impact on the soluble solids content (Table 3.1). Soluble solids content exhibited a slight decrease in berries stored for 80 days compared to ones stored for 53 days, as illustrated in Figure 3.6. Analysis of variance of the results obtained after 53 and 80 days storage period indicated that at least one sample was significantly ($p<0.001$) different from the others (Table 3.1). After 53 days in storage, berries from Box C had the highest soluble solids content (17.5%) while berries from Box A had the lowest soluble solids content (16.4%). However, after 80 days in storage, berries from box D had the highest soluble solids content (16.2%) while berries from Box C had the lowest soluble solids (16.4%).

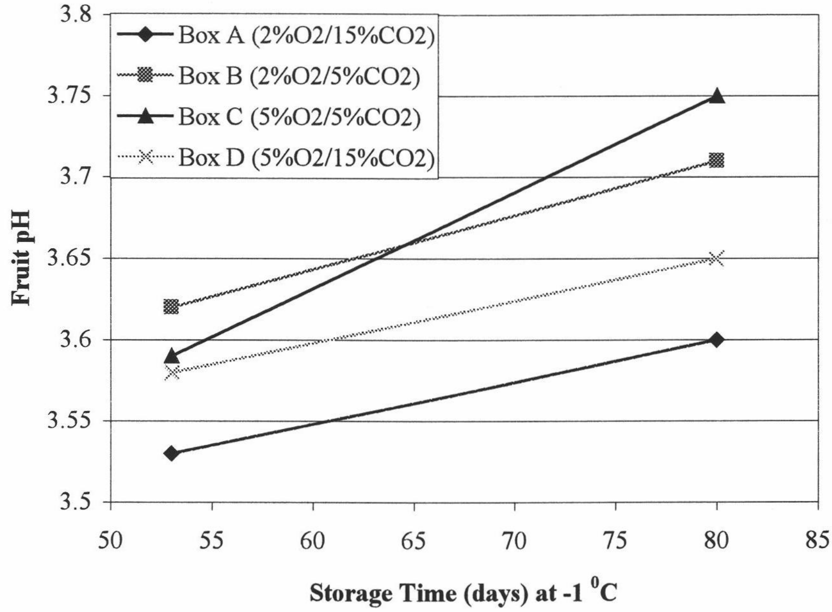

Figure 3.5. Mean fruit pH of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1996 storage season.

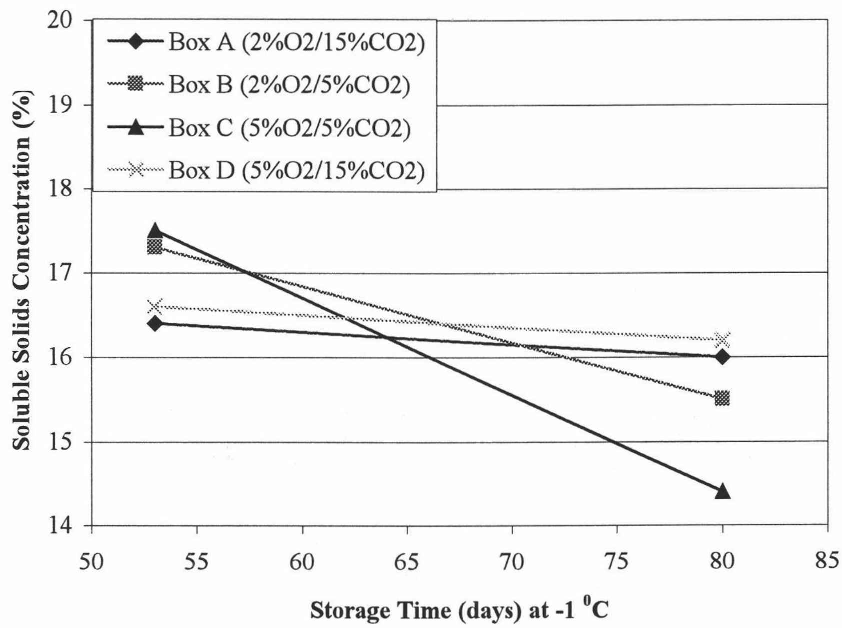

Figure 3.6. Mean soluble solids concentration (%) of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1996 storage season.

3.4.1.5. Titrable Acidity

A generally decline in titrable acidity (as % citric acid) was measured as length of time in storage increased (Figure 3.7). Titrable acidity in the fruit followed an inverse relation with soluble solids. Based on analysis of variance, results obtained after 53 days in storage period indicated that at least one sample was significantly ($p<0.05$) different from the others (Table 3.1). Data obtained after 80 days storage also indicated that at least one sample was significantly ($p<0.001$) different from the others (Table 3.1).

3.4.1.6. Sugar-acid Ratio

Sugar-acid ratio (SS/Ac) increased as the length of time in storage increased (Figure 3.8). Analysis of variance of the results obtained after 53 days in storage indicated that at least one sample was significantly ($p<0.001$) different from the others (Table 3.1). Data obtained after 80 days in storage also indicated that at least one sample was significantly ($p<0.01$) different from the others (Table 3.1).

The ratio of SS/Ac has been one of the criteria for determining maturity of fruit. However, a high SS/Ac ratio does not always signify a superior quality fruit, and neither does a low ratio indicate inferior quality. This is because a high ratio may as a result of fruit juice with low acidity and low soluble solids, or very high acidity and very high soluble solids.

3.4.1.7. Fruit Firmness

Firmness is an important textural attribute in fruits and vegetables in connection with readiness of the crop for harvest and quality evaluation during storage for fresh market. Firmness of fruits has been correlated to such biological and cultural factors as respiratory rate and soil fertilization (Haller, 1941). Morris (1925) defined firmness of apples as the force required to press a marble into the side of an apple.

Berry firmness from each atmospheric treatment decreased as storage time increased (Figure 3.9). The average firmness of berries during the first 53 days in storage from Box A, B, C, D, and samples from Hurst's Berry Farm were 781.92, 863.88, 680.08, 1225.82, and 1230.26 grams, respectively. After 80 days in storage, the average firmness of berries from Box A, B, C, D were 716.24, 618.72, 361.02, 982.94 grams, respectively.

Based on analysis of variance, there was a significant difference in berry firmness from various atmospheric conditions for both storage duration ($p<0.05$). For the 53-day storage period, fruit firmness in Box A differed significantly from fruit in Box D and from samples from the warehouse of Hurst's Berry Farm ($p<0.05$). Berries from Box B had a significant difference in firmness from berries in Box D and those from the warehouse ($p<0.05$). Furthermore, differences in firmness of fruit from Box C and those from box D and from samples from the warehouse of Hurst's Berry Farm were found to be significant ($p<0.05$). For the 80-day storage period, there was no significant difference in berry firmness between fruit from Box A and Box C. Comparisons of fruit firmness of Box A and C, Box A and D, Box B and C, Box B and D, and Box C and D showed significant differences between samples ($p<0.05$).

3.4.1.8. Sensory Evaluations

A sensory evaluation was conducted to determine if consumer acceptability of blueberries stored in different atmospheric conditions differed significantly. Results from a 9-point hedonic scale scoresheet with ratings based on overall appearance were tabulated (Table 3.1), then means and variances were computed. Based on analysis of variance, results indicated that samples presented for acceptance did not significantly differ from one another (Table 3.1). All the samples had an average score from 5.6 to 6.7, which by the hedonic scale was between “like slightly” to “like moderately.”

Results from a 9-point hedonic scale scoresheet with ratings based on overall flavor were tabulated, then means and variances were computed. Based on analysis of variance, results indicated that at least one sample was significantly different from the others (Table 3.1). Significantly difference was identified by use of the Multiple Range Test. From the Multiple Range Test results, the warehouse sample was identified as being significantly different from samples in Box A and Box C. It may be concluded that samples from the warehouse had a significantly higher acceptability on the basis of overall flavor. The warehouse samples had an average score of 6.48, which by the hedonic scale was between “like slightly" and "like moderately." The samples from Box A and Box C had an average score of 4.88 and 4.6, which by the hedonic scale was between “dislike slightly" and "dislike moderately."

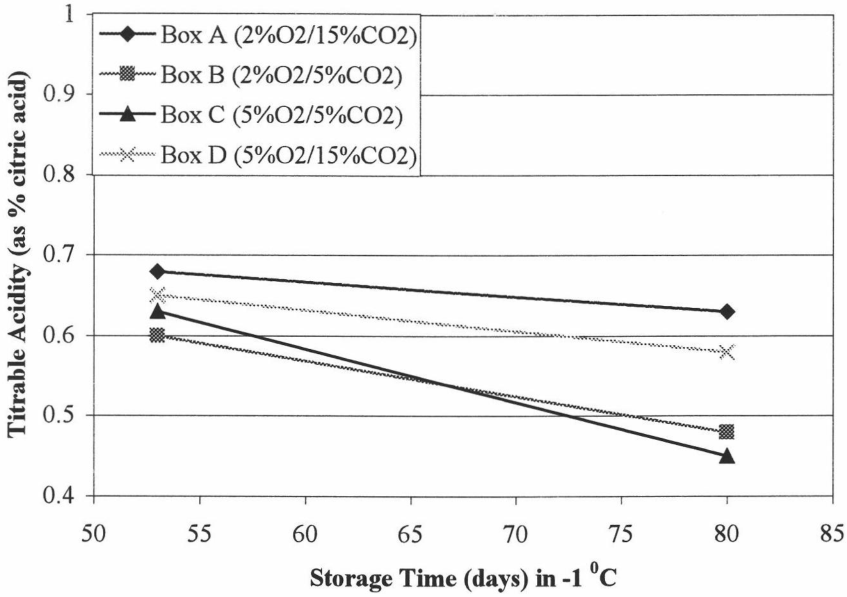

Figure 3.7. Mean titrable acidity (as % Citric Acid) of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1996 storage season.

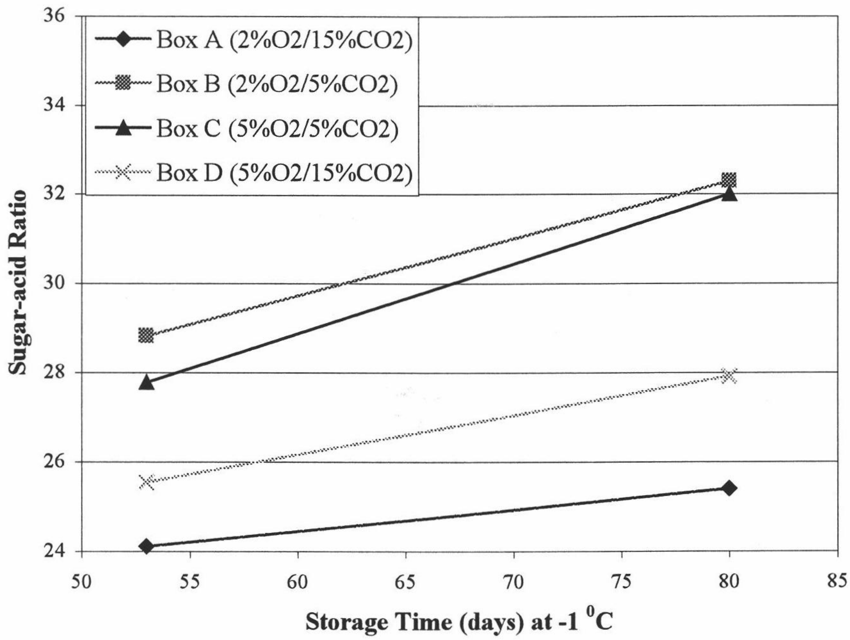

Figure 3.8. Mean sugar-acid Ratio of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1996 storage season.

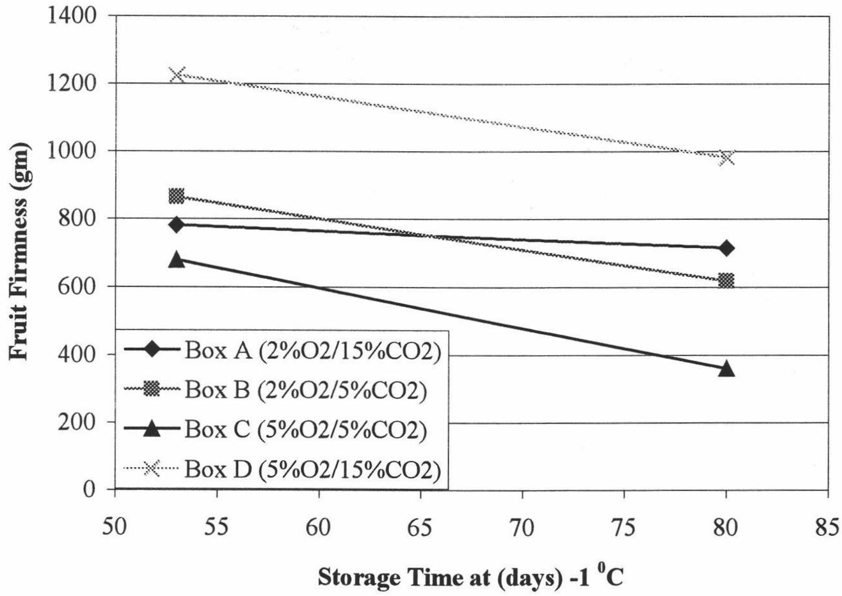

Figure 3.9. Mean fruit firmness of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1996 storage season.

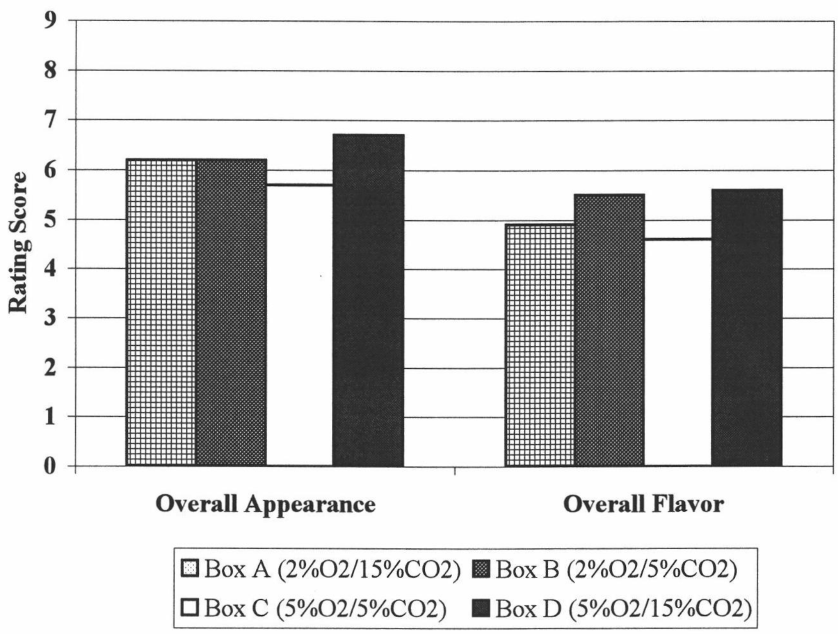

Figure 3.10. Mean score from a 9-point scale scoresheet based on overall appearance and overall flavor after 53 days storage for the 1996 storage season.

Available data from this one-year experiment were inadequate to draw any conclusions. Several suggestions were made to improve the experiment next year in order to acquire more accurate data. The suggestions are listed below:

1. The fruit should not be precooled before transport to the research facility in order to obtain more accurate mass loss data.
2. Relative humidity in the CA containers should be maintained equal to or greater than 95% (Hardenburg et al., 1990).
3. In the 1996 Preliminary Experiment, fruit mass loss in container A and B only were recorded. Fruit mass loss measurements in all containers will be recorded in future experiments.
4. In order to determine the effects of different controlled atmospheric treatments on the fruit quality, berries should be handled as to keep all factors the same except the atmospheric conditions.
5. Physical and chemical analyses including fruit firmness, soluble solids concentration, percent decay, and sensory evaluation, pH, and acid content should be conducted on a fresh berry control sample.
6. From the results of 1996 Preliminary Experiment, the 5% carbon dioxide treatment will be eliminated for future experiments because of the high level of visible fungal decay.

3.4.2. CA Experiments of "Elliott" Blueberries in 1997 and 1998 Storage Season

The effects of oxygen level, carbon dioxide level, storage time (days), and picking year (as block) were statistically analyzed for ten quality attributes of "Elliott" blueberries as shown in Table 3.2. In addition to the main effects, the interaction effects between oxygen level and carbon dioxide level, storage time and oxygen level, storage time and carbon dioxide level, and storage time and carbon dioxide level and oxygen level were also presented in Table 3.2.

3.4.2.1. Cumulative Weight Loss

Oxygen level, and carbon dioxide level, picking year (as block), storage time, interaction between oxygen level and carbon dioxide level, and interaction between storage time and carbon dioxide level significantly influenced weight loss (Table 3.2). Box A had the highest cumulative weight loss percentage in both 1997 and 1998 storage seasons (Figure 3.11). Box C had the lowest cumulative weight loss percentage in both 1997 and 1998 storage season (Figure 3.11). Fruit weight loss was approximately 1.73%, 1.81%, 1.04%, and 1.56% during the first 52 days of 1997 storage for Box A, B, C, and D, respectively (Table 3.3). After 93 days in storage, fruit cumulative weight loss was approximately 2.55%, 2.42%, 1.80%, and 2.41% in 1997 storage for Box A, B, C, and D, respectively (Table 3.3). In the 1998 storage season, fruit weight loss was approximately 1.50%, 1.37%, 0.94%, and 1.12% during 52 days for Box A, B, C, and D, respectively (Table 3.3). After 93 days in storage, fruit cumulative weight loss was approximately 2.27%, 1.88%, 1.44%, and 2.01% for Box A, B, C, and D, respectively (Table 3.3).

Table 3.2. Significant effects of different atmospheric conditions and storage duration on percent weight loss, percent unmarketable fruit, pH, soluble solids, titrable acids, sugar-acid ratio, sensory score, firmness, and color change of "Elliott" blueberries after removal from storage at -1 °C in 1997 and 1998 experiment.

Source of Variation	Weight Loss (%)	Unmarketable fruit (%)	pH	Soluble Solids (%)	Titrable acidity (as % Citric Acid)	Sugar-acid ratio	Firmness (gm)	Color	
								L*Value	Hue Angle
Block (df = 1)									
Year	*	n.s.	n.s.	n.s.	n.s.	n.s.	*	n.s.	n.s.
Whole plot level (df = 6)									
CA (df = 3)									
Oxygen (df = 1)	*	n.s.	n.s.	n.s.	n.s	n.s.	**	n.s.	n.s.
Carbon dioxide (df = 1)	*	n.s.	n.s.	*	**	**	n.s.	n.s.	n.s.
Oxygen * Carbon dioxide (df = 1)	**	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
whole plot error (df=3)									
Subplot level (df = 8)									
Storage time (days) (df =1)	**	**	**	**	**	**	**	*	*
*Days in Storage * Oxygen (df =1)*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
*Days in Storage * Carbon dioxide (df =1)*	*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
*Days in Storage * Oxygen * Carbon dioxide (df=1)*	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Subplot error (df=4)									

n.s. = non significant; * = significant at 5% level; ** = significant at 1% level.

Table 3.3. Effect of different atmospheric conditions and storage duration on percent weight loss, percent unmarketable fruit, pH, soluble solids, titrable acids, sugar-acid ratio, sensory score, firmness, and color change of "Elliott" blueberries after removal from storage at -1 °C in 1997 and 1998 storage season.

Treatment	Year	Weight Loss (%)	Unmarketable fruit (%)	pH	Soluble Solids (%)	Titrable acidity (as % Citric Acid)	Sugar-acid ratio	Sensory Score 1-9		Firmness (gm)	Color	
								Overall Appearance	Overall Flavor		Chroma	Hue Angle
Zero time values	1997	N/A	N/A	2.90	13.5	0.92	14.67	7.6	7.7	1441	3.50	277.16
	1998	N/A	N/A	2.98	15.5	0.88	17.60	7.7	7.2	1206	3.46	281.18
52 days storage												
BOX A (2%O_2/15%CO_2)	1997	1.73	11.31	3.15	14.1	0.89	15.84	7.0	4.9	1076	3.97	278.99
	1998	1.57	13.90	3.20	16.3	0.82	19.81	6.9	4.9	907	3.55	283.90
BOX B (5%O_2/10%CO_2)	1997	1.81	10.87	3.30	18.5	0.80	23.13	7.4	6.6	1254	3.68	283.76
	1998	1.37	14.31	3.36	17.8	0.78	22.83	7.2	6.4	1057	3.55	285.96
BOX C (2%O_2/10%CO_2)	1997	1.04	11.99	3.29	16.3	0.83	19.64	6.7	5.3	1160	3.94	277.34
	1998	0.94	11.28	3.32	17.0	0.79	21.58	6.7	5.6	985	3.63	284.39
BOX D (5%O_2/15%CO_2)	1997	1.56	10.00	3.20	14.5	0.86	16.86	6.8	5.6	1271	4.17	283.14
	1998	1.12	11.68	3.25	16.5	0.77	21.43	7.3	6.5	1064	4.26	283.58
93 days storage												
BOX A (2%O_2/15%CO_2)	1997	2.55	16.54	3.34	16.0	0.75	21.33	N/A	N/A	955	4.00	285.53
	1998	2.27	23.88	3.31	17.7	0.71	24.98	5.9	5.4	780	3.54	288.81
BOX B (5%O_2/10%CO_2)	1997	2.42	21.70	3.57	20.3	0.66	30.76	N/A	N/A	1148	4.27	285.28
	1998	1.88	20.22	3.61	19.0	0.66	28.77	6.4	6.2	908	4.42	290.72
BOX C (2%O_2/10%CO_2)	1997	1.80	28.43	3.42	18.0	0.69	26.09	N/A	N/A	941	4.31	280.54
	1998	1.44	14.66	3.59	17.7	0.66	26.96	6.2	5.9	812	4.11	284.42
BOX D (5%O_2/15%CO_2)	1997	2.41	20.79	3.36	18.3	0.71	25.77	N/A	N/A	1092	4.85	282.75
	1998	2.01	15.75	3.51	18.0	0.68	26.60	6.6	6.1	917	4.47	287.42

3.4.2.2. Unmarketable Fruit Percentage

Unmarketable berries increased significantly as storage time increased ($p<0.01$), as shown in Table 3.2. There was no effect of CA treatment and all the interaction terms; the oxygen level and carbon dioxide level did not have any significant effect on percent unmarketable blueberries from the four atmospheric conditions during the 1997 and 1998 storage seasons, as shown in Table 3.2. Carbon dioxide levels of 10% and 15% and oxygen levels of 2% and 5% also did not have consistent affects on unmarketable fruit percentage.

In the 1997 storage season, after 52 days of the storage, Box C had the highest unmarketable fruit percentage (12.0%). The average percentage of unmarketable fruit from Box A was also relatively high at 11.3%. Box B and Box A had the highest percentage of unmarketable fruit in 1998 storage season at 14.31% and 13.90%, respectively (Figure 3.12). Berries from Box D and Box C had the lowest unmarketable fruit percentage (10.0% and 11.28%) in both 1997 and 1998, respectively. In 1997, the average percentages of unmarketable fruit from Box B and Box D were also relatively low at 10.87% and 10.00%, respectively (Table 3.3).

After 93 days of storage, berries from Box C and Box A had the highest amount of unmarketable fruit (28.43% and 23.88%) in year 1997 and 1998, respectively. Berries from Box A and Box C had the lowest unmarketable fruit (10.0% and 14.66%) in year 1997 and 1998, respectively. In year 1998, the average percentage of unmarketable fruit from Box D was also relatively low at 14.66% (Table 3.3).

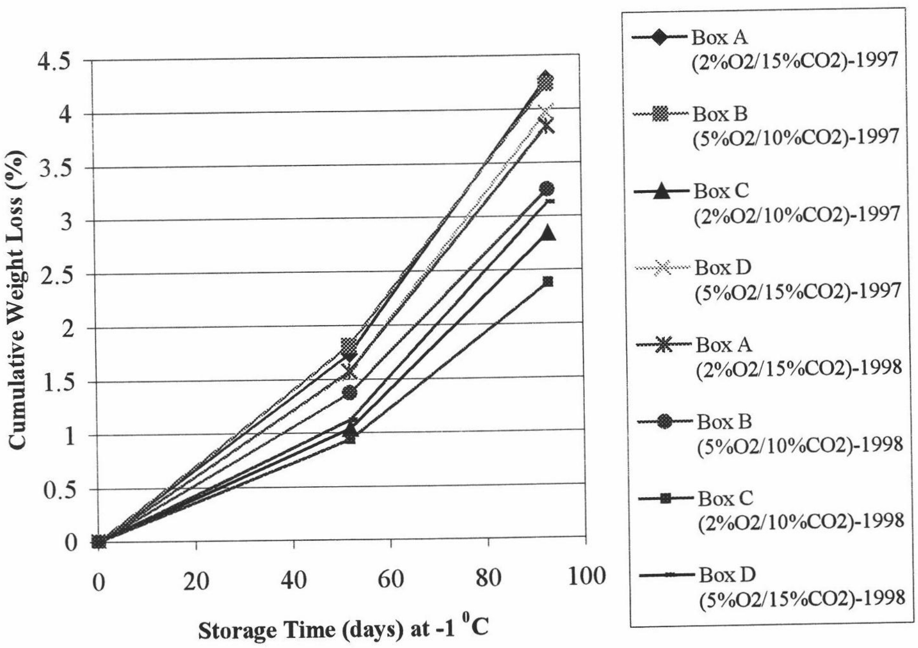

Figure 3.11. Cumulative weight loss (%) of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1997 and 1998 storage seasons.

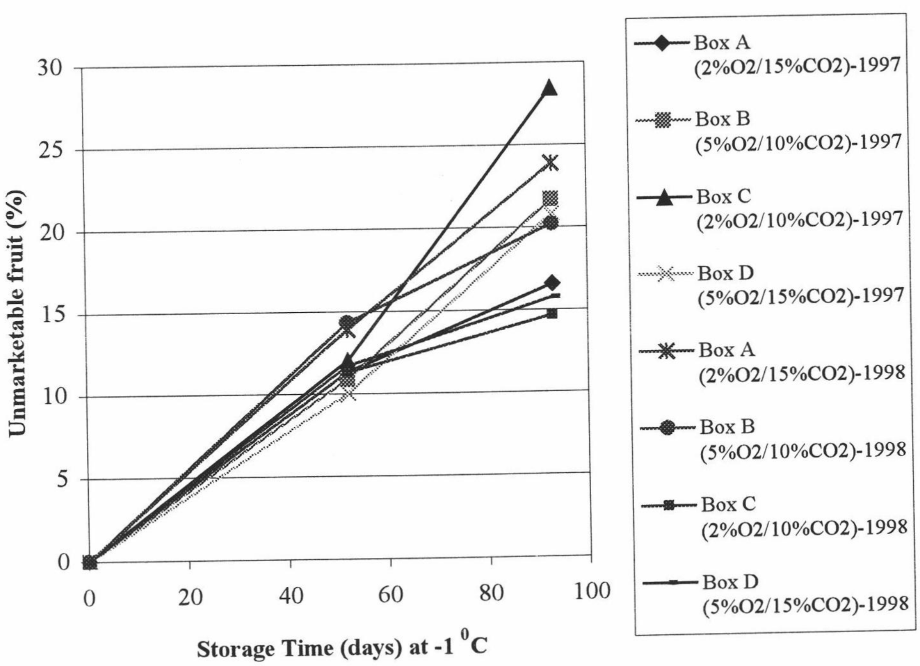

Figure 3.12. Percentages of mean unmarketable fruit of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1997 and 1998 storage seasons.

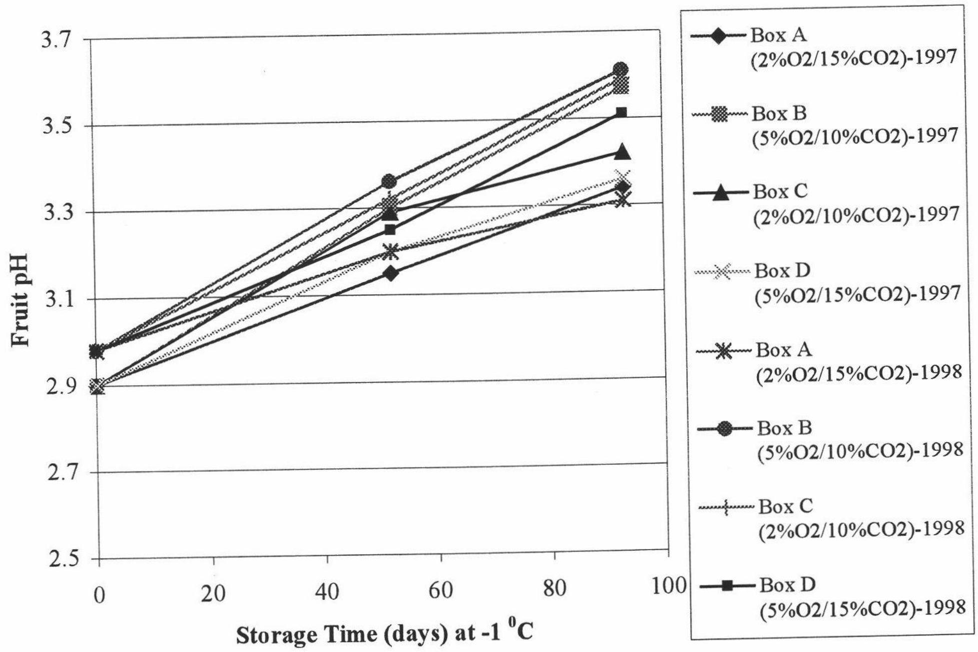

Figure 3.13. Mean fruit pH of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1997 and 1998 storage seasons.

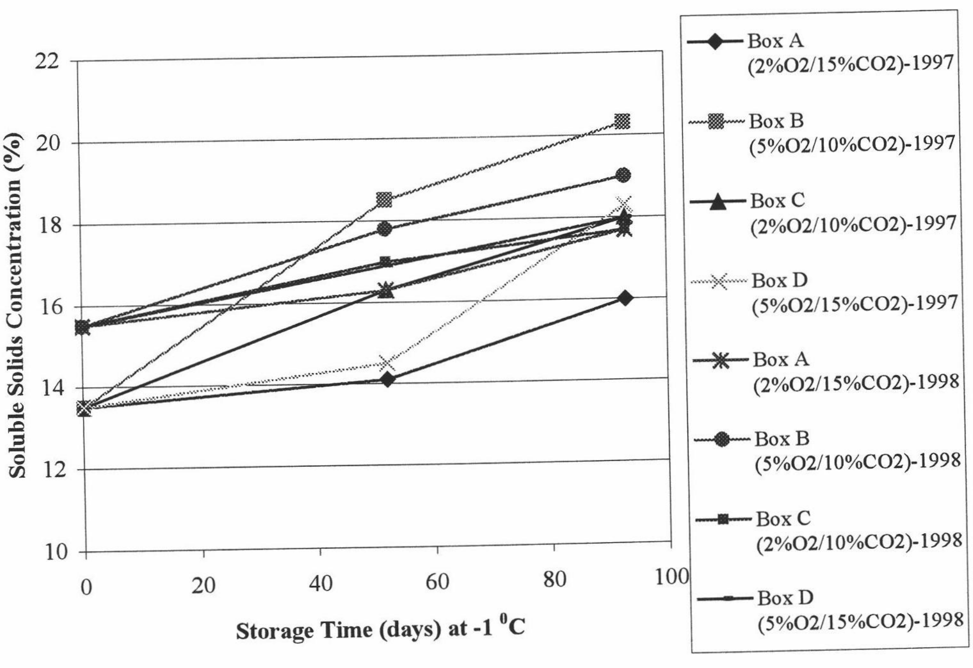

Figure 3.14. Mean soluble solids concentration (%) of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1997 and 1998 storage seasons.

3.4.2.3. Fruit pH

Fruit pH increased significantly as storage time increased ($p<0.05$), as shown in Table 3.2. There was no effect of CA treatment and all the interaction terms; the oxygen level and carbon dioxide level did not have any significant effect on fruit pH from the four atmospheric conditions during the two storage periods in 1997 and 1998 as shown in Table 3.3. Carbon dioxide levels of 10% and 15% and oxygen levels of 2% and 5% also did not have consistent affects on fruit pH.

Fruit pH was measured at the beginning, after 52 days, and after 93 days of storage (Table 3.3). The average fruit pH of the fresh berries prior to storage was 2.9 and 2.98 in the 1997 and 1998 storage seasons, respectively. After 52 days storage period, berries from Box B had the highest fruit pH in both the 1997 and 1998 storage seasons (3.30 and 3.36) while berries from Box A had the lowest fruit pH of 3.15 and 3.2, respectively. Similar to the first storage period (after 93 days storage), Box B also had the highest fruit pH of 3.57 and 3.61 in the 1997 and 1998 storage seasons, respectively. While berries from Box A had the lowest fruit pH of 3.34% and 3.31% in both the 1997 and 1998 storage seasons, respectively.

3.4.2.4. Soluble Solids Concentration

Carbon dioxide and storage time significantly ($p<0.01$) influenced soluble solids concentration (Table 3.2). Soluble solids concentrations were measured at the beginning, after 52 days, and after 93 days of storage, respectively (Table 3.3). Soluble solids content values all increased at the 52 day storage period, then continued to increase during the second period (Figure 3.14). Length of time in storage significantly ($p<0.01$) influenced the soluble solids content of the berries. Carbon dioxide level also significantly ($p<0.05$) effects the soluble solids content of the berries

The average soluble solids concentration of the fresh berries prior to storage was 13.5% and 15.5% in the 1997 and 1998 storage seasons, respectively. After 52 days in storage, berries from Box B had the highest soluble solids concentration in both the 1997 and 1998 storage seasons (18.5% and 17.8%); while berries from Box A in both the 1997 and 1998 storage seasons had the lowest soluble solid concentrations (14.1% and 16.3%). Berries from Box B had the highest soluble solids content (20.3% and 19.0%) in the 1997 and 1998 storage seasons, respectively, while berries from Box A had the lowest soluble solid concentrations (16.0% and 17.7%).

3.4.2.5. Titratable Acidity

Titrable acidity (as % citric acid) decreased significantly as storage time increased ($p<0.01$), as shown in Table 3.2. Titratable acidity (as % citric acid) was measured at the beginning, after 52 days, and after 93 days of storage (Table 3.3). Measured values decreased at 52 days storage period, then continued to decrease during the second storage period (Figure 3.14). Titratable acidity (as % citric acid) decreased significantly as carbon dioxide level increased ($p<0.01$), as shown in Table 3.2. There was no effect of all the interaction terms.

Box A had the highest titratable acid percentages after 52 and 93 days of storage (0.89% and 0.75%, respectively) in the 1997 storage season (Table 5.3).

Similarly, for the 1998 storage season, Box A had the highest titratable acid percentage of 0.82% and 0.71% after 52 and 93 days of storage, respectively (Table 3.3). The titratable acid content of berries from Box C and Box D in the 1997 were slightly different in both storage periods, 0.83% and 0.69% in Box C and 0.86% and 0.71% in Box D, respectively. Box B had the lowest titratable acid percentages after 52 and 93 days of storage (0.80% and 0.66%, respectively) in the 1997 storage season (Table 3.3).

3.4.2.6. Sugar-acid Ratio

Sugar-acid ratio was determined at the beginning, after 52 days and after 93 days of storage (Table 3.3). Fruit samples prior to storage had a sugar-acid ratio of 14.67 and 17.60 in the 1997 and 1998 storage season, respectively. The sugar-acid ratios from different atmospheric conditions during both storage periods in the 1997 and 1998 storage seasons ranged from 15.84 to 30.76. The sugar-acid ratio of berries from Box A and Box D increased as the length of time in storage increased.

Figure 3.16 illustrates sugar-acid ratio as a function of storage time. Storage time significantly influenced sugar-acid ratio ($p<0.01$), as shown in Table 3.2. As storage time increased, mean sugar-acid ratio increased. Sugar-acid ratio increased significantly as carbon dioxide decreased ($p<0.01$, Table 3.2). In the 1997 storage season, the sugar-acid ratio of berries in Box B averaged approximately 30.76 after 93 days storage period and berries in Box B exhibited visible fungal decay. However, there was no visible fungal decay found in Box B after 93 days in storage during in the 1998 storage season.

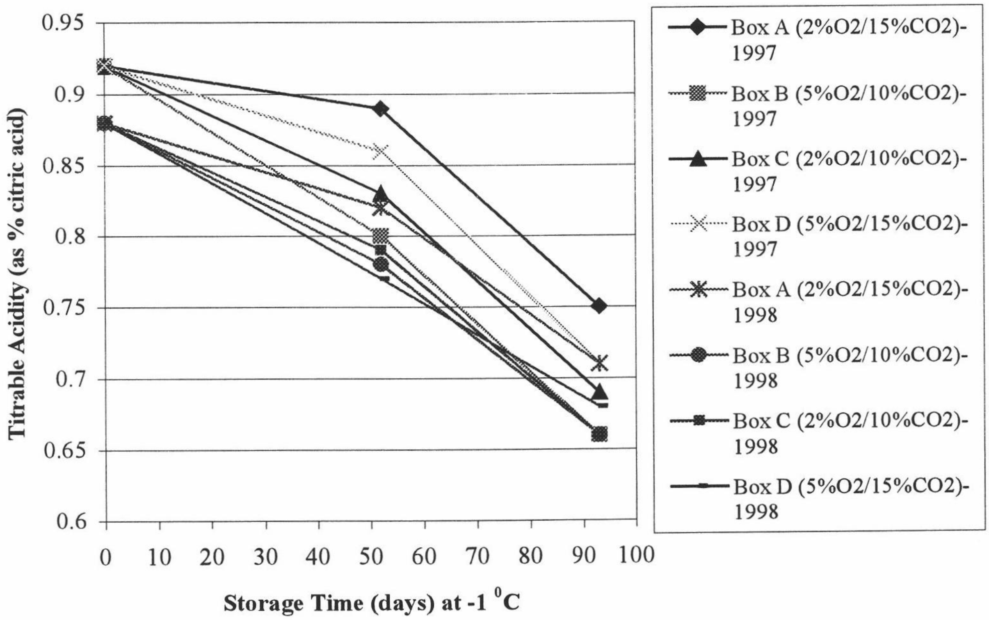

Figure 3.15. Mean titratable acidity (as % Citric Acid) of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1997 and 1998 storage seasons.

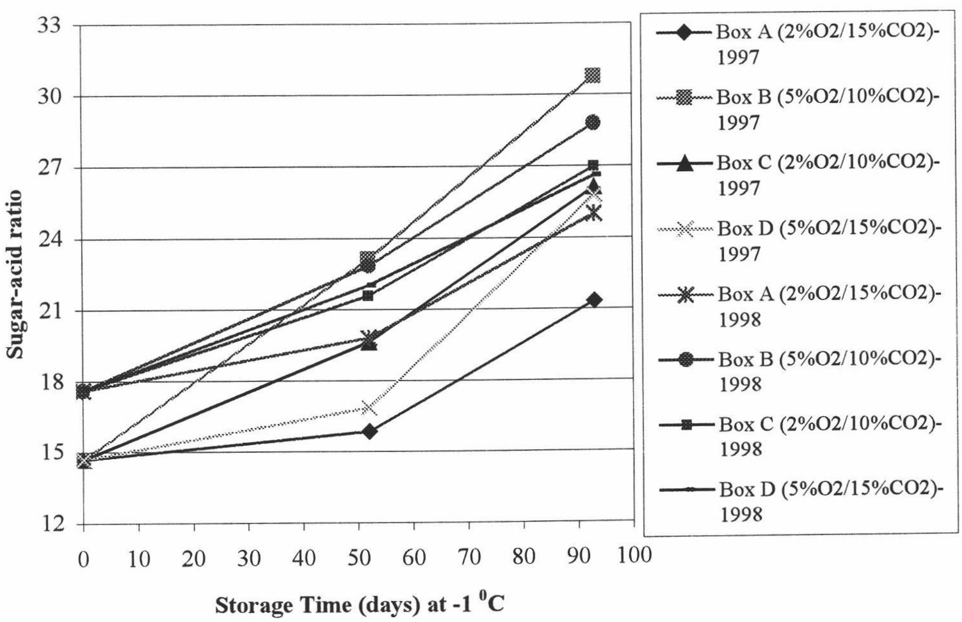

Figure 3.16. Mean sugar-acid ratio of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1997 and 1998 storage seasons.

3.4.2.7. Fruit Firmness

Storage time and Oxygen level significantly ($p<0.01$) influenced fruit firmness (Table 3.2). Fruit firmness exhibited a statistically significant decrease as storage time increased, as shown in Figure 3.17. Berries from different years were statistically different in firmness ($p<0.05$). Fruit firmness decreased significantly as oxygen levels increased. There was no effect of CA treatment and all the interaction terms except the interactions between storage time and oxygen concentration level and carbon dioxide concentration level. Berry firmness values, expressed as compression force in grams, are presented in Table 3.3. Initial berry firmness averaged 1441 grams in 1997 and 1206 grams in 1998. In the 1997 storage season, average firmness of berries after the first 52 days of storage from Box A, B, C, and D were 1075, 1254, 1160, 1271 grams, respectively. After 93 days in storage, the average firmness of berries from Box A, B, C, and D was 955, 1148, 941, and 1092 grams, respectively.

3.4.2.8. Sensory Evaluations

Sensory evaluations were conducted to determine if consumer acceptability of blueberries stored in different atmospheric conditions differed significantly. Results from a 9-point hedonic scale score sheet with ratings based on overall appearance and overall flavor of fruits stored for 52 days in 1997 and both 52 and 93 days in 1998 have been tabulated in Table 3.3. The initial fruit samples stored in 1997 and 1998 were rated high in overall appearance (7.6 and 7.7), which by the hedonic scale, was between "like moderately" and "like very much." General appearances of all fruit samples from different atmospheric conditions were all acceptable. After 52 days in storage, berries from Box B in 1997 and Box D in 1998 were ranked as having the best overall appearance (7.4 and 7.3) while Box C in both storage seasons had the lowest score of 6.7.

No sensory data were recorded after 93 days storage in 1997 due to the presense of visible fungal decay in Box B. After 93 days storage in the 1998 storage season, berries from Box D were ranked as having the best overall appearance (6.6) while Box A had the lowest score of 5.9. Figure 3.18 presents overall appearance scores after the 52 and 93-day storage periods in the 1997 and 1998. Based on analysis of variance, there were no statistical differences found ($p>0.05$) between different atmospheric conditions in both storage seasons. The results indicated that samples from Box A and B, Box A and C, Box A and D, and Box C and D evaluated for acceptance of overall appearance in both storage seasons did not significantly differ from one another. Furthermore, there were no statistical differences found between initial fruit samples and the fruit from Box B stored for 52-days. Figure 3.18 also presents overall flavor quality scores after 52 and 93 days of storage in 1997 and 1998.

Evaluating of overall flavor acceptability data, based on analysis of variance, indicated that at least one sample presented for acceptance was significantly different from the others ($p<0.05$). Results from a 9-point hedonic scale score sheet with ratings based on overall flavor for fruit stored for 52 days were tabulated (Table 3.3), then means and variances were computed. Based on analysis of variance, results indicated that at least one sample was significantly different from the others ($p<0.05$). Significant differences were identified by using the Multiple Range Test. The taste panel preferred the flavor of fruit at the initial inspection over the flavor of all fruit stored for 52 days. Flavor of the initial fruit samples was rated highest at 7.7 and 7.2 in year 1997 and 1998, respectively; which by the hedonic scale was between "like moderately" to "like very much." In the 1997 storage season, the panel generally preferred berries from Box B over berries from Box A, C, and D. This may result from fruit in Box B having the highest sugar-acid ratio. Berries from Box B were also ranked the best for overall flavor, the average score of 6.6, which by hedonic scoring was between "like slightly" to "like moderately." The sample from Box A had the lowest score at 4.9, which by hedonic scoring was between "dislike slightly" to "neither like nor dislike." However, there were no statistical differences found between fruit samples from Box A and C, Box A and D, and Box C and D. In the 1998 storage season, there were no statistical differences found ($p>0.05$) between samples from different atmospheric conditions. The sample from Box A had the lowest scores of 4.9 and 5.4 at 52-days and 93-days of storage, respectively, which by hedonic scale was between "dislike slightly" to "neither like nor dislike" and "neither like nor dislike" to "like slightly." In the 1998 storage season, the panel generally favored berries from Box B and Box D over the berries from Box A and Box C. This may also result from fruit in Box B and Box D having higher sugar-acid ratio than Box A and Box C. Berries from Box B and D, after 52 days of storage, also ranked the best for overall flavor. Their average scores were 6.6 and 6.5, respectively, which by hedonic scoring was between "like slightly" to "like moderately." Likewise, berries from Box B and D, after 93 days of storage were also ranked the best for

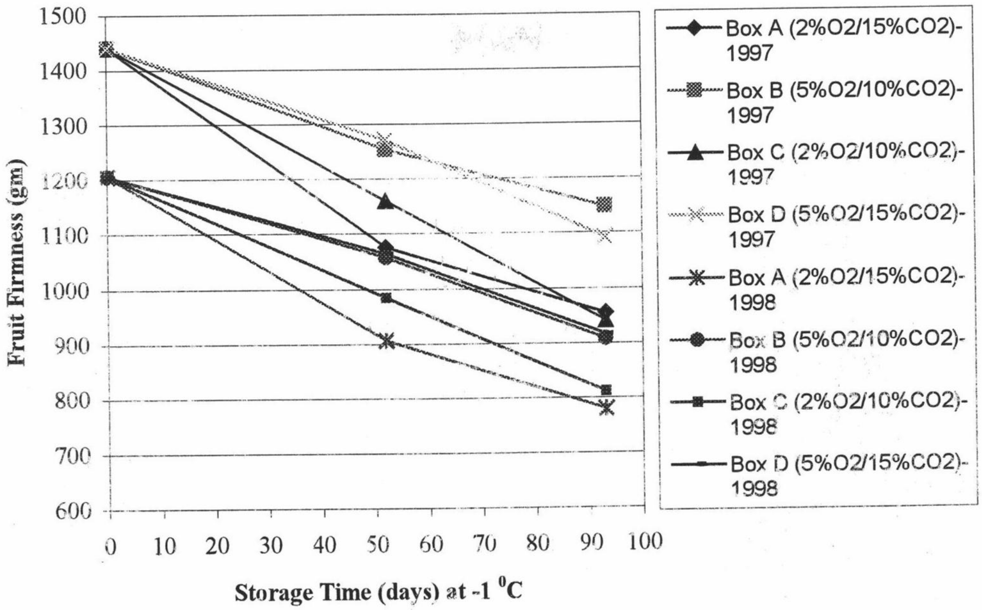

Figure 3.17. Mean fruit firmness of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1997 and 1998 storage seasons.

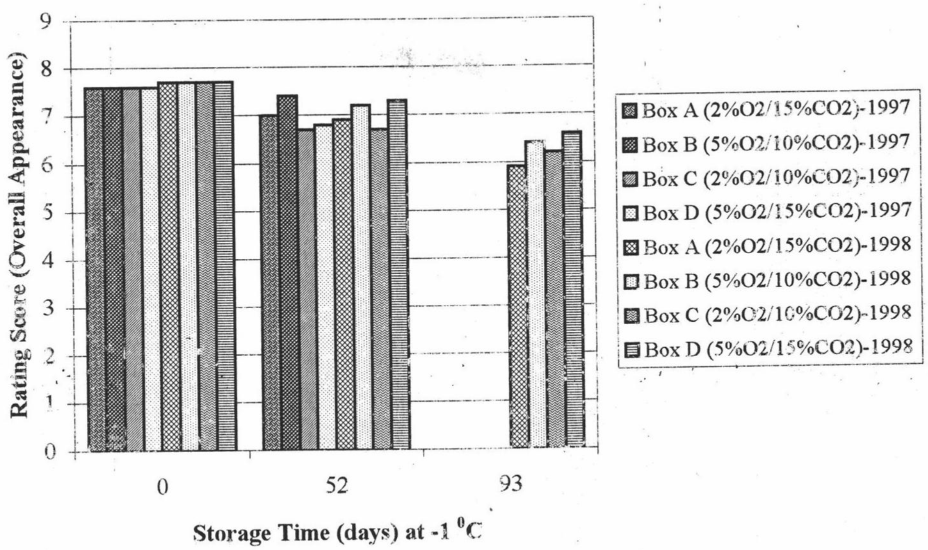

Figure 3.18. Mean score from a 9-point scale scoresheet based on overall appearance after 52 and 93 days of storage for the 1997 and 1998 storage seasons.

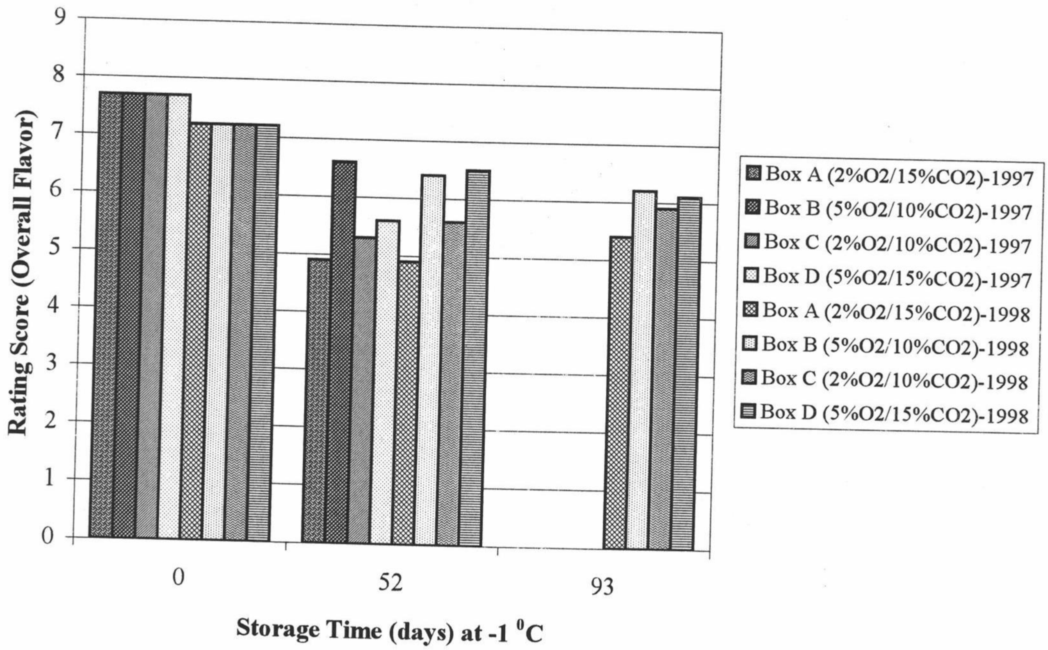

Figure 3.19. Mean score from a 9-point scale scoresheet based on overall flavor after 52 and 93 days of storage for the 1997 and 1998 storage seasons.

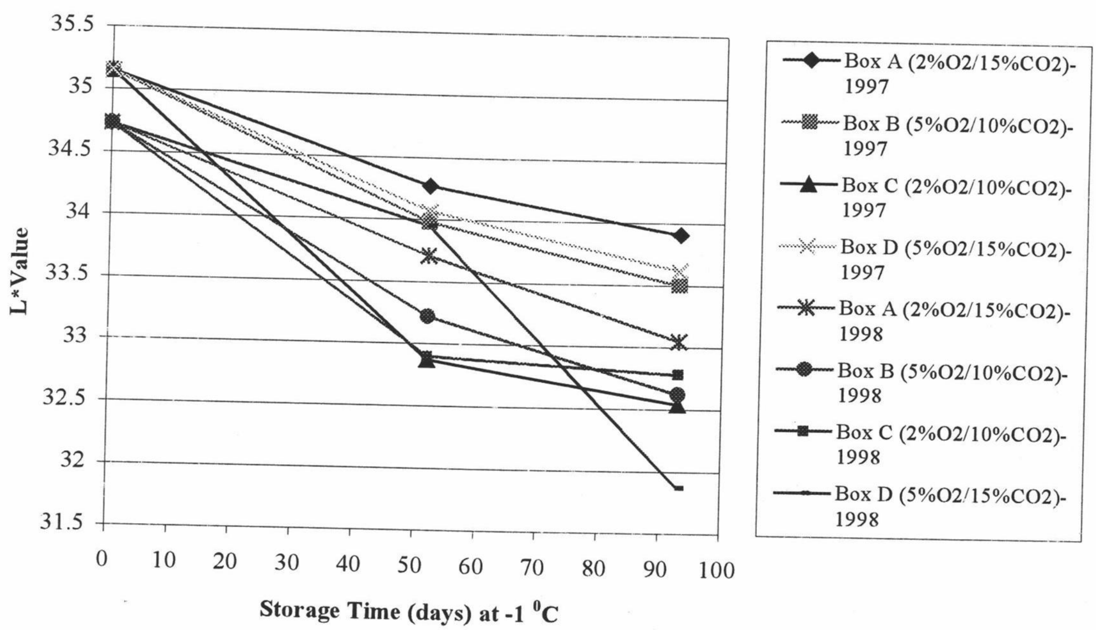

Figure 3.20. Mean L*Value (Minolta CR-300, color change) of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1997 and 1998 storage seasons.

overall flavor. The average scores were 6.2 and 6.1, respectively, which by hedonic scoring was between "like slightly" to "like moderately."

3.4.2.9. Color Change

The tristimulus L* value decreased (higher L* value indicating lighter-colored fruit) as the storage time increased (Figure 3.20). The tristimulus L* values were all decreased at the 52 day-storage period, then continued to decrease during the second storage period (Figure 3.20). At 52 days and 93 days of storage, storage time had a significant ($p<0.05$) effect on the tristimulus L* value (Table 3.2). Saper et al. (1984) found a close relationship between L* value and visual assessments of waxy bloom ($r = 0.75$). L* values of the "Elliott" blueberries ranged from 32.54 to 35.15 and 31.87 to 34.73 in year 1997 and 1998, respectively. There were no significant effects of carbon dioxide and oxygen concentration levels on the tristimulus L* value.
Storage time has significantly effect on the mean hue angle ($p<0.05$). Mean Hue angle increased as the storage increased (Figure 3.22), which indicated the color change from blue to purple. There was no effect of CA treatment and all the interaction terms found. Average hue angle value measure of individual fruits color, ranged between 277.16 to 285.53 and 281.18 to 290.72, respectively.

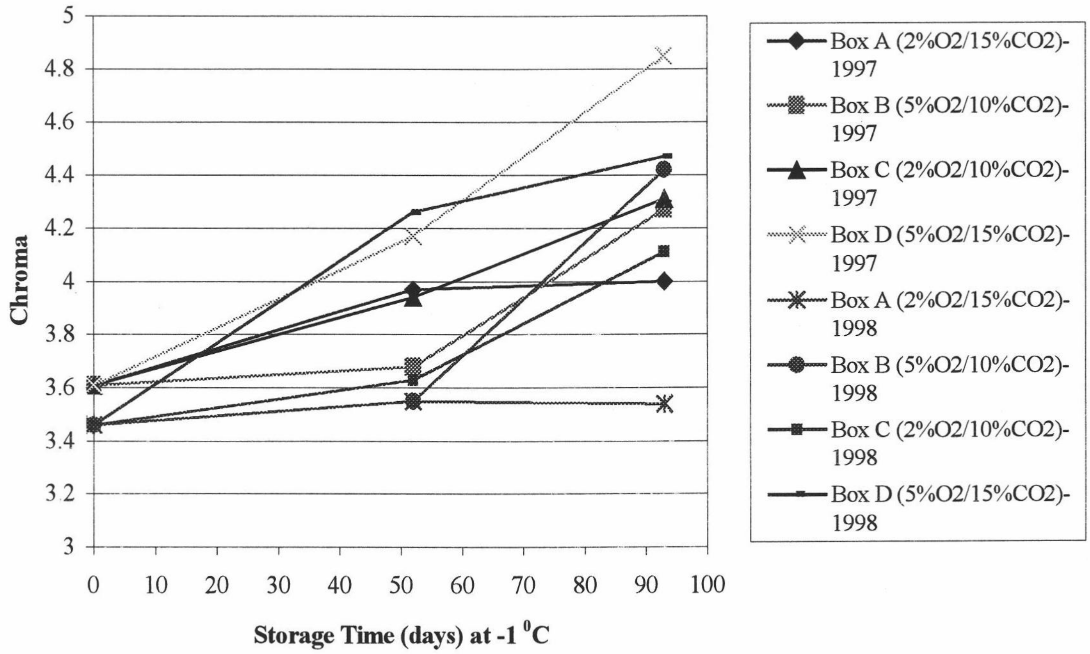

Figure 3.21. Mean chroma (Minolta CR-300, color change) of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1997 and 1998 storage seasons.

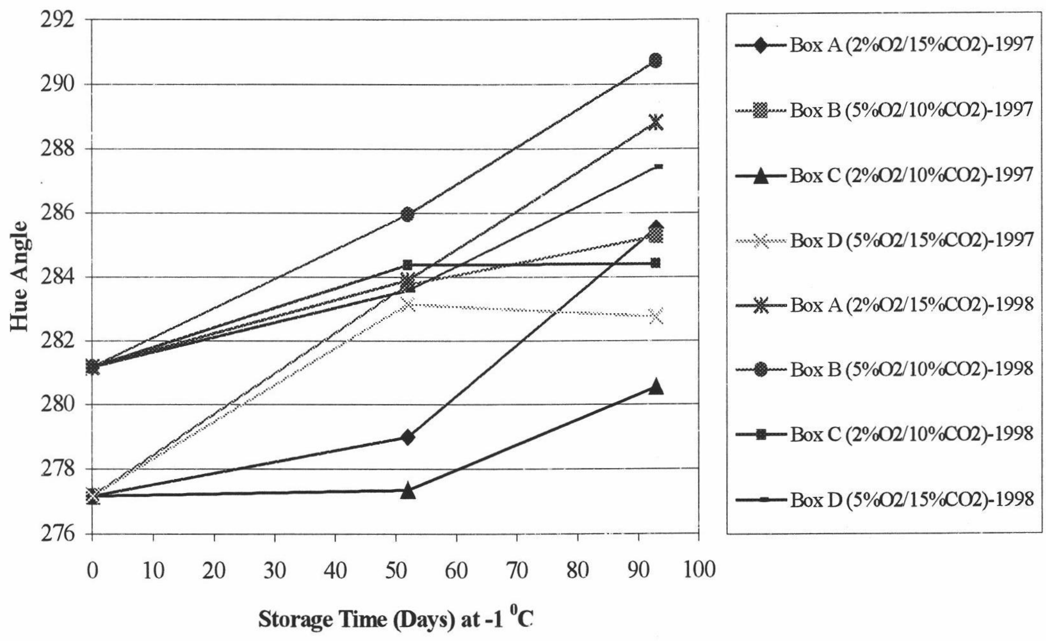

Figure 3.22. Mean hue angle (Minolta CR-300, color change) of "Elliott" blueberries stored in different atmospheric conditions during two periods of the 1997 and 1998 storage seasons.

3.5. CONCLUSIONS

From the results of 1996 preliminary experiment, the following conclusions are stated:

1. High levels of visible fungal decay were found on the berries held under atmosphere combinations of 2% and 5% O_2 with 5% CO_2 after 80 days in storage.
2. Blueberries stored under 2% and 5% with 5% CO_2 after 80 days had soluble-solids-acid ratio (SS/Ac) greater than 30, which indicated poor keeping quality.
3. Fruit stored in 15% CO_2 were firmer than those stored in 5% CO_2.
4. The best fruit flavor and general appearance were from the controlled atmosphere storage condition of 5% O_2 with 15% CO_2.
5. The 15% CO_2 with 2% O_2 and 15% CO_2 with 5% O_2 atmospheres were more effective in maintaining blueberry quality than either 5% CO_2 environment.

The following are conclusions from results obtained from the 1997 and 1998 experiments:

1. Storage time significantly affects all fruit quality attributes.
2. There were significant linear correlations between O_2 levels and percentage weight loss of berries. As O_2 levels decreased from 5% to 2%, percentage weight loss of berries decreased.

3. There were significant linear correlations between CO_2 and percentage weight loss of berries. As CO_2 levels increased from 10% to 15%, percentage weight loss of berries decreased.
4. Interaction between the effects of O_2 level and CO_2 level and between storage time and CO_2 significantly influenced percentage weight loss.
5. Fruit picked in the 1998 lost significantly less weight than fruit picked 1997.
6. There is no evidence that all combinations of 2% and 5% O_2 with 10% and 15% CO_2 significantly influenced percentage unmarketable fruit.
7. There were significant linear correlations between CO_2 levels and soluble solids content. Fruit held in 10% CO_2 lost more sugar than those held in 15% CO_2.
8. Soluble solids content increased over storage time.
9. There was convincing evidence that blueberries held in 15% CO_2 lost less acid than fruit held in 10% CO_2 at level of oxygen.
10. Tritable acidity decreased over storage time.
11. There were significant linear correlations between CO_2 levels and soluble solids-acid ratio (SS/Ac). As carbon dioxide increased, SS/Ac decreased.
12. Sugar-acid ratio increased over storage time.
13. Firmness of blueberries was significantly correlated to CO_2 levels at each level of oxygen. Blueberries stored in 15% CO_2 had higher firmness than fruit stored in 10% CO_2.

14. Oxygen levels of 2% and 5% had no significant effect on berry color change.

15. Carbon dioxide levels of 10% and 15% had no significantly effect on berry color change.

16. Berries held under atmospheres of 5% O_2 with 10% and 15% CO_2 had better general fruit appearance than fruit held under atmospheres of 2% O_2 with 10% and 15% CO_2 after 52 days and 93 days in storage.

17. The best overall fruit flavor were found in fruit stored under atmospheres of 5% O_2 with 10% and 15% CO_2, both after 52 days and 93 days in storage.

18. There were no significant interaction effects between O_2 and CO_2 on any fruit quality attributes except percentage weight loss.

19. Oxygen alone is ineffective in controlling decay of blueberries.

20. Oxygen did not affect the firmness of blueberries after 52 and 93 days in storage.

21. The benefit of high CO_2 on controlling decay of blueberries was positive. Carbon Dioxide levels of 10% and 15% can successfully retarded decay of berries for 93 days in storage.

22. The controlled atmosphere of 5% O_2 and 15% CO_2 appeared to be the most effective in retaining quality in terms of better flavor, general appearance, less weight loss, low SS/Ac, and firmer after 52 and 93 days of storage.

CHAPTER 4

COOLING PROCESS PARAMETERS AND TRANSIENT HEAT TRANSFER ANALYSIS OF BLUEBERRIES EXPOSED TO COOLING IN A CONTROLLED ATMOSPHERE STORAGE

Key Index Words: cooling process parameters, transient heat transfer, blueberries, cooling, and controlled atmosphere storage.

4.1. ABSTRACT

The cooling characteristics of bulk blueberries being cooled with air in a controlled atmosphere (CA) storage was investigated. A simple model was also developed to determine the cooling process parameters including cooling coefficient, lag factor, half cooling times, seven-eight cooling times, and effective heat transfer coefficients. Estimated cooling coefficient, lag factor, half cooling times, and seven-eights cooling times ranged from 0.23 hr^{-1} to 0.40 hr^{-1}; 1.01 to1.05; 1.56 hrs to 2.85 hrs; and 5.57 hrs to 8.81 hrs, respectively. The effective heat transfer coefficient varied from 10.17 W/m^2 K to 16.05 W/m^2 K depending upon berry basket position. The greater the surface area exposed to the cooling medium, the higher the heat transfer coefficients and the lower the half cooling time and the seven-eights cooling time. Very good agreement was found between recorded temperature data and regression dimensionless temperature values. Therefore, the simple model presented in this study can be a useful tool to determine the cooling process parameters in other practical cooling applications.

4.2. INTRODUCTION

Rapid removal of field heat from harvested fruit is desirable to minimize rate of deterioration. Cooling rate depends primarily upon accessibility of the product to the refrigeration medium, temperature difference between the product and the refrigerating medium, velocity of the refrigerating medium, and the kind of cooling medium; i.e., water or air (Hardenburg et al., 1990). As the products are cooled from ambient conditions to their optimal storage temperature, one of four types of precooling methods is commonly used; hydrocooling, air cooling, hydraircooling, or vaccum cooling. The method selected may be based on several criteria, such as cost, convenience, effectiveness, applicability, efficiency, operating conditions, and personal preference in addition to product requirements (Dincer, 1995).

In cooling processes, several important parameters are used to evaluate and present cooling rate data and commodity cooling behavior. Cooling time, lag factor, half cooling time, and seven-eights cooling time for fruits and vegetables are necessary to properly design cooling systems and to establish optimum cooling conditions (Dincer, 1995). Maintenance of ideal product temperature and minimization of water loss are both important. These are achieved by maintaining uniform conditions (i.e., temperature, relative humidity, and air velocity) in the storage environment.

In transient heat transfer during food cooling, the temperature at a given point within the produce depends on cooling time and position. Regardless of the type of cooling technique, knowledge and determination of cooling process parameters are essential to provide efficient and effective fruit cooling at the macro and micro scales

(Dincer, 1997). Many solutions of the effective heat transfer coefficient (h), which include the effect of moisture evaporation, have been proposed. However, this is more complicated and is harder to communicate to the refrigeration industry (Pentima et al., 1988). A problem with the effect of moisture evaporation is that the effective heat transfer coefficient changes with the humidity level of the cooling air and yet this is not as critical with a single product as it is with bulk products in large containers (Pentima et al., 1988). Gaffney et al. (1985) mentioned that the respiratory heat generation and a cooling effect at the product surface have little influence on the cooling rate and it can be neglected in the computation of heat transfer during air-cooling on individual products.

Fruit cooling processes involve transient heat transfer between the cooling medium and solid products. Therefore, estimation of the heat transfer coefficient is important in order to achieved high energy efficiency in practice. The cooling rate of the product is a function of the boundary layer surrounding the product. This is often characterized in the form of a heat transfer coefficient referred to as the product and fluid interface effective heat transfer coefficient. In order to determine the optimum thermal process, the actual heat transfer coefficient must be determined either experimentally or theoretically (Dincer, 1992).

The objective of this research was to determine cooling process parameters in terms of cooling coefficient, lag factor, half cooling times, and seven-eights cooling times, as well as the effective heat transfer coefficient of bulk Elliott blueberries, subjected to cooling in a controlled atmosphere storage.

4.3. MATERIALS AND METHODS

Product quality is directly affected by the length of time required to be cooled from ambient conditions to optimal storage temperature. Storage under refrigerated conditions is used to slow quality deterioration in fruits and vegetables. The objective of refrigeration is to remove heat from the product and to maintain a stable storage temperature for an extended period of time. Room cooling was used for cooling process and storage during all experiments.

Experiments to determine cooling characteristics including cooling process parameters and convective heat transfer coefficients of Elliott blueberries were conducted in 1998. All experiments were carried out in the Postharvest Engineering Research Laboratory (PERL) located in the Bioresource Engineering Department at Oregon State University.

4.3.1. Proposed Mathematical Model

Under one dimensional transient heat transfer, the cooling of individual blueberries can be described by Newton's law of cooling:

$$hA_s(T - T_\infty) = -\rho Vc\frac{dT}{dt} \tag{4.1}$$

or

$$hA_s(T - T_\infty) = -mc\frac{dT}{dt} \tag{4.2}$$

where

h = effective heat transfer coefficient (W/m^2 K)

T = temperature of the object at time t ($^\circ$C)

T_∞ = temperature of the surroundings ($^\circ$C)

m = mass of bulk fruit in the container (kg)

V = volume of container (m^3)

A_s = surface area of the container (m^2)

ρ = fruit bulk density (kg/m^3)

c = specific heat of fruit (J/kg K)

t = time (hr)

Equation 4.1 can be solved analytically for one dimensional heat transfer of an individual spherical product under the following assumption:

1. The fruit is homogeneous, thermal and physical properties of fruits and air do not change with temperature.
2. The initial temperature of the product is uniform.
3. There is no internal heat generation in the individual fruits.
4. There is no conduction heat transfer between individual fruits.
5. There is no temperature gradient within the product.

The dimensionless temperature, which is a function of the product and air medium temperature can be expressed as:

$$\theta = \frac{T - T_\infty}{T_i - T_\infty} \qquad (4.3)$$

then, the above equation (4.3) can be rewritten as:

$$\theta = Je^{(-at)} \tag{4.4}$$

where

T_i = initial value of T (°C)

a = cooling coefficient (1/hr)

J = lag factor

The cooling coefficient is an indicator of the cooling capacity of a food product subject to cooling. The cooling coefficient is expressed as the change in the product temperature per unit time of cooling for each degree temperature difference between the product and its surroundings (Dincer, 1997). Cooling coefficient is also related to the Biot number and size of the product. The lag factor is a function of the size, shape and the thermal properties of the product, such as the effective heat transfer coefficient, thermal conductivity, and thermal diffusivity. The lag factor quantifies the resistance to heat transfer from the product to its surrounding. With this definition it is very clear that the lag factor is directly related to Biot number.

By substituting $\theta = 0.5$ into equation (4.4), the half cooling time can be found as:

$$0.5 = Je^{(-at)} \tag{4.5}$$

Half cooling time is one of the most meaningful parameters in practical fruit storage. Half cooling time is the time required to reduce the product temperature to one-half of the initial difference in temperature between the product and the cooling medium. The cooling times of commodities are mainly influenced by heat transfer characteristics, dimensions and physical properties of commodities; heat transfer characteristics of the cooling medium, and geometric details and heat transfer characteristics of packaging or containers, when used (Dincer, 1997).

Also by substituting $\theta = 0.125$ (1/8) into equation (4.4), the seven-eighths cooling time can be found as:

$$0.125 = Je^{(-at)} \tag{4.6}$$

The effective heat transfer coefficient (h) can then be evaluated by linear regression according to the following equation:

$$\ln \frac{T - T_\infty}{T_i - T_\infty} = \frac{hA_s t}{\rho c V} \tag{4.7}$$

The effective heat transfer coefficient (h) can then be found by determining the slope of the regression analysis by using the following equation:

$$slope = \frac{hA_s}{\rho c V} \tag{4.8}$$

The specific heat (c) can be estimated by using Siebel's correlation at temperatures above the freezing point, in terms of the water content of the food product as follows:

$$c = (0.837 + 3.349W) * 1000 \tag{4.9}$$

where

W = Water content (% by weight)

4.3.2. Experimental Procedures

Four controlled atmosphere (CA) test chambers were used in this research. All four test chambers were arranged inside a walk-in refrigerator. Inside dimensions of the walk-in refrigerator were 1.22 m * 1.52 m * 2.03 m. Positions of the CA test chambers inside the walk-in refrigerator are illustrated in Figure 4.1. The CA test chambers were designed to be gas tight enabling development of controlled atmosphere storage conditions within. The chambers were constructed of 7.6 mm thick plexiglass. Inner dimensions of the CA chambers were 0.64 m * 0.91 m * 0.61 m. Each chamber was equipped with a strain gauge load cell to continuously measure fruit mass loss and thermistors to measure air and fruit temperature during each experiment. Four plexiglass boxes of inner dimension 0.27 m * 0.33 m * 0.21 m were constructed to contain the berry baskets. Each plexiglass box contained 24-pint baskets filled with blueberries. Berry baskets were arranged in two 3 by 4-dimension layers, as illustrated in Figure 4.1 and 4.2. Filled plexiglass boxes were hung from the load cell inside each CA test chamber.

All berries in the heat transfer experiments were tested in bulk and cooled in natural convection environments. Fruit cooling temperature data were achieved by positioned three thermistors in the center of three different baskets. Baskets were selected so a corner basket, a side basket, and a center basket were instrumented. Dew point temperatures were measured with a chilled mirror hygrometer in Box A and Box B. Relative humidity sensors were placed in Box C and Box D. After the test chambers were closed, temperature data were recorded every 10 minutes.

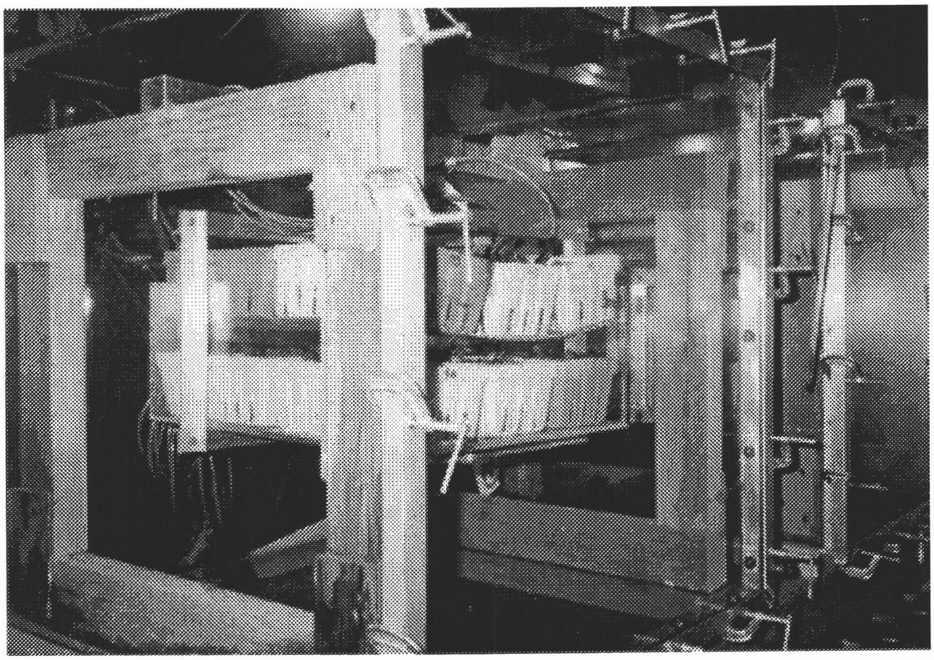

Figure 4.1. Controlled atmosphere test chamber layout in the walk-in cooler.

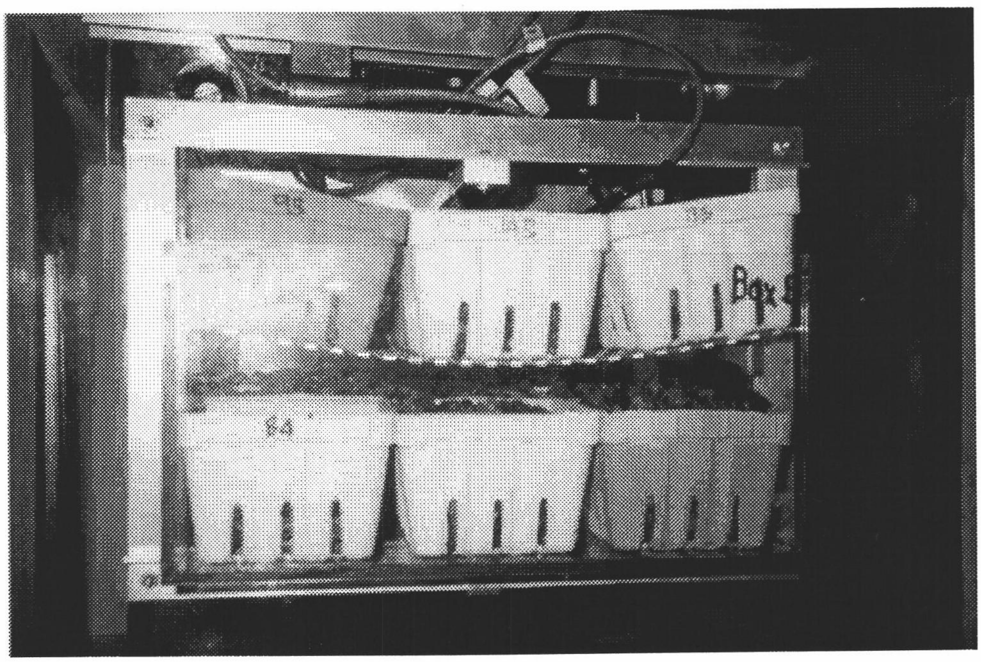

Figure 4.2. Berry basket layout in each controlled atmosphere test chamber.

4.4. RESULTS AND DISCUSSION

Figures 4.3 through 4.6 illustrate recorded air and fruit dry bulb temperatures during cooling of bulk Elliott blueberries in Controlled Atmosphere chambers. Each curve represents the temperature at the center of a specific fruit basket. The berry basket arrangement used in each CA box is shown in the upper right hand corner of the figure. From Figure 4.3 through 4.6, baskets on the edge of the arrangement cooled faster due to a large surface area being exposed to the surrounding cold air. This phenomenon can be seen in all CA boxes. The fruit temperature of two baskets in box A and one in box B were not presented in the results due to failure of the thermistors in both CA chambers. Chamber relative humidity data during berry cooling are illustrated in Figures 4.7 through 4.10. Relative humidity values in Box A and B were about 99% at the beginning of the cooling processes, then decreased to between 95% and 96% after 10 hours. The high peaks in the relative humidity plots in Box A and Box B occurred during chamber's daily defrost cycle. For Box C, the relative humidity was about 97% at the beginning of cooling process and decreased to between 95% and 96%, then remain relatively constant. The relative humidity in Box D was relatively constant between 95% and 96%.

The cooling process parameters, namely cooling coefficient, lag factor, half cooling time, and seven-eights cooling times, as well as the heat transfer coefficients are the parameters for evaluating and representing cooling process. After non-dimentionalizing experimental bulk cooling temperature measurements by using equation (4.3), regression analyses were carried out on these dimensionless temperature data in the exponential form as described in equation (4.4).

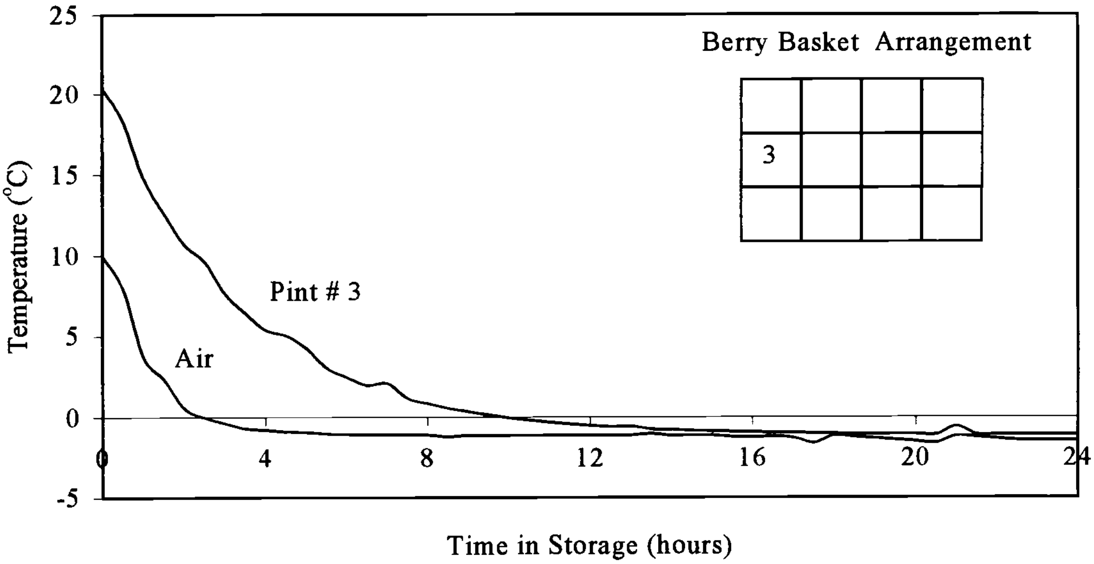

Figure 4.3. Air and fruit dry bulb temperatures in box A during cool down of Elliott blueberries stored in a controlled atmosphere chamber.

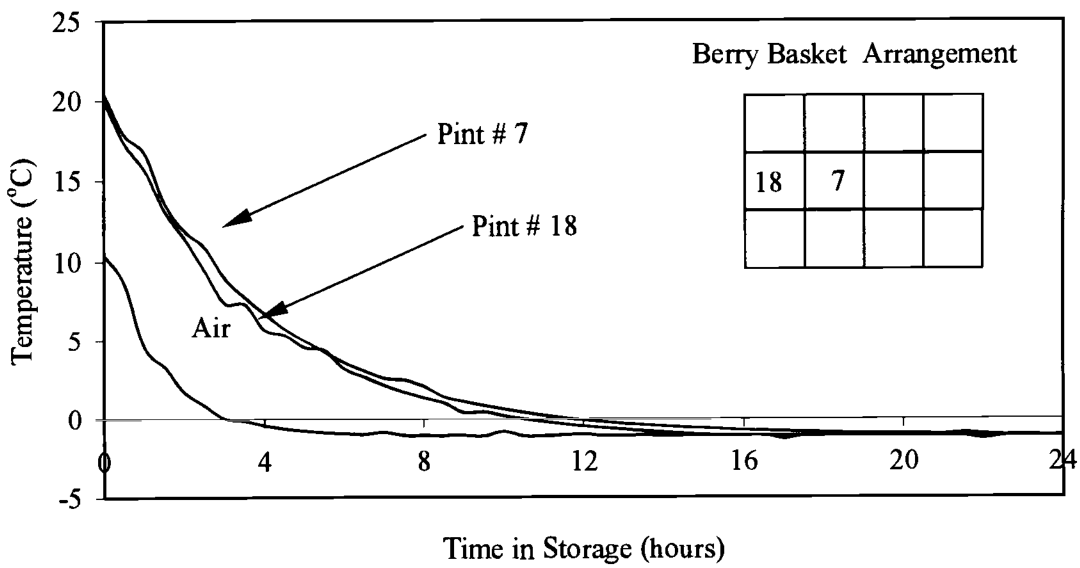

Figure 4.4. Air and fruit dry bulb temperatures in box B during cool down of Elliott blueberries stored in a controlled atmosphere chamber.

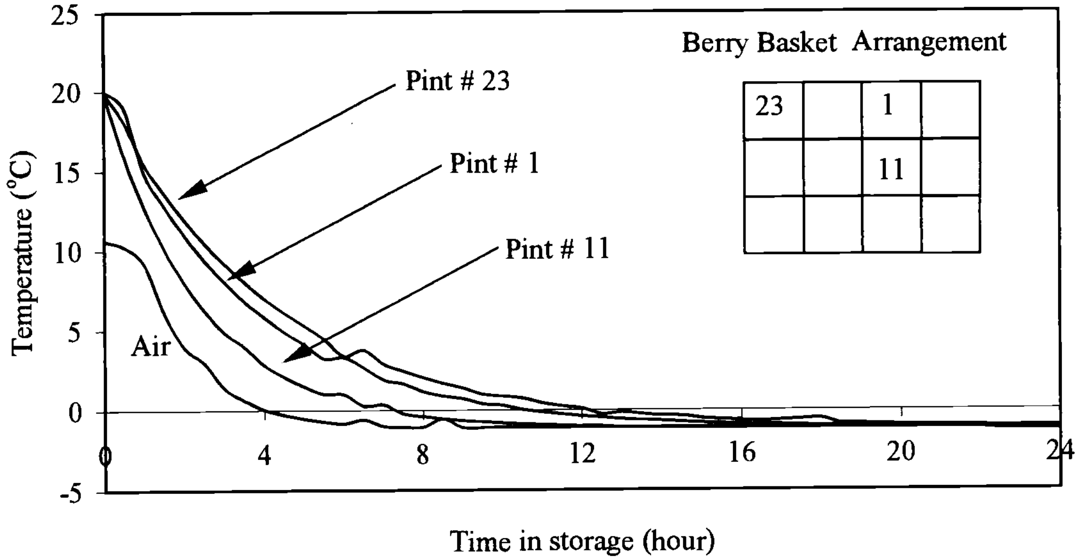

Figure 4.5. Air and fruit dry bulb temperatures in box C during cool down of Elliott blueberries stored in the controlled atmosphere chamber.

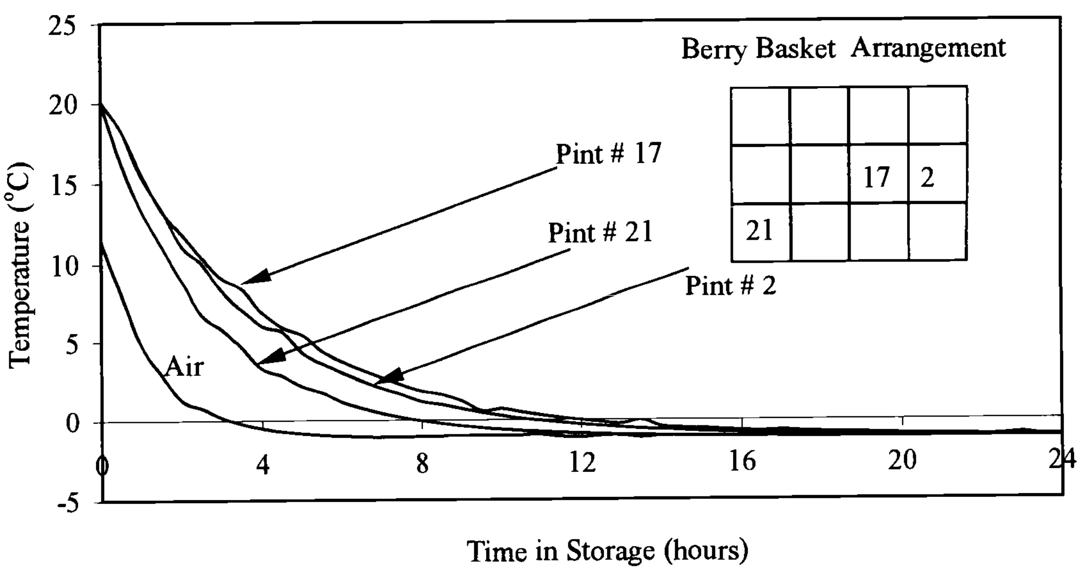

Figure 4.6. Air and fruit dry bulb temperatures in box D during cool down of Elliott blueberries stored in the controlled atmosphere chamber.

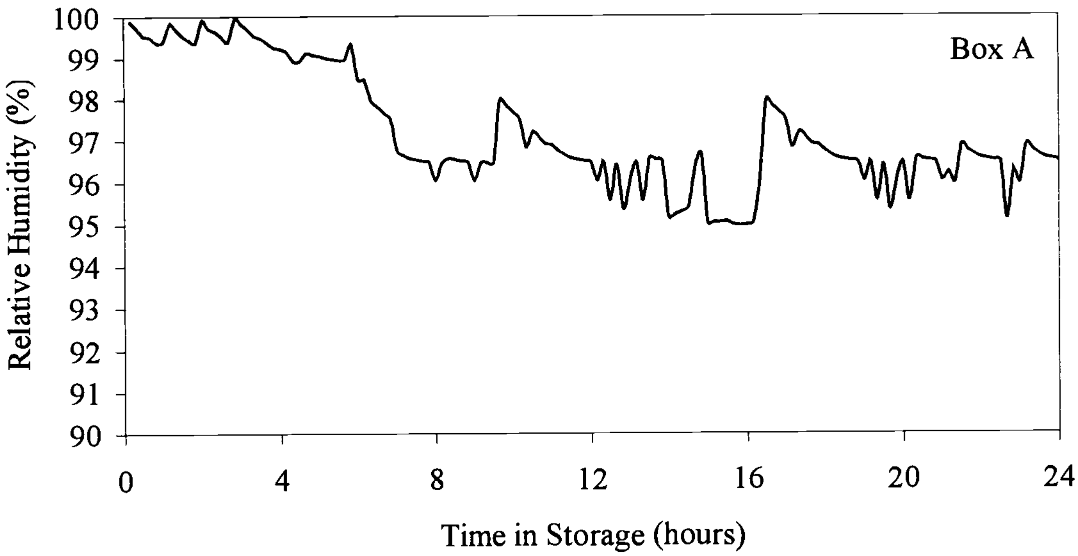

Figure 4.7. Relative Humidity in Box A during cool down of Elliott blueberries stored in the controlled atmosphere chamber.

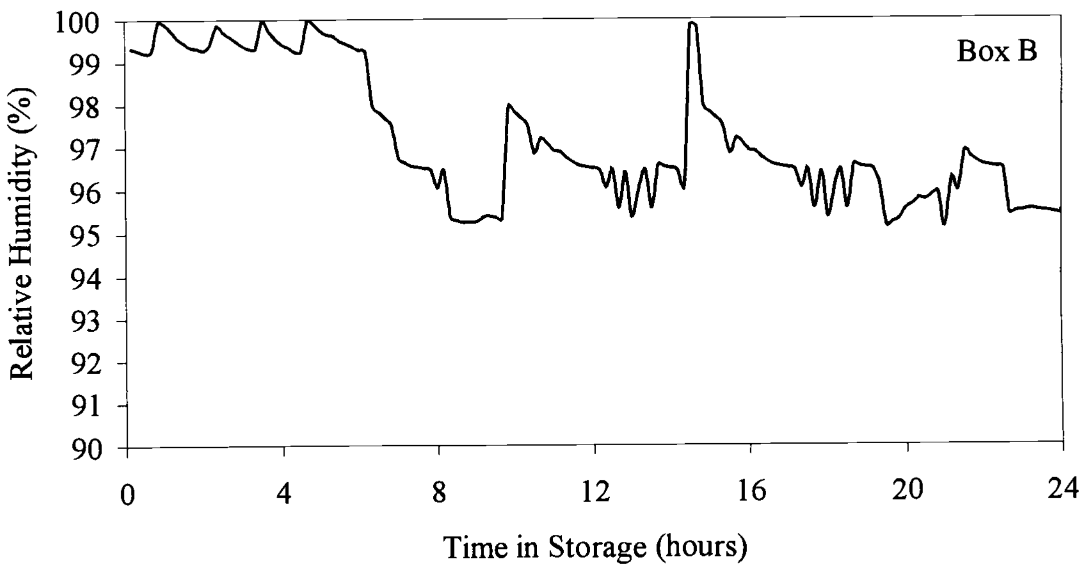

Figure 4.8. Relative Humidity in Box B during cool down of Elliott blueberries stored in the controlled atmosphere chamber.

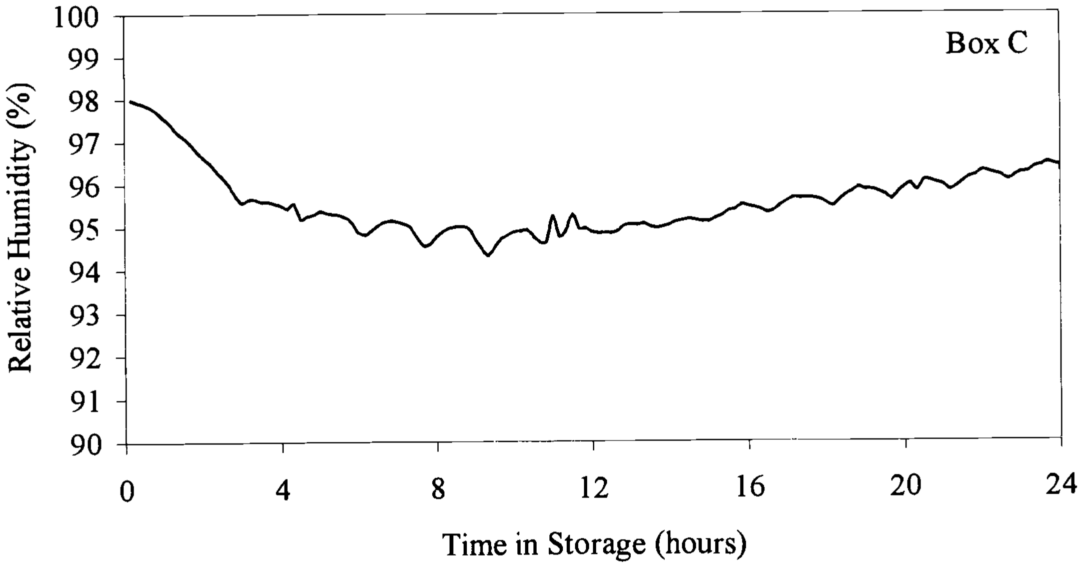

Figure 4.9. Relative Humidity in Box C during cool down of Elliott blueberries stored in the controlled atmosphere chamber.

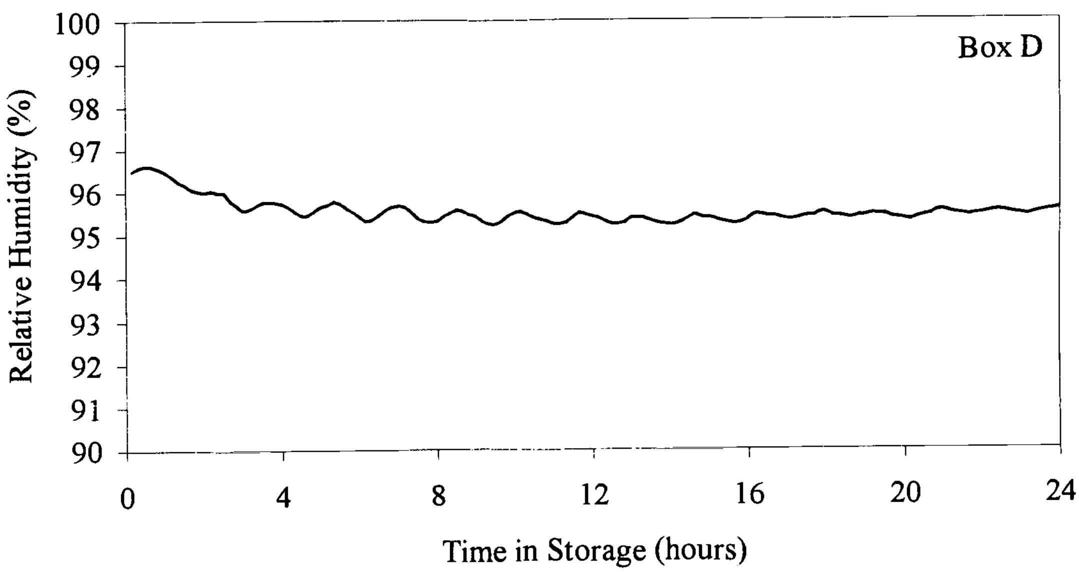

Figure 4.10. Relative Humidity in Box D during cool down of Elliott blueberries stored in the controlled atmosphere chamber.

From regression analysis, the lag factor (*J*) and cooling coefficient (*a*) were determined, then the half cooling times (*H*) and seven-eighths cooling times (*S*) were calculated by using equations (4.5) and (4.6), respectively. The specific heat (*c*) of blueberries was estimated buy using Siebel's correlation as shown in equation (4.9). By using values of cooling coefficient (*a*), specific heat (*c*), ρ, V, and A_s in equation (4.8), the heat transfer coefficients were determined. These values, expressed in terms of *J*, *a*, *H*, *S*, and h for bulk cooling of Elliott Blueberries stored in CA storage, are illustrated in Table 4.1.

Table 4.1 illustrated the regression analysis in the exponential form by using least squares method gives R^2 between 98% to 99%, which indicated a very good agreement between experimental data and regression dimensionless temperature values. The cooling process parameters were affected by the locations of the berry baskets. The cooling coefficients were higher in the baskets located at the edge of the arrangement.

The average cooling coefficient was 0.29. The values of cooling coefficient were found to be highest of 0.41 of the basket located at the edge of arrangement. The baskets located on the side, Box D-pint # 2 and Box B-pint # 8, were also found to have relatively high values of cooling coefficient of 0.36 and 0.33, respectively. The cooling coefficients were higher for the berry baskets located at the edge and on the side of the arrangement than the ones located in the middle of the arrangement. And this indicated that values of cooling coefficient were highly sensitive to the surface area exposed to the cooling medium.

Table 4.1. Cooling process parameters and heat transfer coefficients of bulk Elliott blueberries stored in the controlled atmosphere chamber.

Treatment	J	a (1/hr)	H (hrs)	S (hrs)	R^2	h (W/m^2 K)
Box A-pint # 3	1.03402	0.297767	2.440167	7.095802	98.76%	13.516463
Box B-pint # 7	1.02581	0.252269	2.848664	8.343967	98.44%	11.035359
Box B-pint # 18	1.05145	0.330816	2.246921	6.437451	97.94%	14.387459
Box C-pint # 1	1.03036	0.281540	2.568216	7.492185	99.96%	12.030218
Box C-pint # 11	1.01479	0.237778	2.976848	8.807052	99.80%	10.220564
Box C-pint # 23	1.00431	0.407057	1.558881	4.964533	98.90%	17.651630
Box D-pint # 17	1.00671	0.237312	2.780076	8.621729	99.60%	10.170443
Box D-pint # 21	1.00704	0.367992	1.802054	5.56924	99.96%	16.050933
Box D-pint # 2	1.01130	0.270931	2.599864	7.716644	99.99%	11.508189

Table 4.1 indicated the lag factors, which are the function of the physical properties of the product, are larger than one. This indicated the certain internal resistance to the heat transfer from the product to the surrounding air. The average half cooling times and seven-eighths cooling times were 2.47 hrs and 7.27 hrs, respectively. The half cooling times and seven-eights cooling times were lower for the berry baskets located at the edge of the arrangement than the ones located in the middle of the arrangement. The half cooling times and seven-eighths cooling times ranged from 1.5 hrs to 2.9 hrs and 5.57 hrs to 8.81, respectively.

The effective heat transfer coefficients were higher for the berry baskets located on the edge of the arrangement than the ones located in the middle of the arrangement. The average effective heat transfer coefficients were 12.95 W/m^2 K and ranged from 10.17 W/m^2 K to 17.65 W/m^2 K. As presented above, the cooling process parameters were found to be dependent of the basket position. Therefore, the variations in the cooling process parameters in the same CA container can be explained by the different surface areas exposed to the cooling medium.

The results indicated that this approach is capable of determining the cooling process parameters for bulk storage of blueberries in a simple and accurate way. Additionally, this approach can easily be extended to predict bulk storage cooling different types of fruits.

4.5. CONCLUSIONS

The analysis presented in the study was used to determine the cooling process parameters, such as cooling coefficient, lag factor, half cooling time, and seven-eighths cooling times. Effective heat transfer coefficients for bulk cooling in air medium in controlled atmosphere storage were also evaluated.

The experimental study shows that the variation of heat transfer coefficient of bulk cooling was a function of position. The heat transfer coefficient in bulk berries changed principally with the basket position. The heat transfer coefficients decreased approximately 23%, 11%, 10%, and 30% between the edge of the first row and the center of the first, second, third, and fourth row, respectively. The half cooling times and seven-eighths cooling times decreased and the heat transfer coefficients increased with the increasing surface areas exposed to the cooling medium. The present method presented is a simple and useful tool to determine cooling process parameters in a practical cooling application. In conclusion, as the primary objective of a cooling study, usable data and technical information was produced, which can be used to improve existing cooling systems and provide optimum operating conditions for blueberry storage.

CHAPTER 5

MASS TRANSFER CHARACTERISTICS OF BLUEBERRIES STORED IN CONTROLLED ATMOSPHERE STORAGE CONDITIONS

Key Index Words: "Elliott" blueberries, mass transfer characteristics, mass transfer rates, transpiration coefficients, blueberries, and controlled atmosphere storage.

5.1. ABSTRACT

Moisture loss from fresh fruit during storage results in reduced quality and monetary loss. Elliott blueberry mass transfer characteristic experiments were performed at $-1\ ^0C$ with 80-85% RH in combinations of 2% and 5% O_2 with 5% and 10 CO_2 during the 1996 storage season and at $-1\ ^0C$ with 90-95% RH in combinations of 2% and 5% O_2 with 10% and 15% CO_2 during the 1997 and 1998 storage seasons. Mass transfer rates and environmental conditions were measured in all storage season experiments. Transpiration coefficients were determined in the 1998 experiment. Transpiration coefficients, on a per unit mass and per unit area basis were determined for "Elliott" blueberries stored in bulk refrigerated CA environments. Fruit mass loss was greatest during the cool down period because both respiration and transpiration rates were high, then decreased exponentially. Transpiration rates were constant once environmental condition stabilized. Transpiration coefficients initially high during fruit cooling. After storage conditions were reached, transpiration coefficient stabilized. Controlled atmosphere condition of 5%O_2 and 15%CO_2 (Box D) provided the best result as far as mass transfer. This treatment had the lowest transpiration rate of 0.00023 mg/s•kg•kPa.

5.2. INTRODUCTION

Loss of moisture, with consequent wilting and shriveling, is one of the obvious ways in which freshness of fruit and vegetables is lost (Zomorodi, 1990). Since fruit and vegetables are 80-95% water, they lose moisture rapidly whenever the surrounding RH is less than 80-85%. Moisture losses of 3-6% are usually enough to cause marked deterioration of quality for many kinds of produce. Consequently, it is important to reduce such moisture losses by lowering temperature, raising RH and reducing air movement (Parry, 1993). Water loss equates to loss of saleable weight, and thus constitutes a direct loss in marketing. Accordingly, measures that minimize water loss after harvest will usually enhance profitability (Wills et al., 1998).

Transpiration is defined as the mass transfer process in horticulture crops due to vapor pressure difference between the interior of product and its surrounding. Transpiration includes both water diffusion through the fruit and evaporation at the surface. Water diffusion through the product does not constitute mass loss. Actual mass loss results as internal water diffuses toward the product surface and evaporates into the surrounding air. Because the internal diffusion and evaporation are a linked phenomenon, transpiration is typically defined as a process of evaporation of water from the fruit to the atmosphere. Transpiration rate is the mass of moisture transpired per unit mass of commodity per unit time (Sastry et al., 1978). The transpiration coefficient of a fruit is then defined as the mass of moisture transpired per unit mass of commodity, per unit environmental water vapor pressure deficit per unit time (Sastry et al., 1978). Transpiration rate and coefficient can also be expressed on a per unit surface area basis.

Moisture loss from fruits has been separated into two realms, driving force (water vapor pressure deficit) and resistance to moisture loss (Sastry, 1985). Driving force is affected by evaporative cooling, dissolved substances, and respiratory heat. Resistance to moisture loss is affected by air velocity, product shape and size, and fruit condition.

Fruits and vegetables continue to carry out their normal life process of respiration after harvest and the heat produced will accumulate in the product and raise its temperature unless removed. Respiration is highly correlated to temperature, and is double or tripled for every 10 ^{0}C increase in product temperature (USDA, Handbook 66). Most researchers neglect carbon mass loss due to carbon dioxide production rates when comparing moisture loss to total mass loss. Chau et al. (1988), using data listed in USDA Handbook 66, stated for seventeen commodities that carbon dioxide mass evolved from transpiration rate was negligible compared to total mass loss. Gaffney et al. (1985) reported carbon dioxide mass loss rates of 0.27, 0.034, and 0.04% of total weight loss for apples stored at 5 ^{0}C, and 50, 60, and 70% relative humidity, respectively. However, Bohling and Hellickson (1998) found that during long-term CA storage of Red Delicious apples at 1 ^{0}C in 1%CO_2 and 2%O_2, mass loss due to respiration was approximately 16.9% of total mass loss.

When moisture evaporates from fruit, the heat required to evaporate the water is removed from the product thus providing a cooling effect. This reduces surface temperature, which causes the vapor pressure at the evaporating surface to decrease (Sastry, 1985). The reduced surface vapor pressure decreases the vapor pressure difference between the fruit and surrounding air The reduce vapor pressure difference decreases the transpiration rate. Sastry and Buffington (1982) derived a steady-state model to determine transpiration rates of spherical fruits with skins. The fruit temperature immediately beneath the skin was assumed to be the fruit evaporating temperature. This model included the influences of evaporative cooling and the heat of respiration. Chau et al. (1987) also used the temperature immediately beneath the product skin to be the evaporating surface temperature. Since water in most foods is bound in various ways to other components of the product, the vapor pressure at the evaporating surface is frequently lower than the saturation vapor at the same temperature (Sastry et al., 1988). Sastry (1978) also stated that water inside fruit contains dissolved sugars and gases, which reduce the fruit surface vapor pressure. Therefore, the vapor pressure of the fruit surface is equivalent to the vapor pressure of a solution.

Most researchers found that air movement past fruit to have slight but not significant effect on the transpiration rate when thermal equilibrium existed between the fruit and surrounding air (Sastry et al., 1978). Air movement during product cooling increased transpiration rates since large temperature differences exist between the fruit and surrounding air. Gaffney et al., 1985 reported that air velocity had no significant effect on water loss rates from apples except at very high relative humidities.

Size, shape, and surface area all affect fruit transpiration rate (Sastry et al., 1978). Fruit with a large area to mass ratio will transpire more water vapor than fruit with a small surface area to mass ratio (Sastry 1985). Products with large surface area to mass ratios provide a larger area per unit mass for moisture loss to occur.

Karmarkar and Joshi (1940) noted that small fruits possessed thinner skins than large fruit, which could cause additional difference in transpiration rates. Shape also affects surface area to mass ratio. Chau et al. (1987) stated that transpiration coefficients based on surface area provide accurate results as mass loss is directly proportional to surface area. However fruits surface areas are extremely difficult to accurately measured. The magnitude of error introduced into determination of transpiration coefficients based on surface area measurements may be significant. Transpiration rate based on mass would be more useful for calculations since precise determination of mass is readily achievable (Sastry et al., 1978). Transpiration rates on a per kilogram basis could be used by commercial storages to determine product loss percentages during long term storage.

Fruit surface structure and physiological characteristics also affect transpiration rates. Different varieties of the same commodity have different epidermal structures and different resistances to moisture loss (Sastry et al., 1978). Fruit surfaces are almost entirely covered with a layer of natural wax, which is largely impervious to moisture loss (Sastry et al., 1978). The fruit skin and waxy layer offer large resistance to moisture loss. However, stem scars, wounds, and cracks in the surface allow moisture loss. Wax coating structure is more important than thickness. Cuts and bruises damage wax and skin layers and allow direct exposure of fruit flesh to surrounding air. Young fruit may have unhealed cuts and bruises, which allow increased moisture loss and infection from pathogen. Skin permeability is affected by dehydration during moisture loss (Sastry, 1985). Skin drying causes tissue turgidity to decrease and reduces permeability to water vapor loss. Furthermore, immature and over mature fruits transpire faster than mature fruit (Sastry et al., 1978).

Predicting water loss is helpful for estimating the shelf life of fresh produce and designing storage and packing conditions. Accurate estimation of water loss can be valuable for controlling and managing the storage facilities particularly in controlled atmosphere (CA) storage, where weight can not be easily measured without disturbing the storage atmosphere.

The objective of this study was to determine mass transfer characteristics and, accurately quantify transpiration rates and transpiration coefficients for "Elliott" blueberries stored in bulk under different atmospheric conditions.

5.3. MATERIALS AND METHODS

5.3.1. Proposed Mathematical Model

The rate of moisture loss from fruits and vegetable can be expressed by the following equation:

$$\dot{m} = K_m (P_s - P_a) \qquad (5.1)$$

where

$\dot{m}$ = rate of moisture loss (mg/s•kg or mg/s•m^2)

K_m = overall transpiration coefficient (mg/s•kg•kPa or mg/s•m^2•kPa)

P_s = water vapor pressure at evaporating surface (kPa)

P_a = water vapor pressure of surrounding air (kPa)

In most cases, the transpiration coefficient in equation 5.1 was stated as mass transfer coefficient (k). However Fockens and Meffert (1972) discussed that the overall mass transfer coefficient is not the only a function of the product skin but is related to the resistance to molecular diffusion of water vapor from the product surface to the free air stream. Therefore the rate of moisture loss from the product is:

$$K_m = \frac{1}{\frac{1}{K_a} + \frac{1}{K_s}} \tag{5.2}$$

where

K_a = air film mass transfer coefficient (mg/s•kg•kPa or mg/s•m^2•kPa)

K_s = skin mass transfer coefficient (mg/s•kg•kPa or mg/s•m^2•kPa)

The skin coefficient (K_s) is dependent upon the structure and properties of the product skin and the air film coefficient (K_a) is dependent upon the size of the product as well as the properties and flow rate of the surrounding air. It has been shown that the resistance attributed to K_a can be a significant portion of the total resistance for products with a relatively high skin coefficient, K_s, thus making air velocity past the product surface an important variable when calculating moisture loss rates or when measuring transpiration coefficients for these products.

The water vapor pressure calculated at the product surface is not of pure water but consists of certain substances dissolved in water (Gaffney et al., 1985). These substances result in a lowering of the saturation vapor pressure.

If the mole fraction of water in solution is known, the water vapor pressure at the surface of fruits and vegetables can be calculated using Raoult's law:

$$\frac{P_s}{P_o} = X_a \tag{5.3}$$

where

P_s = vapor pressure of water over the solution, fruit surface vapor pressure (kPa)

P_o = vapor pressure of pure water (kPa)

X_a = mole fraction of water in solution

The vapor pressure of the solution could be calculated if the concentration of all sugars were known. Determination of sugar concentration is difficult, so another approach was needed. The presence of dissolved substances reduces the freezing point as well as the vapor pressure of a solution. Gaffney et al. (1985) equated vapor pressure lowering with freezing point depression to obtain vapor pressure lowering as a function of freezing point depression, as follows:

$$\Delta T_f = K_f m_b \tag{5.4}$$

Combining equation (5.3) and (5.4) gives:

$$\frac{P_s}{P_o} = \frac{1}{1 + \frac{0.018 \Delta T_f}{K_f}} \tag{5.5}$$

Using the freezing point depression for blueberries from ASHRAE (1985) or Helman and Singn (1981), equation (5.5) yields:

$$P_s = 0.985P_o \tag{5.6}$$

Compared to P_s, P_a is easy to measure at low relative humidities. As relative humidity increases, P_a becomes more difficult to measure accurately and a small error in measurement of the dew point temperature results in a magnified error in K_m and K_s.

5.3.2. Experimental Procedures

Four controlled atmosphere (CA) test chambers were used in this research. All four test chambers were arranged inside a walk-in refrigerator. Inside dimensions of the walk-in refrigerator were 1.22 m * 1.52 m * 2.03 m. The CA test chambers were designed to be gas tight enabling development of controlled atmosphere storage conditions within. The chambers were constructed of 7.6 mm thick plexiglass. Inner dimensions of the CA chambers were 0.64 m * 0.91 m * 0.61 m. Each test chamber was equipped with a strain gauge load cell apparatus to measure fruit mass loss, the plexiglass boxes of berry was suspended from a strain gage load cell to enable continuous measurement of berry mass without disrupting the fruit or the environment throughout the storage periods. Each chamber was also equipped with thermistors to measure air and fruit temperature during each experiment. Four plexiglass boxes of inner dimension 0.27 m * 0.33 m * 0.21 m were constructed to contain the berry baskets. Each plexiglass box contained 24-pint baskets filled with blueberries. Dimension of pint baskets are illustrated in Figure 5.1. Berry baskets were arranged in two 3 by 4-dimension layers. A filled plexiglass box was hung from the load cell inside each CA test chamber.

All berries in the mass transfer experiments were tested in bulk and cooled in still air using refrigerated conditions in different controlled atmosphere environments. In 1996 preliminary experiment, load cell apparatus were only installed in CA test chamber A and B. In year 1997 and 1998 experiments, load cell apparatus were installed in all four CA test chambers (Box A, B, C, and D). Dew point temperatures were measured with a chilled mirror hygrometer in Box A and Box B. Relative humidity sensors were placed in Box C and Box D. After the test chamber was closed, berry bulk and chamber air temperatures were continuously recorded every 10 minutes throughout the storage periods.

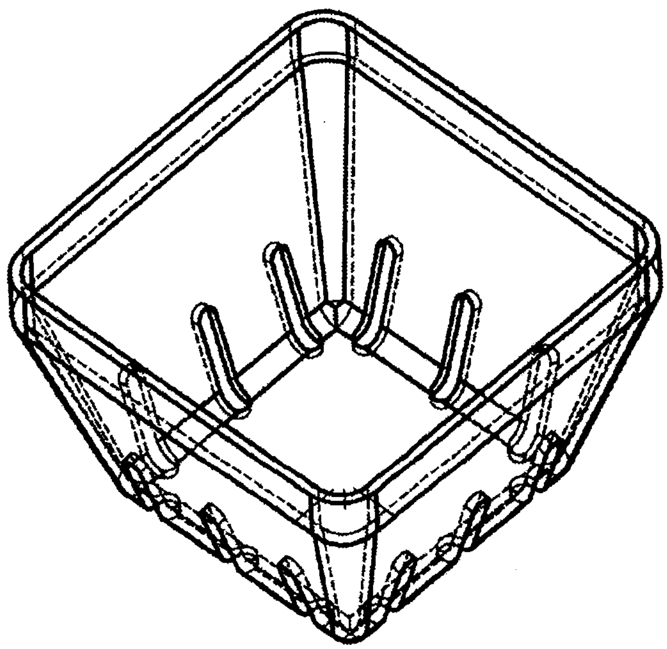

Figure 5.1. Fiber basket layout.

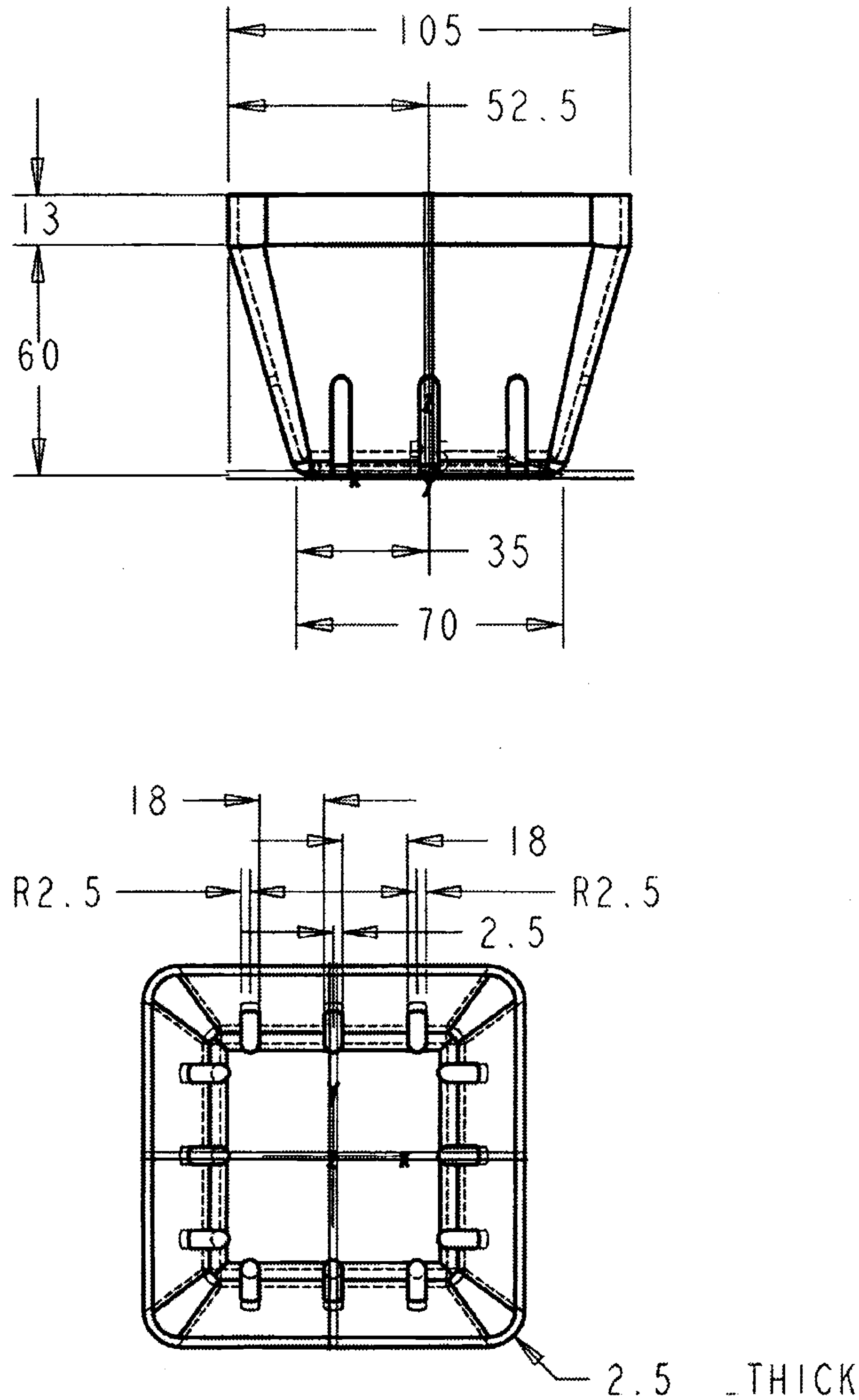

Figure 5.2. Dimensions of fiber basket used in berry experiments (mm).

5.4. RESULTS AND DISCUSSION

Fruit mass loss is directly related to respiration activity and atmosphere relative humidity. Mass loss from the time fruit are separated from the host plant until cooled to storage temperature as well as during subsequence storage is critical to overall quality. Appendix B shows fruit mass loss curves in each chamber plotted from the load cell measurements during 1996, 1997, and 1998 experiments. Transpiration from fruit is directly proportional to the vapor pressure differential between the fruit and its surroundings. Curves fitted to mass loss data recorded during this period are typically exponential or power law equations (Appendix B). Once fruit has been cooled to storage temperature, mass loss is essentially linear unless environmental conditions are changed (Appendix B). Table 5.1 lists initial berry mass, average mass loss per second, and surface area of the berry pint baskets exposed to surrounding air in each test chamber during the first 24 hours of storage during the 1996, 1997, and 1998 experiments. In the 1996 preliminary experiment, the average ambient air temperatures in Box A (2%O_2-15%CO_2), Box B (2%O_2-5%CO_2), Box C (5%O_2-5%CO_2), and Box D (5%O_2-15%CO_2) ranged between 0 ^{0}C-0.1 ^{0}C. Average relative humidity in the CA chambers ranged between 80-85% in both Box A and B (dew point hygrometers were installed only in Box A and B). The average ambient air temperature and average relative humidity during the 1997 experiment in Box A (2%O_2-15%CO_2), Box B (5%O_2-10%CO_2), Box C (2%O_2-10%CO_2), and Box D (5%O_2-15%CO_2) were approximately 0.1 ^{0}C and 95%, 0 ^{0}C and 93%, 0 ^{0}C and 87%, 0 ^{0}C and 85%, respectively. The average mass loss rates during the first 24 hours for the 1996 and 1997 storage seasons in all CA boxes were 0.0002 and 0.0005 mg/kg·s,

Table 5.1. Initial masses, average mass loss during first 24 hours, and surface area of blueberries in different atmospheric conditions.

TREATMENT	INITIAL MASS (kg)	AVERAGE MOISTURE LOSS RATE (mg/kg·s) (During the first 24 hours)	SURFACE AREA (m^2)
1996 STORAGE SEASON			
BOX A ($2\%O_2/15\%CO_2$)	6.591	0.0002	0.278
BOX B ($2\%O_2/5\%CO_2$)	7.157	0.0002	0.278
1997 STORAGE SEASON			
BOX A ($2\%O_2/15\%CO_2$)	8.768	0.0005	0.278
BOX B ($5\%O_2/10\%CO_2$)	8.890	0.0005	0.278
BOX C ($2\%O_2/10\%CO_2$)	8.947	0.0005	0.278
BOX D ($5\%O_2/15\%CO_2$)	8.591	0.0005	0.278
1998 STORAGE SEASON			
BOX A ($2\%O_2/15\%CO_2$)	8.151	0.0004	0.278
BOX B ($5\%O_2/10\%CO_2$)	8.570	0.0004	0.278
BOX C ($2\%O_2/10\%CO_2$)	8.673	0.0004	0.278
BOX D ($5\%O_2/15\%CO_2$)	8.965	0.0005	0.278

Table 5.2. Average mass loss, transpiration rate ($\dot{m}$), and correlation coefficients (R^2) in different atmospheric conditions.

TREATMENT	AVERAGE MOISTURE LOSS RATE (mg/kg·s)	TRANSPIRATION RATE ($\dot{m}$) (mg/s)	R^2 (%)
1996 STORAGE SEASON			
BOX A ($2\%O_2/15\%CO_2$)	0.00007	0.0005	99.68%
BOX B ($2\%O_2/5\%CO_2$)	0.00007	0.0005	99.82%
1997 STORAGE SEASON			
BOX A ($2\%O_2/15\%CO_2$)	0.00004	0.0002	99.22%
BOX B ($5\%O_2/10\%CO_2$)	0.00004	0.0002	98.29%
BOX C ($2\%O_2/10\%CO_2$)	0.00003	0.0002	99.22%
BOX D ($5\%O_2/15\%CO_2$)	0.00003	0.0002	99.71%
1998 STORAGE SEASON			
BOX A ($2\%O_2/15\%CO_2$)	0.00003	0.0002	98.72%
BOX B ($5\%O_2/10\%CO_2$)	0.00003	0.0002	98.37%
BOX C ($2\%O_2/10\%CO_2$)	0.00003	0.0002	98.35%
BOX D ($5\%O_2/15\%CO_2$)	0.00003	0.0002	99.08%

respectively. In 1998 storage season, mass loss rates during the first 24 hours were 0.0004 mg/kg·s in Box A, Box B, and Box C, however mass loss rate in Box D was a little higher of 0.0005 mg/kg·s. Fruit mass loss is greatest during the cool down period because both respiration and transpiration rates are high. Cooling characteristics during cool down period were not affected by controlled atmosphere gas conditions, as the atmosphere had not been stabilized before cooling occurred. As fruit temperature decrease and CA conditions were established, respiration rate decreased. Also, as the water vapor pressure difference between the fruit surface and the surroundings decreased, transpiration rate decreased. The average mass loss rate during the first 24 hours of 1996 storage was at lowest compared to the 1997 and 1998 experiments because the fruit had been precooled at Hurst's Berry Farm prior to placement in the experiment, in spite of the fact that, the average relative humidity in all chambers were lower than those in the 1997 and 1998 experiments.

Mass versus time curves for all storage seasons were plotted and are shown in Appendix B. Data breaks in Figure B.13 were due to power failures turning off the recording microprocessor. Simple linear regression was used to determine transpiration rates then correlation coefficients (R^2) were determined (Table 5.2). Average mass loss per second, transpiration rate, and correlation coefficients in each test chamber are illustrated in Table 5.2. Mass loss versus time from different atmospheric conditions exhibited the same characteristics. Fruit in Box A and Box B stored in the 1998 storage season had the least average mass loss rate (0.00003 mg/kg·s). Fruit in Box A, B, C, and D stored in 1996 experienced the most mass loss during storage (0.00007 mg/kg·s).

Comparison of transpiration rates of "Elliott" blueberries in three storage seasons showed that 1996 storage season had the highest transpiration rate at 0.0005 mg/s while the transpiration rates for 1997 and 1998 storage seasons were the same at 0.0002 mg/s. The reason for higher transpiration rates observed in the year 1996 was the lower relative humidity (80-85%) in all the test chambers compared to the higher relative humidities of 93-95% in Box A and Box B in the 1997 and 1998 storage seasons.

Table 5.3 lists average temperatures of air surrounding the fruit, the fruit surface, and air dew point through the 1998 storage seasons. Average air partial water vapor pressure at saturation (P_{ws}), surrounding air water vapor pressure (P_a), and relative humidity in Box A and Box B were calculated by using psychrometric equations in ASHRAE (1985) as shown in Table 5.4. Fruit surface temperature below surrounding dry bulb temperature implies evaporative cooling outweighed the heat of respiration. The opposite is true when fruit dry bulb temperature exceeds surrounding air temperature.

Berry surface temperature was used to calculated P_o. The known freezing point depression (T_f) of the fruit and P_o value, then were used to calculate P_s by using equation 5.6. After storage temperature was reached, average values for relative humidity, P_{ws}, P_a, P_o, and P_s were determined. Table 5.5 presents T_f, VPL, and values for P_o and P_s. Average values for Table 5.5 and 5.6 were determined after storage temperatures were reached. Values of T_f for berry was obtained from ASHRAE (1981).

Table 5.3. Average fruit surface temperatures, surrounding air dry bulb temperature and dew point temperatures after storage conditions were reached.

TREATMENT	FRUIT SURFACE TEMPERATURE (°C)	AIR DRY BULB TEMPERATURE (°C)	AIR DEW POINT (°C)
1998 STORAGE SEASON			
BOX A ($2\%O_2/15\%CO_2$)	-0.9	-0.8	-1.5
BOX B ($5\%O_2/10\%CO_2$)	-0.9	-0.8	-1.5
BOX C ($2\%O_2/10\%CO_2$)	-1.0	-0.9	N/A
BOX D ($5\%O_2/15\%CO_2$)	-1.0	-0.9	N/A

Table 5.4. Average surrounding air water vapor pressure, saturation vapor pressures and relative humidity after storage conditions were reached.

TREATMENT	P_a (kPa)	P_{ws} (kPa)	RH (%)
1998 STORAGE SEASON			
BOX A ($2\%O_2/15\%CO_2$)	0.53748	0.57352	93.8%
BOX B ($5\%O_2/10\%CO_2$)	0.54004	0.56989	94.8%
BOX C ($2\%O_2/10\%CO_2$)	0.48138	0.56316	85.5%
BOX D ($5\%O_2/15\%CO_2$)	0.46703	0.56315	82.9%

Table 5.5. Freezing point depression, vapor pressure lowering (VPL) effect, average fruit vapor pressure at saturation and average fruit vapor pressure in different atmospheric conditions.

TREATMENT	T_f (°C)	VPL (P_s/P_o)	P_s (kPa)	P_o (kPa)
1998 STORAGE SEASON				
BOX A (2%O_2/15%CO_2)	1.6	0.98442	0.56513	0.57407
BOX B (5%O_2/10%CO_2)	1.6	0.98442	0.56513	0.57407
BOX C (2%O_2/10%CO_2)	1.6	0.98500	0.55498	0.56343
BOX D (5%O_2/15%CO_2)	1.6	0.98500	0.55441	0.56285

Table 5.6. Ellitott blueberry transpiration coefficients on a mass and area basis in different atmospheric conditions.

TREATMENT	AIR VELOCITY	K_m (mg/s•kg•kPa)	K_m (area) (mg/s•m^2•kPa)
1998 STORAGE SEASON			
BOX A (2%O_2/15%CO_2)	still	0.00079	0.02383
BOX B (5%O_2/10%CO_2)	still	0.00086	0.02585
BOX C (2%O_2/10%CO_2)	still	0.00027	0.00819
BOX D (5%O_2/15%CO_2)	still	0.00023	0.00696

Appendix B illustrates recorded relative humidity levels in Box A, Box B, Box C, and Box D during 1997 storage, respectively. Surrounding air temperature history of Elliott blueberries for Box A, B, C, and D during 1997 storage season are also shown in Appendix B. Air dew point, fruit, the surrounding air temperature, and relative humidity histories during the 1998 storage season for Box A and Box B are illustrated in Appendix B. Appendix B also presents fruit and the surrounding air temperatures during 1998 storage season for Box C and Box D. The spikes shown correspond to the daily defrost cycle. Surrounding air temperature air dew point, and fruit surface temperature, increased approximately 1.5 ^{0}C during the period when the evaporator coil was electrically heated to remove accumulated ice. Peak dew point, air, and fruit temperatures occurred immediately after the defrost cycle. At that point, the evaporator fans resumed operation and circulate warm air until the evaporator coil was cooled back to set-point temperature. Relative humidity values for Box C and D during 1998 storage season were presented in Appendix B. Relative humidity levels in Box A and Box B were typically higher than in Boxes C and D. However, the relative humidity sensors used in Boxes C and D are not as accurate as the dew point sensors used in Boxes A and B.

Table 5.6 lists transpiration coefficients on a per unit mass basis (K_m) and on a per unit area basis (K_{area}). Transpiration coefficients determined on a per unit mass basis (K_m) were calculated using Equation 5.1. Several assumptions were made in calculating the transpiration coefficients. The total measured mass loss was assumed to be due to transpiration only. Carbon loss has often been neglected and assumed that the transpiration rate and transpiration coefficients depend solely on water vapor difference. Physiologically, respiration rate affects transpiration rate since respiratory heat generation directly affects the value of P_s. Transpiration coefficients initially increased during fruit cooling. Initial increases were due to fruit cooling, where the vapor pressure difference decreased over time. After storage conditions were reached, the transpiration coefficient was not dependent on time. The vapor pressure difference in the CA chamber was small as environmental conditions were near saturation. Therefore, a small deviation in the air dew point temperature had a large influence on the calculated vapor pressure difference.

Values of P_s, P_a, transpiration rate, and initial mass were used to determine K_m for each set of known surrounding air temperature, dew point, and fruit surface temperatures. In order to determine K_{area}, accurate measurement of fruit surface area is required. All berry experiments used pint berry baskets (Figure 5.1) in the layout of commercial flat (3 by 4-dimention layers). The exposed portion of the berries was considered to be the top and sides of the berry baskets. The total exposed berry surface area was calculated to be 0.278 m^2.

Transpiration coefficients on a per unit mass basis (K_m) for Box A (2%O_2-15%CO_2), B (5%O_2-10%CO_2), C (2%O_2-10%CO_2), and D (5%O_2-15%CO_2) during 1998 storage season were 0.00079, 0.00086, 0.00027, and 0.00023 mg/s•kg•kPa, respectively. Transpiration coefficients on a per unit area basis (K_{area}) were for Box A, B, C, and D during 1998 storage season were 0.02383, 0.02585, 0.00819, and 0.00696 mg/s•m^2•kPa, respectively. Fruit from Box D (5%O_2-15%CO_2) had the lowest value of both K_m and K_{area}, while fruit from Box B (5%O_2-10%CO_2) had the highest value of both K_m and K_{area}. This observation supports the fact that actual differences in chamber humidity levels may have been less than the data indicate. The major reason of the difference between mass transfer coefficient values in each box should be the effects of oxygen and carbon dioxide concentration levels, which affect the respiratory heat generation, rather than the effects of differences in relative humidity levels.

5.5. CONCLUSIONS

Experiments were conducted to determine bulk mass transfer characteristics for Elliott blueberries in different controlled atmosphere conditions. Since fruits are normally stored in bulk, mass transfer rates were determined in bulk storage in refrigerated CA environments. Transpiration rates were constant once environmental condition stabilized. Accurate determination of fruit mass loss rate during storage is important to maintain fruit quality, therefore the availability of accurate transpiration coefficient data would be most applicable when used to estimate performance for fruit held for long periods in storage facilities.

Overall transpiration rates were 0.0005, 0.0002, and 0.0002 mg/s in the 1996, 1997, and 1998 storage seasons, respectively. The transpiration coefficient, on a per unit mass basis (K_m), for Box A (2%O_2-15%CO_2), B (5%O_2-10%CO_2), C (2%O_2-10%CO_2), and D (5%O_2-15%CO_2), during 1998 storage season, were 0.00079, 0.00086, 0.00027, and 0.00023 mg/s•kg•kPa, respectively. Transpiration coefficients on a per unit area basis (K_{area}), for Box A, B, C, and D during 1998 storage season, were 0.02383, 0.02585, 0.00819, and 0.00696 mg/s•m^2•kPa, respectively. Transpiration coefficients relate mass loss to vapor pressure differential between fruit surfaces and their environment. Mass loss of Elliott blueberries stored in controlled atmosphere environments has not been researched in the past. Therefore, the effects of a controlled atmosphere on transpiration coefficients have not been determined. Controlled atmosphere conditions of 5%O_2 and 15%CO_2 (Box D) provided the best result as far as mass transfer is concerned. Since relative humidity and surrounding air temperature in all CA test chambers were similar, the difference of transpiration coefficients for each CA condition could be attributed mainly to the affect of the oxygen and carbon dioxide levels presented in the CA test chambers.

CHAPTER 6

THESIS SUMMARY

The first part of this research was to determine if controlled atmosphere (CA) storage could be used to extend the market period of fresh Pacific Northwest Elliott blueberries and to evaluate the effects different storage atmospheres have on fruit quality. To summarize the results from the 1996, 1997, and 1998 experiments, the influence of storage duration on fruit quality attributes was more important than the atmospheric conditions, since storage duration significantly affects all fruit quality attributes. There were significant linear correlations between both O_2 and CO_2 levels and percentage weight loss of berries. As O_2 levels decreased from 5% to 2%, percentage weight loss of berries decreased. As CO_2 levels increased from 10% to 15%, percentage weight loss of berries decreased. Fruit held in 10% CO_2 lost more sugar and acid than those held in 15% CO_2. Oxygen alone is ineffective in controlling decay of blueberries. There were no significant interaction effects between O_2 and CO_2 on any fruit quality attributes except percentage weight loss. Firmness of blueberries was significantly correlated to CO_2 levels at each levels of oxygen. Blueberries stored in 15% CO_2 had higher firmness than fruit stored in 10% CO_2. Oxygen did not affect the firmness of blueberries after 52 and 93 days in storage

The benefit of high CO_2 on controlling decay of blueberries was positive. Carbon Dioxide levels of 10% and 15% can successfully retarded decay of berries for 93 days in storage. The controlled atmosphere of 5% O_2 and 15% CO_2 appeared to be the most effective in retaining quality in terms of better flavor, general appearance, less weight loss, low SS/Ac, and firmer after 52 and 93 days of storage. Berries held under atmospheres of 5% O_2 with 10% and 15% CO_2 had better general fruit appearance than fruit held under atmospheres of 2% O_2 with 10% and 15% CO_2 after 52 days and 93 days in storage. The best overall fruit flavors were found in fruit stored under atmospheres of 5% O_2 with 10% and 15% CO_2, both after 52 days and 93 days in storage. Based on the results, the combination of 5% O_2 with 15% CO_2 is found to be the optimum CA regime, which is a useful supplement for extending the postharvest life and quality of "Elliott" Blueberry fruits for approximately three months.

The second and the third part of this research also investigated heat and mass transfer characteristics during cooling and storage of fresh blueberries in controlled atmosphere environments. Based on the heat transfer results, the heat transfer coefficient in bulk berries changed principally with the basket position. The heat transfer coefficients decreased approximately 23%, 11%, 10%, and 30% between the edge of the first row and the center of the first, second, third, and fourth row, respectively. The half cooling times and seven-eighths cooling times decreased and the heat transfer coefficients increased with the increasing surface areas exposed to the cooling medium. The present method presented is a simple and useful tool to determine cooling process parameters in a practical cooling application. In conclusion, as the primary objective of a cooling study, usable data and technical information was produced, which can be used to improve existing cooling systems and provide optimum operating conditions for blueberry storage. Furthermore, the mass transfer characteristics of blueberry were conducted to determine transpiration rates and coefficients in CA chambers with controlled relative humidity (90-95% RH) to match relative humidity inside commercial storage. The transpiration coefficient, on a per unit mass basis (K_m), for Box A (2%O_2-15%CO_2), B (5%O_2-10%CO_2), C (2%O_2-10%CO_2), and D (5%O_2-15%CO_2), during 1998 storage season, were 0.00079, 0.00086, 0.00027, and 0.00023 mg/s•kg•kPa, respectively. Transpiration coefficients on a per unit area basis (K_{area}), for Box A, B, C, and D during 1998 storage season, were 0.02383, 0.02585, 0.00819, and 0.00696 mg/s•m^2•kPa, respectively. Controlled atmosphere conditions of 5%O_2 and 15%CO_2 (Box D) provided the best result as far as mass transfer is concerned. Since relative humidity and surrounding air temperature in all CA test chambers were similar, the difference of transpiration coefficients for each CA condition could be attributed mainly to the affect of the oxygen and carbon dioxide levels presented in the CA test chambers. Transpiration rates of berry were constant once environmental condition stabilized. Accurate determination of fruit mass loss rate during storage is important to maintain fruit quality, therefore the availability of accurate transpiration coefficient data would be most applicable when used to estimate performance for fruit held for long periods in storage facilities.

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APPENDICES

APPENDIX A

QUALITY DATA OF ELLIOTT BLUEBERRIES

Figure A.1. Scoresheet for the 9-point Hedonic Scale for consumer acceptance test of fresh blueberries.

EVALUATION OF FRESH BLUEBERRIES

Instructions

Place a mark in the box which you feel best describes how you like this product in overall appearance and overall flavor categories:

PLEASE EVALUATE SAMPLES FOLLOWING THE ORDER PRESENTED

Sample No. ________

Overall Appearance	like extreme- ly	like very much	like moder- ately	like slight- ly	neither like nor dislike	dislike slight- ly	dislike moder- ately	dislike very much	dislike extream- ly
Overall Flavor	like extreme- ly	like very much	like moder- ately	like slight- ly	neither like nor dislike	dislike slight- ly	dislike moder- ately	dislike very much	dislike extream- ly

Sample No. ________

Overall Appearance	like extreme- ly	like very much	like moder- ately	like slight- ly	neither like nor dislike	dislike slight- ly	dislike moder- ately	dislike very much	dislike extream- ly
Overall Flavor	like extreme- ly	like very much	like moder- ately	like slight- ly	neither like nor dislike	dislike slight- ly	dislike moder- ately	dislike very much	dislike extream- ly

THANK YOU

Comments: ______________________________

____

Name ______________________________ **Date** __________

TABLE A.1. Weight loss percentage during two storage periods in the 1996 storage season.

TREATMENT	MASS LOSS	
	52 days storage	80 days storage
BOX A ($2\%O_2/15\%CO_2$)	3.25%	1.26%
BOX B ($2\%O_2/5\%CO_2$)	3.41%	0.89%
BOX C ($5\%O_2/5\%CO_2$)	N/A	N/A
BOX D ($5\%O_2/15\%CO_2$)	3.34%	4.28%

TABLE A.2. Unmarketable fruit percentage (%) from various atmospheric conditions during two storage periods in the 1996 storage season.

TREATMENT	Unmarketable Fruit Percentage(1996)	
	53 days storage	80 days storage
BOX A ($2\%O_2/15\%CO_2$)		
REP 1	10.28%	20.31%
REP 2	6.65%	16.81%
AVE.	**8.47%**	**18.56%**
BOX B ($2\%O_2/5\%CO_2$)		
REP 1	9.41%	30.99%
REP 2	11.08%	23.17%
AVE.	**10.25%**	**27.08%**
BOX C ($5\%O_2/5\%CO_2$)		
REP 1	13.44%	23.30%
REP 2	11.51%	30.42%
AVE.	**12.48%**	**26.86%**
BOX D ($5\%O_2/15\%CO_2$)		
REP 1	3.37%	14.03%
REP 2	1.67%	15.57%
AVE.	**2.52%**	**14.80%**
WAREHOUSE ($5\%O_2/15\%CO_2$)		
REP 1	6.51%	N/A
REP 2	5.27%	N/A
AVE.	**5.89%**	N/A

TABLE A.3. Fruit pH from four different atmospheric conditions during two storage periods in the 1996 storage season.

Replication	BoxA ($2\%O_2/15\%CO_2$)		BoxB ($2\%O_2/5\%CO_2$)		BoxC ($5\%O_2/5\%CO_2$)		BoxD ($5\%O_2/15\%CO_2$)	
	53 days storage	80 days storage	53 days storage	80 days storage	53 days storage	80 days storage	53 days storage	80 days storage
1	3.55	3.61	3.61	3.73	3.57	3.72	3.57	3.68
2	3.52	3.62	3.63	3.69	3.58	3.75	3.57	3.62
3	3.53	3.58	3.61	3.71	3.61	3.77	3.61	3.65
Avg.	**3.53**	**3.60**	**3.62**	**3.71**	**3.59**	**3.75**	**3.58**	**3.65**

An average pH value of sample from warehouse after 53 days was 3.53

TABLE A.4. Soluble solids concentration (%) of fruit from different atmospheric conditions during two storage periods in the 1996 storage season.

Replication	BoxA ($2\%O_2/15\%CO_2$)		BoxB ($2\%O_2/5\%CO_2$)		BoxC ($5\%O_2/5\%CO_2$)		BoxD ($5\%O_2/15\%CO_2$)	
	53 days storage	80 days storage	53 days storage	80 days storage	53 days storage	80 days storage	53 days storage	80 days storage
1	16.8	16.7	17.5	15.2	17.8	14.2	16.6	16.5
2	16.0	16.3	17.3	15.8	17.0	14.8	17.0	16.2
3	16.5	16.5	17.0	15.5	17.7	14.2	16.2	16.0
Avg.	**16.4**	**16.0**	**17.3**	**15.5**	**17.5**	**14.4**	**16.6**	**16.2**

An average soluble solids value of sample from warehouse after 53 days was 15.00

TABLE A.5. Titrable acidity (as % Citric Acid) of fruit from different atmospheric conditions during two storage periods in the 1996 storage season.

Replication	BoxA ($2\%O_2/15\%CO_2$)		BoxB ($2\%O_2/5\%CO_2$)		BoxC ($5\%O_2/5\%CO_2$)		BoxD ($5\%O_2/15\%CO_2$)	
	53 days storage	80 days storage	53 days storage	80 days storage	53 days storage	80 days storage	53 days storage	80 days storage
1	0.69	0.65	0.62	0.46	0.65	0.46	0.68	0.57
2	0.70	0.58	0.58	0.48	0.63	0.46	0.63	0.55
3	0.65	0.65	0.61	0.49	0.61	0.43	0.65	0.61
Avg.	**0.68**	**0.63**	**0.60**	**0.48**	**0.63**	**0.45**	**0.65**	**0.58**

An average titrable acidity (as % Citric Acid) value of sample from warehouse after 53 days was 0.68

TABLE A.6. Sugar-acid ratio of fruit from different atmospheric conditions during two storage periods in the 1996 storage season.

Replication	BoxA ($2\%O_2/15\%CO_2$)		BoxB ($2\%O_2/5\%CO_2$)		BoxC ($5\%O_2/5\%CO_2$)		BoxD ($5\%O_2/15\%CO_2$)	
	53 days storage	80 days storage	53 days storage	80 days storage	53 days storage	80 days storage	53 days storage	80 days storage
1	24.35	25.69	28.23	33.04	27.38	30.87	24.41	28.95
2	22.86	28.10	29.83	32.92	26.98	32.17	26.98	29.45
3	25.38	25.38	27.87	31.63	29.02	33.02	24.92	26.23
Avg.	**24.12**	**25.40**	**28.83**	**32.29**	**27.78**	**32.00**	**25.54**	**27.93**

An average sugar-acid ratio value of sample from warehouse after 53 days was 22.06

TABLE A.7. Results from a 9-point hedonic scale scoresheet based on overall appearance after 53 days storage in the 1996 storage season.

CONSUMER NO.	BoxA ($2\%O_2/15\%CO_2$)	BoxB ($2\%O_2/5\%CO_2$)	BoxC ($5\%O_2/5\%CO_2$)	BoxD ($5\%O_2/15\%CO_2$)	Warehouse ($5\%O_2/15\%CO_2$)
1	6	8	3	7	4
2	4	4	4	8	5
3	4	5	5	4	3
4	7	7	7	7	6
5	7	7	8	8	9
6	5	5	7	8	8
7	9	7	7	8	8
8	7	4	3	7	5
9	7	6	6	5	3
10	7	8	7	9	7
11	5	7	6	5	7
12	8	2	7	8	7
13	8	8	7	8	4
14	6	7	7	6	2
15	5	4	4	5	5
16	4	4	4	4	3
17	6	7	7	6	5
18	8	7	8	7	3
19	7	7	7	7	7
20	6	6	6	7	7
21	8	7	7	8	8
22	5	7	4	8	6
23	2	8	3	8	6
24	7	7	3	5	8
25	6	7	6	4	4
AVG.	**6.2**	**6.2**	**5.7**	**6.7**	**5.6**

A hedonic scale of 1 to 9 :
9 = like extremely, 8= like very much, 7= like moderately, 6=like slightly, 5= neither like nor dislike, 4= dislike slightly, 3=dislike moderately, 2= dislike very much, 1= dislike extremely.

TABLE A.8. Results from a 9-point hedonic scale scoresheet based on overall flavor after 53 days storage in the 1996 storage season.

CONSUMER NO.	BoxA ($2\%O_2/15\%CO_2$)	BoxB ($2\%O_2/5\%CO_2$)	BoxC ($5\%O_2/5\%CO_2$)	BoxD ($5\%O_2/15\%CO_2$)	Warehouse ($5\%O_2/15\%CO_2$)
1	4	8	4	8	7
2	6	5	5	5	5
3	6	7	7	7	6
4	6	5	3	5	6
5	4	7	5	7	9
6	2	7	4	7	8
7	6	5	6	5	9
8	7	6	2	6	4
9	4	7	5	7	4
10	3	4	5	6	8
11	4	8	7	5	7
12	6	3	5	7	8
13	8	7	6	5	6
14	4	6	4	6	4
15	6	4	5	6	6
16	3	3	2	3	4
17	5	2	8	3	8
18	4	2	2	1	6
19	1	3	2	6	3
20	6	6	6	7	7
21	4	7	7	8	8
22	6	2	4	2	7
23	2	8	2	9	8
24	8	7	5	3	8
25	7	8	4	6	6
AVG.	**4.9**	**5.5**	**4.6**	**5.6**	**6.5**

A hedonic scale of 1 to 9 :

9 = like extremely, 8= like very much, 7= like moderately, 6=like slightly, 5= neither like nor dislike, 4= dislike slightly, 3=dislike moderately, 2= dislike very much, 1= dislike extremely

TABLE A.9. Berry firmness expressed as compression force in grams during two storage periods in the 1996 storage season.

Replication No.	BoxA ($2\%O_2/15\%CO_2$)		BoxB ($2\%O_2/5\%CO_2$)		BoxC ($5\%O_2/5\%CO_2$)		BoxD ($5\%O_2/15\%CO_2$)		Warehouse ($5\%O_2/15\%CO_2$)
	53 days	80 days	53 days	80 days	53 day	80 days	53 days	80 days	53 days
1	734	613	1006	1317	629	306	980	961	1460
2	789	556	550	440	1677	361	620	573	1164
3	1145	704	1274	505	572	312	1032	731	1300
4	515	1406	445	363	938	384	937	722	1157
5	759	777	1399	1114	1429	378	1833	698	856
6	615	824	600	266	940	925	1181	1003	829
7	954	506	1066	676	546	370	1678	1243	898
8	1113	781	750	479	1011	925	1547	1661	1175
9	729	709	1529	514	501	312	1688	1022	1025
10	629	669	944	425	1667	259	997	1124	1089
11	879	656	927	859	740	282	720	1437	643
12	507	818	389	890	396	599	618	476	1239
13	722	667	776	778	899	874	533	1106	1400
14	597	610	1541	956	454	421	1028	1395	1064
15	798	547	649	626	595	146	1395	691	831
16	740	474	1718	650	476	265	652	989	918
17	606	856	479	555	363	363	1588	1031	1705
18	884	1006	535	846	501	265	1047	1226	1282
19	1014	416	1808	562	370	169	632	825	1295
20	836	1156	540	361	432	116	638	557	1299
21	659	662	418	516	1093	238	883	603	1080
22	807	573	380	474	448	341	775	1444	1075
23	772	609	563	871	494	148	1047	684	1517
24	1039	522	857	329	708	619	823	2066	887
25	905	472	808	288	728	424	2050	1435	1632
26	697	477	1039	985	515	358	651	706	1616
27	740	580	510	418	301	341	503	927	1181
28	760	883	1053	1087	586	792	1360	956	1373
29	760	388	871	997	830	352	1016	654	1046
30	921	844	1236	734	751	274	9888	794	673
31	665	552	959	892	453	469	820	653	1340
32	984	719	682	640	1047	159	463	909	1079
33	531	735	1148	1183	514	409	1425	1230	1470
34	701	909	791	269	1285	595	1273	865	1460
35	559	765	1025	1006	403	306	1093	1657	971
36	531	822	1167	570	541	215	844	1077	1989
37	710	683	675	304	734	448	679	1206	1460
38	1065	715	1085	756	588	372	1751	953	1679
39	519	825	639	575	609	176	763	1561	940
40	868	542	431	166	579	335	1368	1051	1598
41	1578	935	816	239	736	227	1587	1043	1423
42	879	570	844	524	692	135	999	1032	1422
43	649	1048	767	366	336	210	1931	683	1046
44	982	390	788	358	403	441	535	589	903
45	896	578	710	486	419	217	729	387	1479
46	769	1201	567	392	407	157	1083	653	992
47	765	719	1281	428	1213	164	617	909	1679
48	531	869	1079	632	631	185	1658	1230	903
49	640	720	653	814	405	574	644	865	1373
50	649	754	427	455	419	338	689	854	1598
AVG.(gm)	**782**	**716**	**864**	**619**	**680**	**361**	**1226**	**983**	**1230**

TABLE A.10. Weight loss percentage during two storage periods from various atmospheric conditions in the 1997 storage season.

TREATMENT	MASS LOSS	
	52 days storage	93 days storage
BOX A (2%O_2/15%CO_2)	1.73%	2.55%
BOX B (5%O_2/10%CO_2)	1.81%	2.42%
BOX C (2%O_2/10%CO_2)	1.04%	1.80%
BOX D (5%O_2/15%CO_2)	1.56%	2.41%

TABLE A.11. Unmarketable Fruit Percentage from various atmospheric conditions during two storage periods in the 1997 storage season.

TREATMENT	Unmarketable Fruit Percentage (1997)	
	52 days storage	93 days storage
BOX A (2%O_2/15%CO_2)		
REP 1	10.24%	16.28%
REP 2	12.72%	14.58%
REP 3	10.97%	18.75%
AVG.	**11.31%**	**16.54%**
BOX B (5%O_2/10%CO_2)		
REP 1	10.87%	22.35%
REP 2	9.71%	23.17%
REP 3	12.04%	19.58%
AVG.	**10.87%**	**21.70%**
BOX C (2%O_2/10%CO_2)		
REP 1	12.07%	30.92%
REP 2	12.38%	27.63%
REP 3	11.51%	26.74%
AVG.	**11.99%**	**28.43%**
BOX D (5%O_2/15%CO_2)		
REP 1	11.83%	19.80%
REP 2	8.94%	20.91%
REP 3	9.23%	21.65%
AVG.	**10.00%**	**20.79%**

TABLE A.12. Fruit pH from four different atmospheric conditions during two storage periods in the 1997 storage season.

Replication	Initial value 8/25/97	BoxA ($2\%O_2/15\%CO_2$)		BoxB ($5\%O_2/10\%CO_2$)		BoxC ($2\%O_2/10\%CO_2$)		BoxD ($5\%O_2/15\%CO_2$)	
		52 days storage	93 days storage	52 days storage	93 days storage	52 days storage	93 days storage	52 days storage	93 days storage
1	2.90	3.09	3.35	3.37	3.57	3.27	3.45	3.20	3.37
2	2.88	3.17	3.37	3.22	3.60	3.33	3.39	3.24	3.40
3	2.93	3.19	3.29	3.30	3.55	3.28	3.43	3.17	3.31
Avg.	**2.90**	**3.15**	**3.34**	**3.30**	**3.57**	**3.29**	**3.42**	**3.20**	**3.36**

TABLE A.13. Soluble solids concentration (%) of fruit from different atmospheric conditions during two storage periods in the 1997 storage season.

Replication	Initial value 8/25/97	BoxA ($2\%O_2/15\%CO_2$)		BoxB ($5\%O_2/10\%CO_2$)		BoxC ($2\%O_2/10\%CO_2$)		BoxD ($5\%O_2/15\%CO_2$)	
		52 days storage	93 days storage	52 days storage	93 days storage	52 days storage	93 days storage	52 days storage	93 days storage
1	13.5	13.8	16.0	18.4	20.2	16.8	18.2	14.5	18.5
2	13.8	14.5	16.3	18.5	20.8	17.0	17.8	14.7	18.2
3	13.1	14.1	15.8	18.6	19.8	15.2	17.9	14.2	18.3
Avg.	**13.5**	**14.1**	**16.0**	**18.5**	**20.3**	**16.3**	**18.0**	**14.5**	**18.3**

TABLE A.14. Titrable acidity (as % Citric Acid) of fruit from different atmospheric conditions during two storage periods in the 1997 storage season.

Replication	Initial value 8/25/97	BoxA ($2\%O_2/15\%CO_2$)		BoxB ($5\%O_2/10\%CO_2$)		BoxC ($2\%O_2/10\%CO_2$)		BoxD ($5\%O_2/15\%CO_2$)	
		52 days storage	93 days storage	52 days storage	93 days storage	52 days storage	93 days storage	52 days storage	93 days storage
1	0.93	0.90	0.75	0.82	0.63	0.83	0.67	0.91	0.68
2	0.91	0.88	0.74	0.77	0.69	0.81	0.69	0.85	0.70
3	0.93	0.89	0.75	0.81	0.67	0.75	0.72	0.83	0.75
Avg.	**0.92**	**0.89**	**0.75**	**0.80**	**0.66**	**0.83**	**0.69**	**0.86**	**0.71**

TABLE A.15. Sugar-acid ratio of fruit from different atmospheric conditions during two storage periods in the 1997 storage season.

Replication	Initial value 8/25/97	BoxA ($2\%O_2/15\%CO_2$)		BoxB ($5\%O_2/10\%CO_2$)		BoxC ($2\%O_2/10\%CO_2$)		BoxD ($5\%O_2/15\%CO_2$)	
		52 days storage	93 days storage	52 days storage	93 days storage	52 days storage	93 days storage	52 days storage	93 days storage
1	14.52	15.33	21.33	22.44	32.06	20.24	27.16	15.93	27.21
2	15.16	16.48	22.03	24.03	30.14	20.99	25.80	17.29	26.00
3	14.09	15.84	21.07	22.96	29.55	20.27	24.86	17.11	24.40
Avg.	**14.67**	**15.84**	**21.33**	**23.13**	**30.76**	**19.64**	**26.09**	**16.86**	**25.77**

TABLE A.16. Results from a 9-point hedonic scale scoresheet based on overall appearance after 52 days storage in the 1997 storage season.

CONSUMER NO.	INITIAL VALUE (0 DAY)	BOX A ($2\%O_2/15\%CO_2$)	BOX B ($5\%O_2/10\%CO_2$)	BOX C ($2\%O_2/10\%CO_2$)	BOX D ($5\%O_2/15\%CO_2$)
1	7	8	8	8	8
2	7	7	8	7	7
3	8	6	6	8	6
4	8	7	8	7	7
5	9	8	8	4	4
6	8	7	6	6	5
7	8	6	7	8	7
8	8	4	8	8	9
9	8	7	7	6	8
10	8	7	7	5	7
11	8	8	8	4	3
12	8	7	8	5	6
13	6	8	9	7	8
14	7	7	7	7	8
15	7	8	8	7	8
16	7	6	7	7	7
17	8	8	9	7	9
18	8	8	7	8	4
19	8	5	7	8	5
20	8	9	8	7	8
21	6	8	7	8	7
22	7	7	7	7	6
23	8	7	8	7	8
24	8	7	7	7	7
25	7	6	7	4	7
26	8	7	7	7	7
27	7	4	5	5	5
28	9	7	7	7	7
29	6	7	9	8	7
30	7	8	8	8	8
AVG.	**7.6**	**7.0**	**7.4**	**6.7**	**6.8**

A hedonic scale of 1 to 9 :
9 = like extremely, 8= like very much, 7= like moderately, 6=like slightly, 5= neither like nor dislike, 4= dislike slightly, 3=dislike moderately, 2= dislike very much, 1= dislike extremely

TABLE A.17. Results from a 9-point hedonic scale scoresheet based on overall flavor after 52 days storage in the 1997 storage season.

CONSUMER NO.	INITIAL VALUE (0 DAY)	BOX A ($2\%O_2/15\%CO_2$)	BOX B ($5\%O_2/10\%CO_2$)	BOX C ($2\%O_2/10\%CO_2$)	BOX D ($5\%O_2/15\%CO_2$)
1	7	2	3	9	4
2	7	4	7	6	4
3	8	4	6	7	3
4	8	6	8	3	4
5	9	3	8	2	4
6	8	7	5	7	6
7	8	5	6	6	3
8	7	3	6	7	8
9	8	7	5	7	6
10	7	4	7	2	6
11	8	3	6	2	6
12	8	7	8	2	6
13	7	7	8	7	7
14	8	4	5	7	8
15	7	7	5	6	8
16	8	6	8	8	6
17	8	7	9	4	8
18	8	3	8	8	6
19	8	5	6	7	2
20	8	7	7	2	5
21	8	6	3	3	6
22	7	5	7	8	5
23	8	4	7	7	5
24	7	6	7	4	8
25	8	4	8	4	4
26	6	5	7	5	7
27	9	3	8	6	5
28	7	3	7	4	7
29	7	5	8	6	8
30	8	5	5	4	4
AVG.	7.7	**4.9**	**6.6**	**5.3**	**5.6**

A hedonic scale of 1 to 9 :
9 = like extremely, 8= like very much, 7= like moderately, 6=like slightly, 5= neither like nor dislike, 4= dislike slightly, 3=dislike moderately, 2= dislike very much, 1= dislike extremely

TABLE A.18. Berry firmness expressed as compression force in grams during two storage periods in the 1997 storage season.

Replication No.	Initial Value (0 day)	BoxA $(2\%O_2/15\%CO_2)$		BoxB $(5\%O_2/10\%CO_2)$		BoxC $(2\%O_2/10\%CO_2)$		BoxD $(5\%O_2/15\%CO_2)$	
		52 days	93 days	52 days	93 days	52 days	93 days	53 days	93 days
1	1627	1105	895	1307	1112	726	973	1378	1040
2	1376	1043	618	1258	1056	1225	811	1228	847
3	1305	1214	989	1213	1588	1131	943	1459	742
4	1619	1069	824	908	1395	1372	975	1587	1107
5	1462	987	912	1199	1447	1583	906	1366	707
6	1355	1305	925	1274	954	1408	1043	1306	772
7	1413	1343	1147	1098	1221	826	1002	1423	1413
8	1272	1219	1078	1298	1698	729	811	1259	1074
9	1346	988	996	1185	963	787	985	1632	902
10	1508	963	873	1669	879	1113	1054	1264	991
11	1622	1122	925	1102	1098	1127	987	1336	976
12	1360	1079	899	1298	1047	1165	1029	1278	1030
13	1280	1069	746	989	1105	1253	988	988	1336
14	1430	902	875	1113	1225	1354	996	1299	1392
15	1225	1085	1231	1324	1031	909	944	1227	1024
16	1604	1036	1247	1430	1022	908	1123	1182	1102
17	1392	1063	1024	855	1325	1079	1045	1702	1064
18	1304	991	972	1465	1254	1070	1006	1547	968
19	1593	906	852	1563	1089	1054	866	1389	789
20	1503	1145	698	987	1127	1336	854	882	1215
21	1634	1042	1222	1145	1183	1590	1069	1288	1458
22	1036	1053	1328	1298	1085	1002	948	1107	1298
23	1341	1236	776	1789	1042	1065	1210	896	1057
24	1168	1106	916	1686	1116	1042	836	1311	1169
25	1344	1078	855	808	987	1053	879	852	1168
26	1224	1456	883	1039	1456	991	964	1365	901
27	1651	964	775	1352	1174	1080	957	1296	1214
28	1513	1079	927	1053	1268	1097	984	1360	1283
29	1449	965	689	871	998	1526	978	1039	995
30	1596	1025	945	1236	1051	1289	874	1025	789
31	1274	1144	1147	959	1777	997	860	823	986
32	1487	1056	1203	1469	1085	839	1079	1261	987
33	1478	897	1078	1148	1179	1277	874	1304	1130
34	1492	1247	1095	1389	1005	1524	954	1178	1285
35	1298	1289	1061	1025	965	1258	848	1358	1369
36	1789	1102	888	1167	1297	1369	854	1654	1074
37	1560	976	794	1555	756	1463	922	1287	1213
38	1649	1063	859	1298	1146	1078	874	1165	1198
39	1509	1053	995	1470	1289	912	919	1263	888
40	1378	868	896	1379	1363	1115	853	1547	987
41	1423	997	999	1481	982	1274	976	1087	1178
42	1422	1066	871	1365	987	1098	958	1298	921
43	1246	1247	863	1397	653	1297	867	1539	1376
44	1356	982	652	1721	1431	851	987	1147	1287
45	1398	955	1071	1277	1222	1289	966	898	1360
46	1487	748	908	898	944	962	975	1478	1141
47	1596	1004	1075	955	961	1795	986	969	1222
48	1598	1201	968	1478	1193	1261	1102	1264	1234
49	1374	992	745	1254	1230	1275	864	1269	944
50	1675	1256	857	1222	959	1157	978	1472	993
AVG.(gm)	**1441**	**1076**	**955**	**1254**	**1148**	**1160**	**941**	**1271**	**1092**

TABLE A.19. Minolta Chromameter L*a*b* Values, Chroma, and Hue angle of berry from different atmospheric conditions during two storage periods in the 1997 storage season.

Treatment	L*value		a*value		b*value		Chroma		Hue angle	
	52 days storage	93days storage	52 days storage	93days storage	52 days storage	93days storage	52 days storage	93days storage	52 days storage	93days storage
BOX A ($2\%O_2/15\%CO_2$)	34.27	33.91	0.62	1.07	-3.92	-3.85	3.97	4.00	278.99	285.53
BOX B ($5\%O_2/10\%CO_2$)	33.98	33.50	0.97	1.55	-3.55	-3.98	3.68	4.27	283.76	285.28
BOX C ($2\%O_2/10\%CO_2$)	32.87	32.54	0.72	1.06	-3.87	-4.14	3.94	4.31	277.34	280.54
BOX D ($5\%O_2/15\%CO_2$)	34.07	33.62	0.95	1.07	-4.07	-4.73	4.17	4.85	283.14	282.75

Initial L*, a*, b*, chroma, and hue angle values were 35.15, 0.45, -3.58, 3.61, and 277.16, respectively.

TABLE A.20. Weight loss percentage during two storage periods in 1998 storage season.

TREATMENT	MASS LOSS	
	52 days storage	93 days storage
BOX A ($2\%O_2/15\%CO_2$)	1.50%	2.27%
BOX B ($5\%O_2/10\%CO_2$)	1.37%	1.88%
BOX C ($2\%O_2/10\%CO_2$)	0.94%	1.44%
BOX D ($5\%O_2/15\%CO_2$)	1.12%	2.01%

TABLE A.21. Unmarketable fruit percentage from various atmospheric conditions during two storage periods in the 1998 storage season.

TREATMENT	Unmarketable Fruit %(1998) 52days storage	TREATMENT	Unmarketable Fruit %(1998) 93 days storage
BOX A (2%O2/15%CO2)		BOX A (2%O2/15%CO2)	
Pint # 05	14.79%	Pint # 06	26.18%
Pint # 10	13.57%	Pint # 07	23.36%
Pint # 01	13.62%	Pint # 14	24.80%
Pint # 11	14.25%	Pint # 19	22.58%
Pint # 04	13.27%	Pint # 22	22.50%
AVG.	**13.90%**	**AVG.**	**23.88%**
BOX B (5%O2/10%CO2)		BOX B (5%O2/10%CO2)	
Pint # 14	13.29%	Pint # 01	17.18%
Pint # 05	12.92%	Pint # 16	20.89%
Pint # 15	16.02%	Pint # 18	22.90%
Pint # 13	15.82%	Pint # 19	21.33%
Pint # 10	13.53%	Pint # 17	18.78%
AVG.	**14.31%**	**AVG.**	**20.22%**
BOX C (2%O_2/10%CO_2)		BOX C (2%O_2/10%CO_2))	
Pint # 05	13.56%	Pint # 24	15.28%
Pint # 11	8.71%	Pint # 06	13.09%
Pint # 12	12.73%	Pint # 09	14.82%
Pint # 03	11.06%	Pint # 12	16.38%
Pint # 10	10.36%	Pint # 20	13.74%
AVG.	**11.28%**	**AVG.**	**14.66%**
BOX D (5%O_2/15%CO_2)		BOX D (5%O_2/15%CO_2)	
Pint # 03	11.33%	Pint # 13	17.88%
Pint # 09	12.27%	Pint # 08	14.61%
Pint # 14	11.70%	Pint # 16	15.29%
Pint # 11	11.47%	Pint # 23	14.61%
Pint # 22	11.63%	Pint # 15	16.35%
AVG.	**11.68%**	**AVG.**	**15.75%**

TABLE A.22. Fruit pH from four different atmospheric conditions in the 1998 storage season.

Replication NO.	Initial Value (8/24/98)	Box A ($2\%O_2/15\%CO_2$)		Box B ($5\%O_2/10\%CO_2$)		Box C ($2\%O_2/10\%CO_2$)		Box D ($5\%O_2/15\%CO_2$)	
		52days storage	93days storage	52days storage	93days storage	52days storage	93days storage	52days storage	93days storage
1	2.87	3.19	3.29	3.38	3.63	3.30	3.61	3.24	3.51
2	3.18	3.21	3.32	3.38	3.59	3.33	3.57	3.20	3.53
3	2.85	3.19	3.31	3.35	3.60	3.31	3.60	3.23	3.49
4	3.21	3.20	3.28	3.31	3.62	3.33	3.59	3.20	3.47
5	2.81	3.23	3.30	3.39	3.60	3.31	3.60	3.21	3.55
AVG	**2.98**	**3.20**	**3.31**	**3.36**	**3.61**	**3.32**	**3.59**	**3.25**	**3.51**

TABLE A.23. Soluble solids concentration (%) of fruit from different atmospheric conditions in the 1998 storage season.

Replication NO.	Initial Value (8/24/98)	Box A ($2\%O_2/15\%CO_2$)		Box B ($5\%O_2/10\%CO_2$)		Box C ($2\%O_2/10\%CO_2$)		Box D ($5\%O_2/15\%CO_2$)	
		52days storage	93days storage	52days storage	93days storage	52days storage	93days storage	52days storage	93days storage
1	15.4	16.2	17.3	17.7	19.1	16.8	17.6	16.5	18.0
2	15.8	16.5	17.5	18.0	18.8	17.1	17.8	16.6	18.2
3	15.2	16.0	17.9	17.8	19.0	17.0	17.7	16.5	17.8
4	15.7	16.2	18.0	17.8	19.2	17.2	17.9	16.4	17.9
5	15.5	16.5	17.7	17.7	18.8	16.9	17.7	16.5	18.0
AVG	**15.5**	**16.3**	**17.7**	**17.8**	**19.0**	**17.0**	**17.7**	**16.5**	**18.0**

TABLE A.24. Titrable acidity (as % Citric Acid) of fruit from different atmospheric conditions in the 1998 storage season.

Replication NO.	Initial Value (8/24/98)	Box A ($2\%O_2/15\%CO_2$)		Box B ($5\%O_2/10\%CO_2$)		Box C ($2\%O_2/10\%CO_2$)		Box D ($5\%O_2/15\%CO_2$)	
		52days storage	93days storage	52days storage	93days storage	52days storage	93days storage	52days storage	93days storage
1	0.87	0.85	0.71	0.80	0.65	0.79	0.66	0.77	0.69
2	0.87	0.82	0.73	0.79	0.68	0.78	0.67	0.78	0.67
3	0.90	0.80	0.70	0.76	0.65	0.80	0.66	0.77	0.67
4	0.88	0.82	0.70	0.77	0.65	0.80	0.65	0.76	0.68
5	0.89	0.82	0.70	0.78	0.67	0.77	0.65	0.77	0.67
AVG	**0.88**	**0.82**	**0.71**	**0.78**	**0.66**	**0.79**	**0.66**	**0.77**	**0.68**

TABLE A.25. Sugar-acid ratio of fruit from different atmospheric conditions in the 1998 storage season.

Replication NO.	Initial Value (8/24/98)	Box A ($2\%O_2/15\%CO_2$)		Box B ($5\%O_2/10\%CO_2$)		Box C ($2\%O_2/10\%CO_2$)		Box D ($5\%O_2/15\%CO_2$)	
		52days storage	93days storage	52days storage	93days storage	52days storage	93days storage	52days storage	93days storage
1	17.70	19.06	24.37	22.13	29.38	21.27	26.67	21.43	26.09
2	18.16	20.12	23.97	22.78	27.65	21.92	26.57	21.28	27.16
3	16.89	20.00	25.57	23.42	29.23	21.25	26.82	21.43	26.57
4	17.84	19.76	25.71	23.12	29.54	21.50	27.54	21.58	26.32
5	17.42	20.12	25.29	22.69	28.06	21.95	27.23	21.43	26.87
AVG	**17.60**	**19.81**	**24.98**	**22.83**	**28.77**	**21.58**	**26.96**	**21.43**	**26.60**

TABLE A.26. Results from a 9-point hedonic scale scoresheet based on overall appearance after 52days storage in the 1998 storage season.

CONSUMER NO.	INITIAL VALUE (0 DAY)	BOX A ($2\%O_2/15\%CO_2$)	BOX B ($5\%O_2/10\%CO_2$)	BOX C ($2\%O_2/10\%CO_2$)	BOX D ($5\%O_2/15\%CO_2$)
1	8	8	8	8	8
2	8	7	8	8	7
3	7	7	7	7	7
4	7	7	7	7	7
5	8	4	5	5	6
6	7	6	7	4	7
7	8	7	7	7	7
8	9	8	8	7	8
9	8	7	7	7	7
10	8	8	7	8	7
11	8	9	8	7	8
12	8	5	7	8	5
13	9	8	7	8	8
14	6	7	8	7	9
15	8	6	7	7	7
16	8	8	8	7	8
17	7	8	8	7	8
18	8	6	8	5	7
19	7	8	8	4	6
20	8	7	6	5	7
21	7	4	8	8	9
22	8	6	7	8	7
23	8	7	6	6	7
24	8	8	7	4	6
25	7	7	7	7	7
26	7	6	6	7	7
27	8	7	8	7	7
28	7	8	8	8	8
29	8	7	7	7	8
30	7	7	7	6	8
AVG.	**7.7**	**6.9**	**7.2**	**6.7**	**7.3**

A hedonic scale of 1 to 9 :
9 = like extremely, 8= like very much, 7= like moderately, 6=like slightly, 5= neither like nor dislike, 4= dislike slightly, 3=dislike moderately, 2= dislike very much, 1= dislike extremely

TABLE A.27. Results from a 9-point hedonic scale scoresheet based on overall flavor after 52days storage in the 1998 storage season.

CONSUMER NO.	INITIAL VALUE (0 DAY)	BOX A ($2\%O_2/15\%CO_2$)	BOX B ($5\%O_2/10\%CO_2$)	BOX C ($2\%O_2/10\%CO_2$)	BOX D ($5\%O_2/15\%CO_2$)
1	8	5	7	8	7
2	7	5	8	4	8
3	6	5	7	6	7
4	6	3	6	6	7
5	8	3	4	8	6
6	6	4	8	5	4
7	7	6	7	4	8
8	8	5	7	4	4
9	8	5	7	7	8
10	7	6	3	8	6
11	9	7	7	3	7
12	7	5	6	2	5
13	7	3	8	7	7
14	7	7	7	8	8
15	8	6	8	4	6
16	8	7	6	8	7
17	8	7	8	7	7
18	7	7	8	7	7
19	6	3	6	2	7
20	7	4	7	2	6
21	7	3	6	6	8
22	6	5	6	6	3
23	9	7	5	7	6
24	7	3	7	2	5
25	7	6	7	3	4
26	6	4	6	6	6
27	8	4	7	6	8
28	7	1	3	9	8
29	8	4	5	6	8
30	7	6	6	7	7
AVG.	**7.2**	**4.9**	**6.4**	**5.6**	**6.5**

A hedonic scale of 1 to 9 :
9 = like extremely, 8= like very much, 7= like moderately, 6=like slightly, 5= neither like nor dislike, 4= dislike slightly, 3=dislike moderately, 2= dislike very much, 1= dislike extremely

TABLE A.28. Results from a 9-point hedonic scale scoresheet based on overall appearance after 93 days storage in the 1998 storage season.

CONSUMER NO.	INITIAL VALUE (0 DAY)	BOX A ($2\%O_2/15\%CO_2$)	BOX B ($5\%O_2/10\%CO_2$)	BOX C ($2\%O_2/10\%CO_2$)	BOX D ($5\%O_2/15\%CO_2$)
1	8	4	5	7	8
2	8	6	6	7	6
3	7	8	8	8	8
4	7	6	6	5	5
5	8	7	7	7	7
6	7	6	8	7	8
7	8	8	8	8	8
8	9	8	6	5	5
9	8	7	9	8	8
10	8	5	6	5	7
11	8	7	8	8	8
12	8	8	8	8	8
13	9	6	8	6	5
14	6	6	6	6	7
15	8	2	6	6	7
16	8	4	6	8	6
17	7	7	5	3	7
18	8	6	6	8	8
19	7	5	6	7	6
20	8	7	4	6	4
21	7	6	5	5	5
22	8	6	7	6	5
23	8	7	7	6	8
24	8	5	6	5	6
25	7	6	7	5	7
26	7	4	5	6	6
27	8	5	5	6	6
28	7	5	6	4	6
29	8	3	5	4	5
30	7	7	8	6	7
AVG.	7.7	**5.9**	**6.4**	**6.2**	**6.6**

A hedonic scale of 1 to 9 :
9 = like extremely, 8= like very much, 7= like moderately, 6=like slightly, 5= neither like nor dislike, 4= dislike slightly, 3=dislike moderately, 2= dislike very much, 1= dislike extremely

TABLE A.29. Results from a 9-point hedonic scale scoresheet based on overall flavor after 93 days storage in the 1998 storage season.

CONSUMER NO.	INITIAL VALUE (0 DAY)	BOX A ($2\%O_2/15\%CO_2$)	BOX B ($5\%O_2/10\%CO_2$)	BOX C ($2\%O_2/10\%CO_2$)	BOX D ($5\%O_2/15\%CO_2$)
1	8	7	8	8	4
2	7	7	6	7	6
3	6	4	6	7	4
4	6	5	7	3	6
5	8	6	5	6	8
6	6	4	7	8	5
7	7	3	7	5	6
8	8	4	5	5	6
9	8	7	8	8	4
10	7	5	7	8	5
11	9	7	8	7	8
12	7	5	6	7	7
13	7	6	8	6	4
14	7	7	4	7	6
15	8	4	6	4	8
16	8	4	6	8	6
17	8	7	6	4	8
18	7	7	5	8	8
19	6	4	6	7	7
20	7	7	6	7	4
21	7	2	5	3	3
22	6	5	5	5	8
23	9	6	7	5	7
24	7	4	5	4	6
25	7	5	5	4	6
26	6	5	6	6	7
27	8	6	6	5	7
28	7	6	7	5	7
29	8	7	7	6	7
30	7	6	6	5	4
AVG.	**7.2**	**5.4**	**6.2**	**5.9**	**6.1**

A hedonic scale of 1 to 9 :
9 = like extremely, 8= like very much, 7= like moderately, 6=like slightly, 5= neither like nor dislike, 4= dislike slightly, 3=dislike moderately, 2= dislike very much, 1= dislike extremely

TABLE A.30. Berry firmness expressed as compression force in grams in the 1998 storage season.

Replication No.	Initial Value (0 day)	BoxA ($2\%O_2/15\%CO_2$)		BoxB ($5\%O_2/10\%CO_2$)		BoxC ($2\%O_2/10\%CO_2$)		BoxD ($5\%O_2/15\%CO_2$)	
		52 days	93 days	52 days	93 days	52 days	93 days	53 days	93 days
1	1223	895	575	1343	961	998	853	1180	915
2	1320	765	1137	1061	845	1127	916	1291	847
3	1097	1100	875	945	918	906	862	945	984
4	1193	596	589	918	880	916	815	1030	1051
5	1085	687	652	1307	848	962	780	1094	1010
6	987	1015	503	1021	1083	1097	799	978	1106
7	1245	990	782	1245	854	961	857	1141	1078
8	1263	1388	709	984	992	1017	796	974	987
9	1310	841	601	931	831	916	531	1210	911
10	1007	855	624	947	990	836	658	1106	872
11	1154	805	876	1005	881	870	788	999	1064
12	1268	607	720	951	1002	875	916	1214	949
13	945	851	1125	905	863	998	682	973	974
14	1013	706	632	1037	1001	1170	789	949	755
15	1255	513	572	977	966	962	616	1158	986
16	1287	1107	726	1365	910	824	837	1097	741
17	1147	847	527	1299	1013	926	624	1241	899
18	1098	881	1041	1080	841	906	874	991	950
19	1254	927	415	874	867	874	711	1097	865
20	1299	823	1094	911	756	1127	897	1281	955
21	1432	806	835	1017	1157	987	987	949	857
22	1078	898	839	1039	905	974	798	979	956
23	1194	999	689	971	845	1239	659	1075	852
24	1241	1013	734	1097	796	1045	926	1145	796
25	1326	877	819	978	1007	789	880	877	800
26	1237	905	986	1327	873	852	889	987	719
27	1179	643	796	1005	978	796	745	1018	818
28	1258	985	1085	1264	824	1228	791	985	974
29	1057	1287	812	920	962	998	810	988	863
30	1312	854	567	1178	735	867	733	1102	743
31	1265	1174	727	978	848	743	882	1094	894
32	1103	890	629	922	780	1136	875	1063	890
33	1356	879	937	937	678	893	810	882	835
34	1098	882	1072	1329	997	934	799	991	1078
35	1277	967	545	993	1054	1145	821	1030	947
36	1132	883	797	1005	987	1056	932	1187	935
37	1053	676	823	1391	881	1145	841	1116	945
38	1222	840	847	911	848	1027	796	1057	977
39	1247	732	758	1210	987	968	774	1122	835
40	1264	759	634	897	989	971	875	936	871
41	1165	967	659	1115	883	1106	819	1216	743
42	1107	938	798	1391	769	934	823	879	883
43	1287	1067	894	1007	915	1078	915	1058	949
44	1355	1172	967	1080	811	799	879	1032	905
45	1244	1045	663	985	1069	1037	798	1124	863
46	1278	919	987	853	987	1156	867	861	978
47	1178	1111	1003	816	995	995	832	978	1124
48	1285	1259	798	967	778	1021	743	1273	977
49	1342	756	644	1175	883	1078	875	1195	911
50	1277	962	893	980	876	985	801	1048	1021
AVG.(gm)	**1206**	**907**	**780**	**1057**	**908**	**985**	**812**	**1064**	**917**

TABLE A.31. Minolta Chromameter L*a*b* Values, Chroma, and Hue angle of berry from different atmospheric conditions in the 1998 storage season.

Treatment	L*value		a*value		b*value		Chroma		Hue angle	
	52 days storage	93days storage	52 days storage	93days storage	52 days storage	93days storage	52 days storage	93days storage	52 days storage	93days storage
BOX A ($2\%O_2/15\%CO_2$)	33.71	33.05	0.77	1.06	-3.46	-3.33	3.55	3.54	283.90	288.81
BOX B ($5\%O_2/10\%CO_2$)	33.22	32.62	1.03	1.52	-3.93	-4.14	3.55	4.42	285.96	290.72
BOX C ($2\%O_2/10\%CO_2$)	32.90	32.78	0.68	1.00	-3.40	-3.97	3.63	4.11	284.39	284.42
BOX D ($5\%O_2/15\%CO_2$)	33.95	31.87	0.98	1.34	-4.14	-4.27	4.26	4.47	283.58	287.42

Initial L*, a*, b*, chroma, and hue angle values were 34.73, 0.67, -3.39, 3.46, and 281.18, respectively.

APPENDIX B

AIR-FRUIT TEMPERATURE DATA AND FRUIT MASS VERSUS TIME

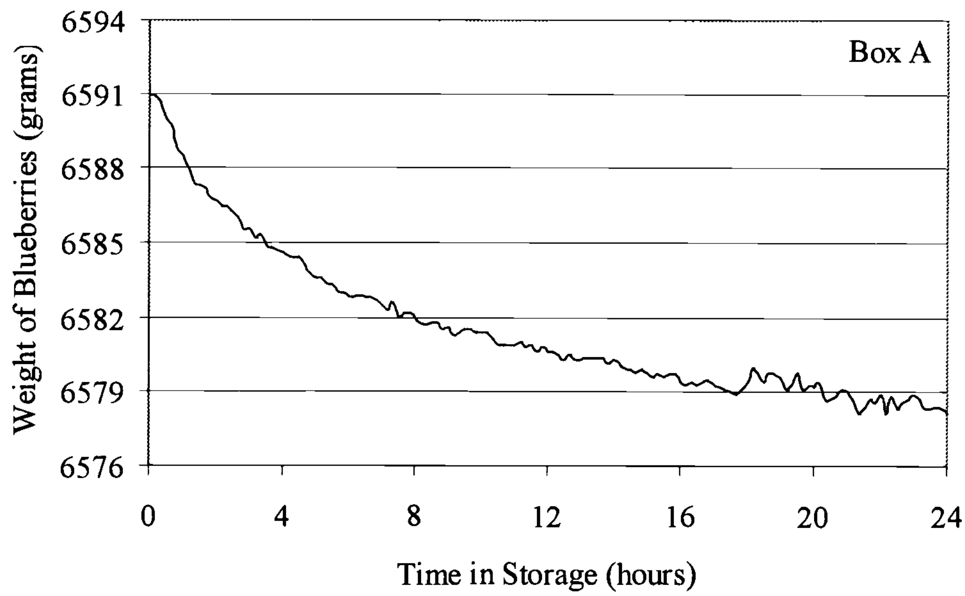

Figure B.1. Mass loss during the first 24 hours of Elliott blueberries stored in $2\%O_2$-$15\%CO_2$ in the 1996 storage season.

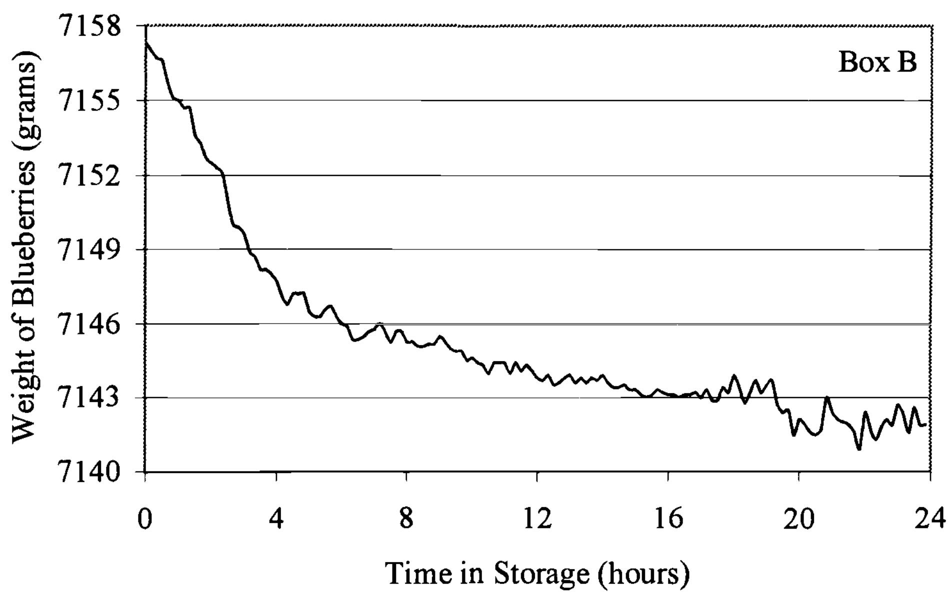

Figure B.2. Mass loss during the first 24 hours of Elliott blueberries stored in $2\%O_2$-$5\%CO_2$ in the 1996 storage season.

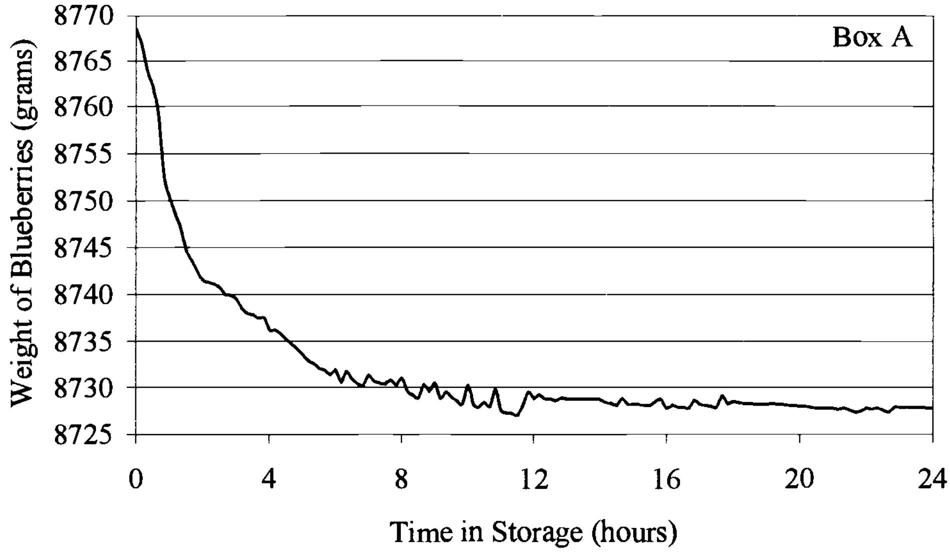

Figure B.3. Mass loss during the first 24 hours of Elliott blueberries stored in 2%O_2-15%CO_2 in the 1997 storage season.

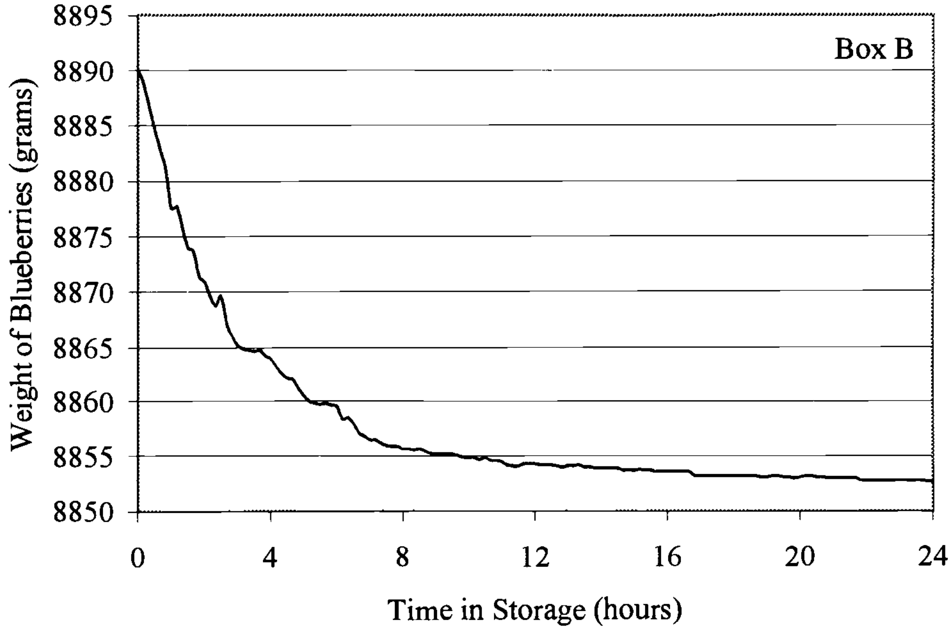

Figure B.4. Mass loss during the first 24 hours of Elliott blueberries stored in 2%O_2-15%CO_2 in the 1997 storage season.

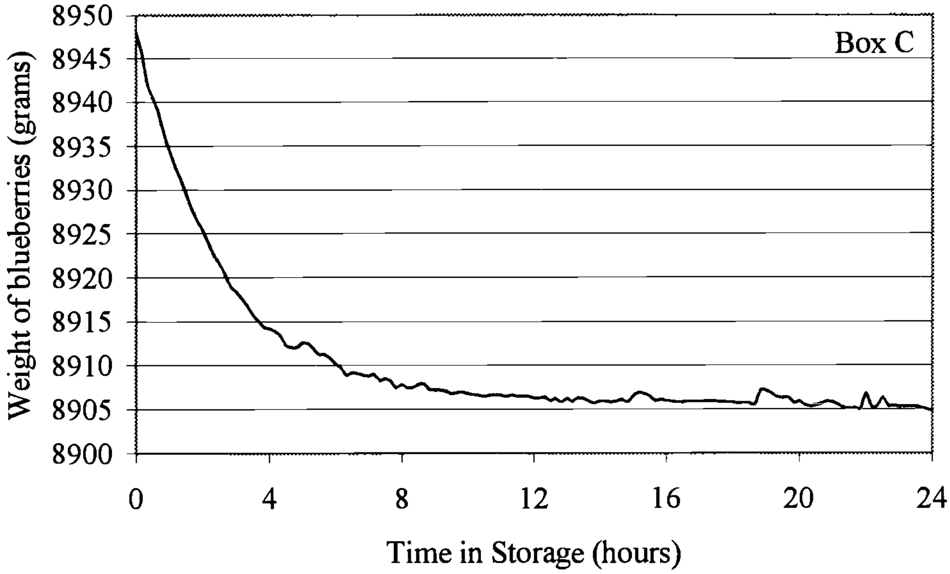

Figure B.5. Mass loss during the first 24 hours of Elliott blueberries stored in 2%O_2-10%CO_2 in the 1997 storage season.

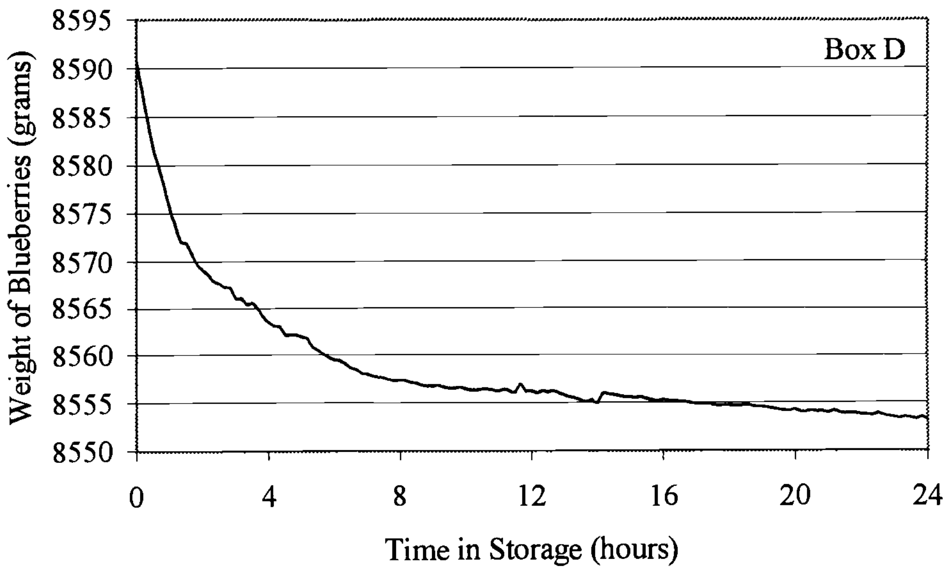

Figure B.6. Mass loss during the first 24 hours of Elliott blueberries stored in 5%O_2-15%CO_2 in the 1997 storage season.

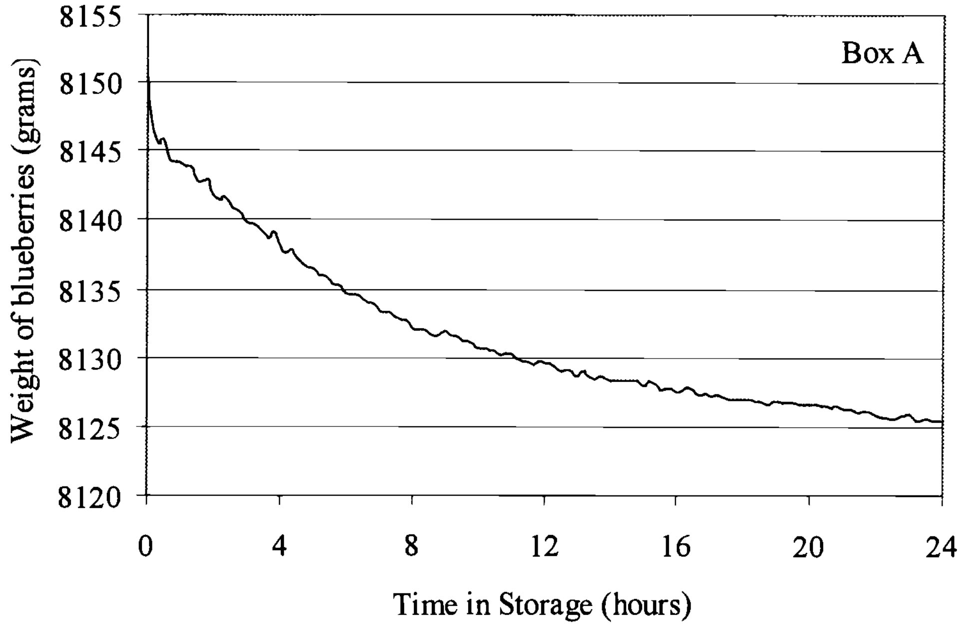

Figure B.7. Mass loss during the first 24 hours of Elliott blueberries stored in $2\%O_2$-$15\%CO_2$ in the 1998 storage season.

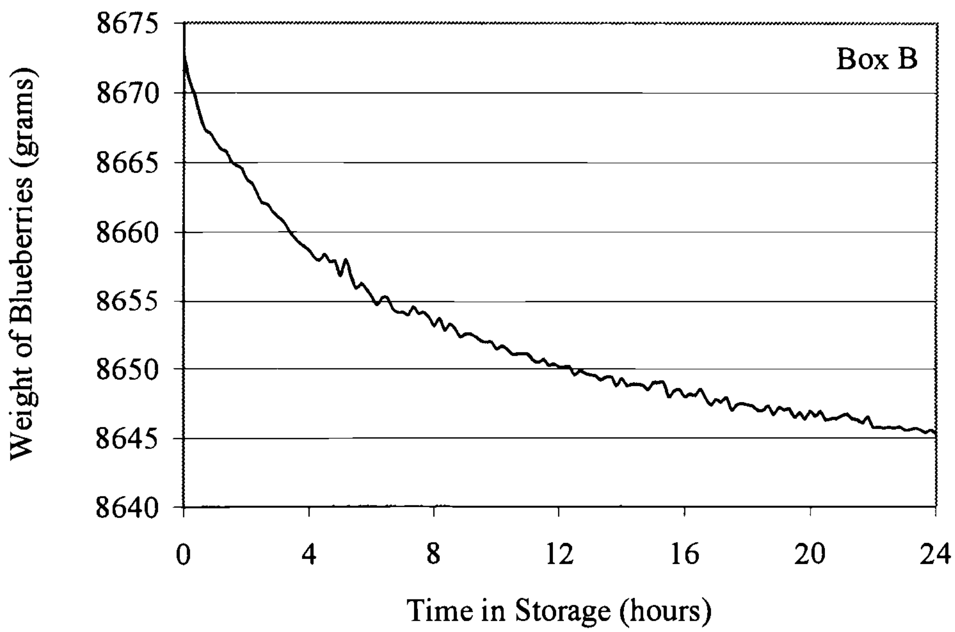

Figure B.8. Mass loss during the first 24 hours of Elliott blueberries stored in $5\%O_2$-$10\%CO_2$ in the 1998 storage season.

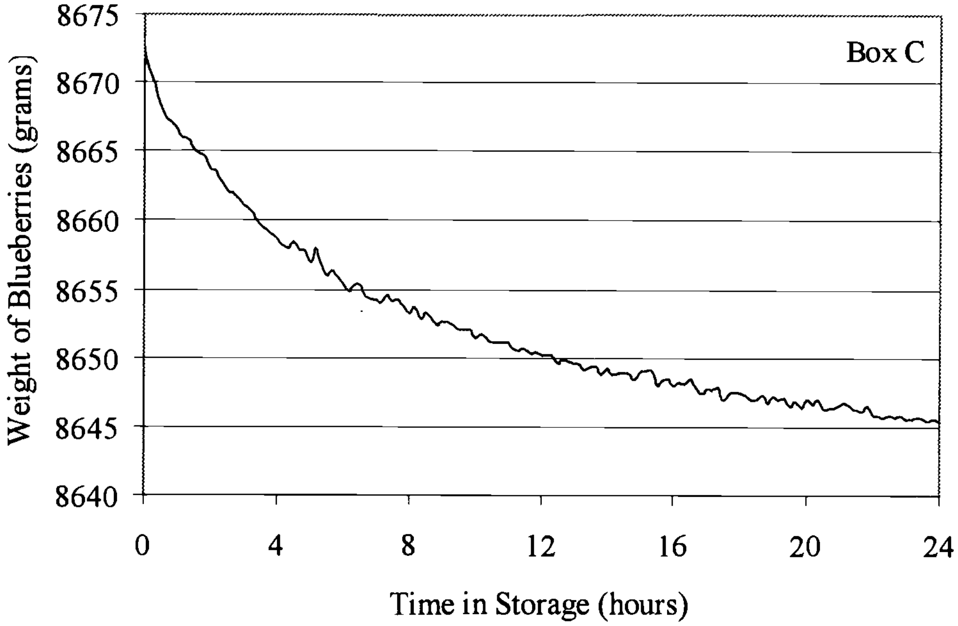

Figure B.9. Mass loss during the first 24 hours of Elliott blueberries stored in 2%O_2-10%CO_2 in the 1998 storage season.

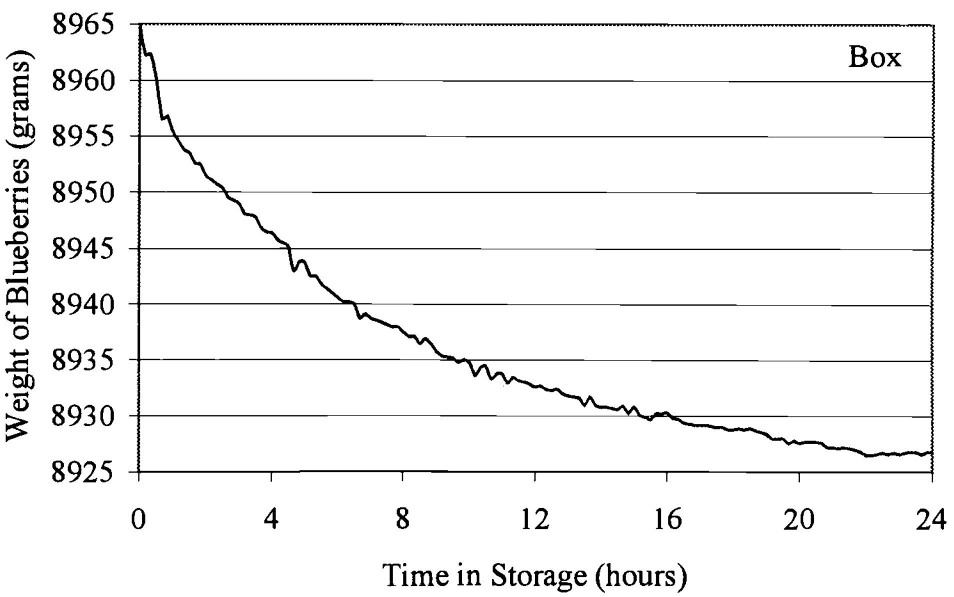

Figure B.10. Mass loss during the first 24 hours of Elliott blueberries stored in 5%O_2-15%CO_2 in the 1998 storage season.

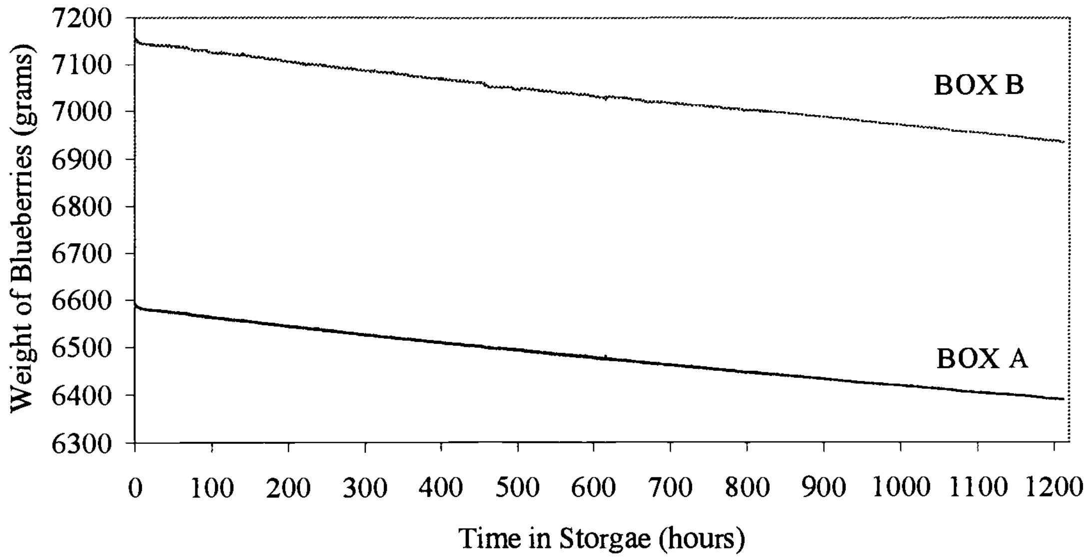

Figure B.11. Mass versus time of Elliott blueberries stored in different atmospheric conditions in the 1996 storage season.

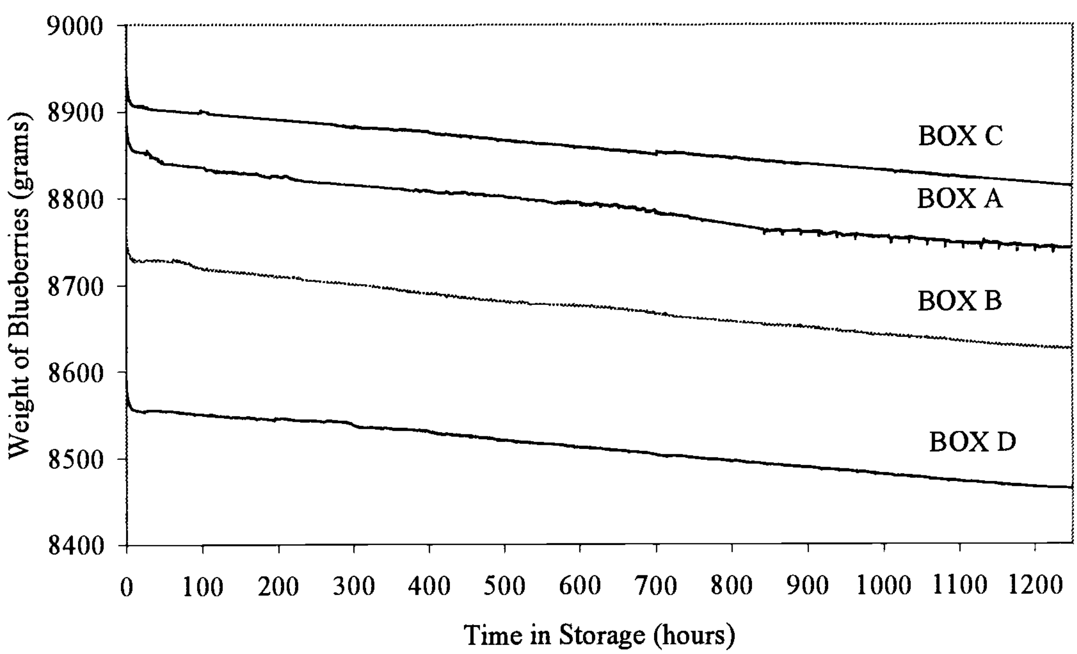

Figure B.12. Mass versus time of Elliott blueberries stored in different atmospheric conditions in the 1997 storage season.

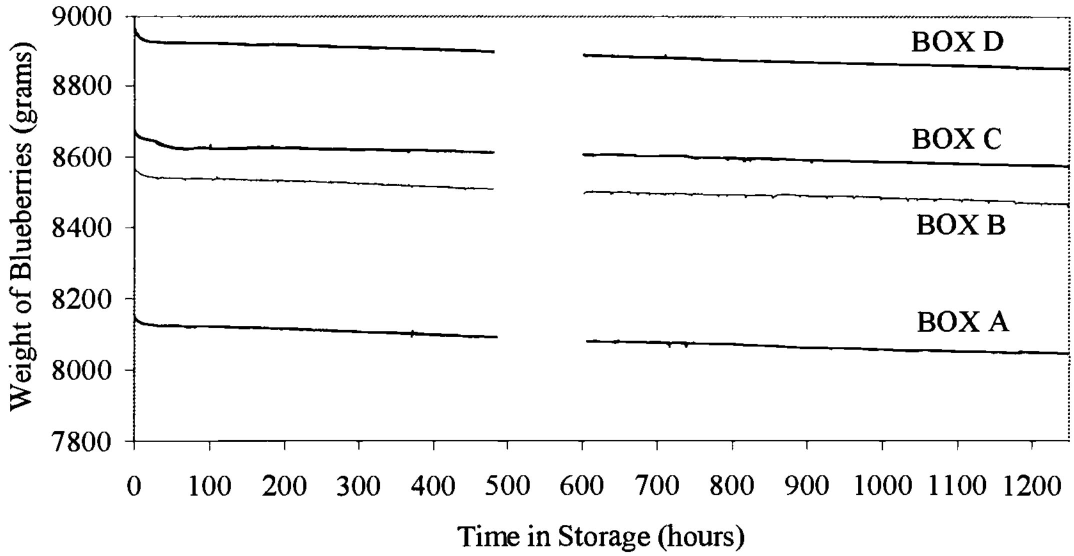

Figure B.13. Mass versus time of Elliott blueberries stored in different atmospheric conditions in the 1998 storage season.

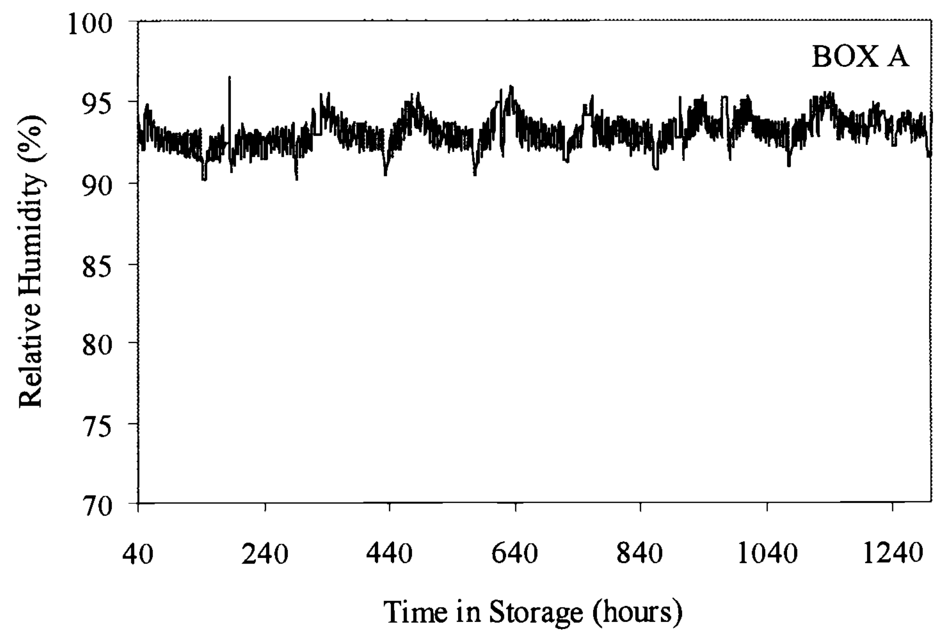

Figure B.14. Relative Humidity (%) history of Elliott blueberries stored in $2\%O_2$-$15\%CO_2$ in the 1997 storage season.

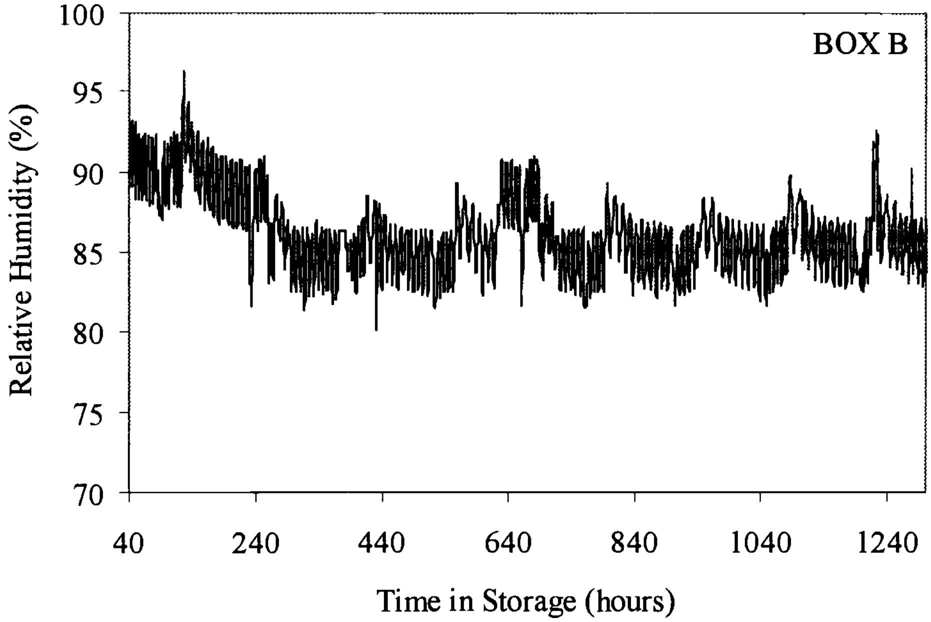

Figure B.15. Relative Humidity (%) history of Elliott blueberries stored in 5%O_2-10%CO_2 in the 1997 storage season.

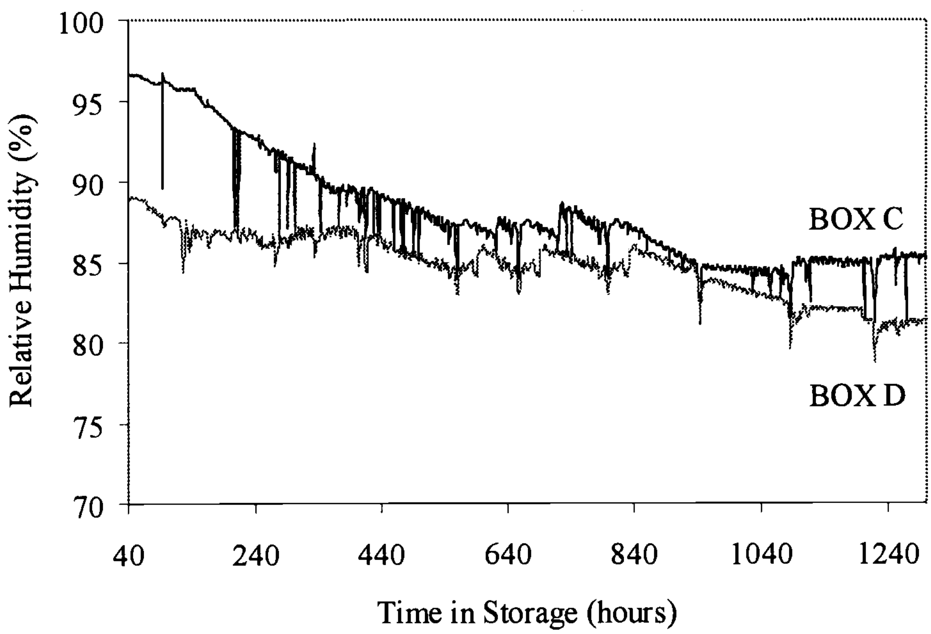

Figure B.16. Relative Humidity (%) history of Elliott blueberries stored in 2%O_2-10%CO_2 and 5%O_2-15%CO_2 in the 1997 storage season.

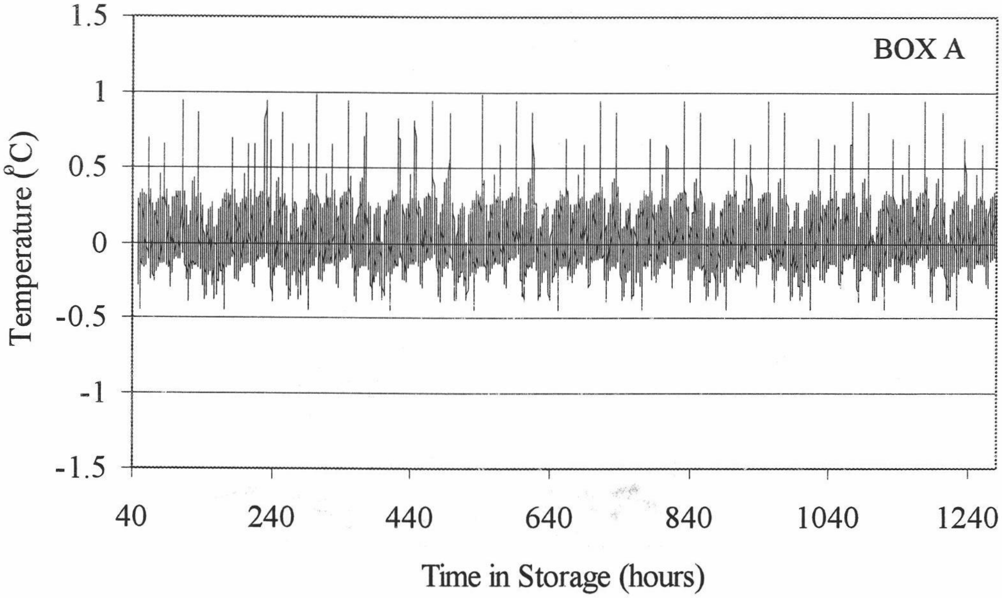

Figure B.17. Ambient air temperature history of Elliott blueberries stored in 2%O_2-15%CO_2 in the 1997 storage season.

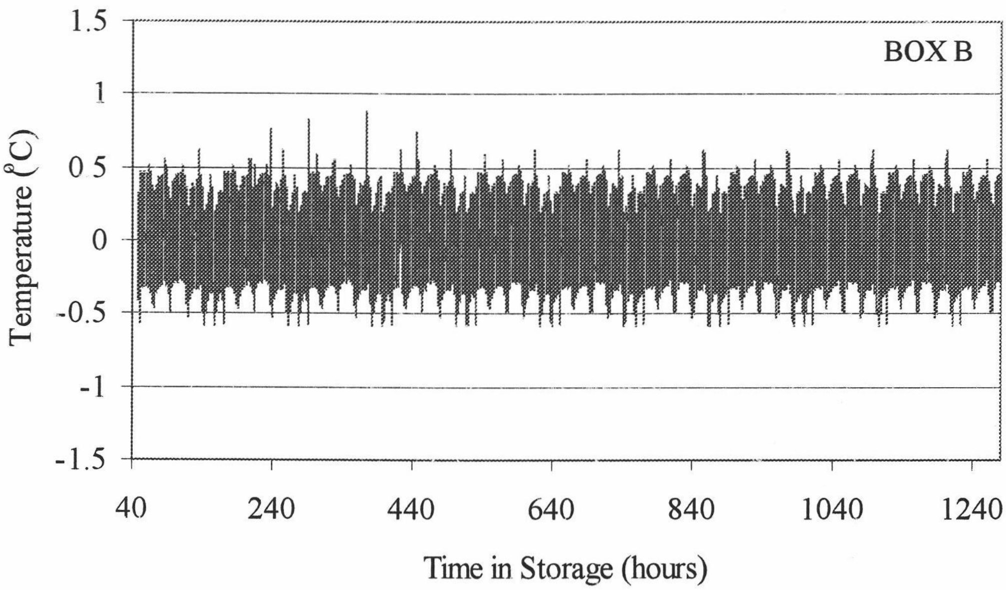

Figure B.18. Ambient air temperature history of Elliott blueberries stored in 5%O_2-10%CO_2 in the 1997 storage season.

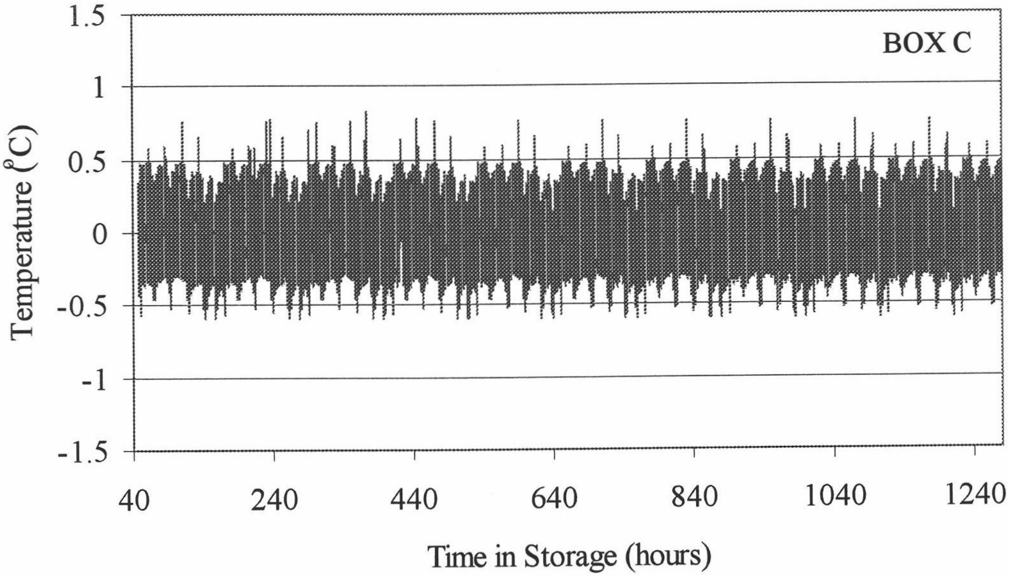

Figure B.19. Ambient air temperature history of Elliott blueberries stored in $2\%O_2$-$10\%CO_2$ in the 1997 storage season.

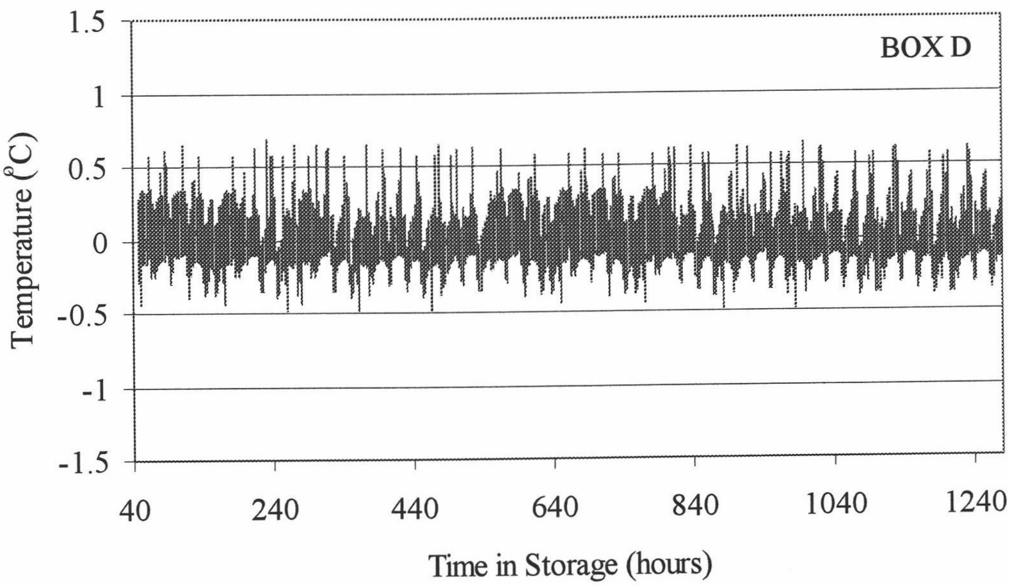

Figure B.20. Ambient air temperature history of Elliott blueberries stored in $5\%O_2$-$15\%CO_2$ in the 1997 storage season.

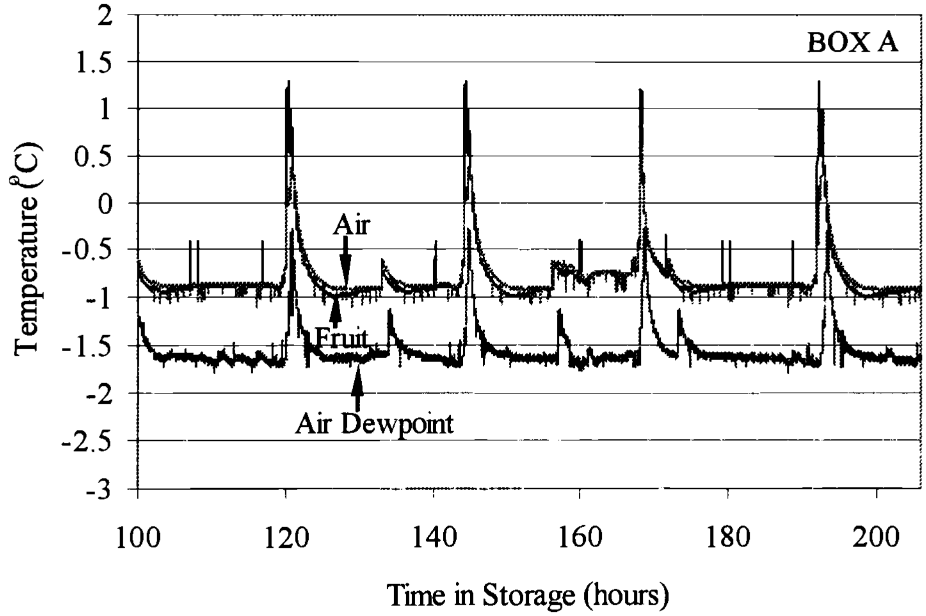

Figure B.21. Ambient air temperature history of Elliott blueberries stored in 2%O_2-15%CO_2 in the 1998 storage season.

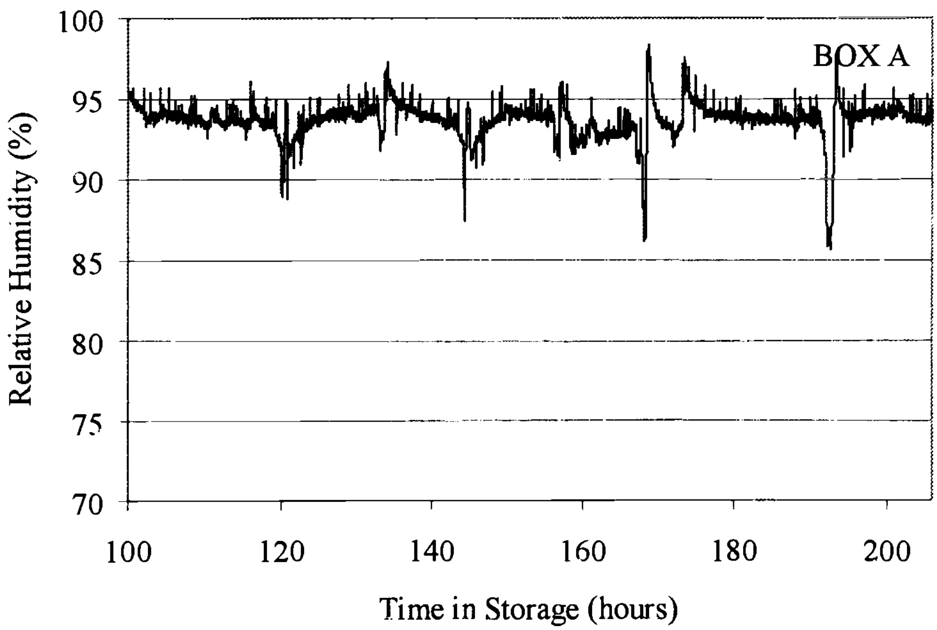

Figure B.22. Relative Humidity (%) of Elliott blueberries stored in 5%O_2-15%CO_2 in the 1998 storage season.

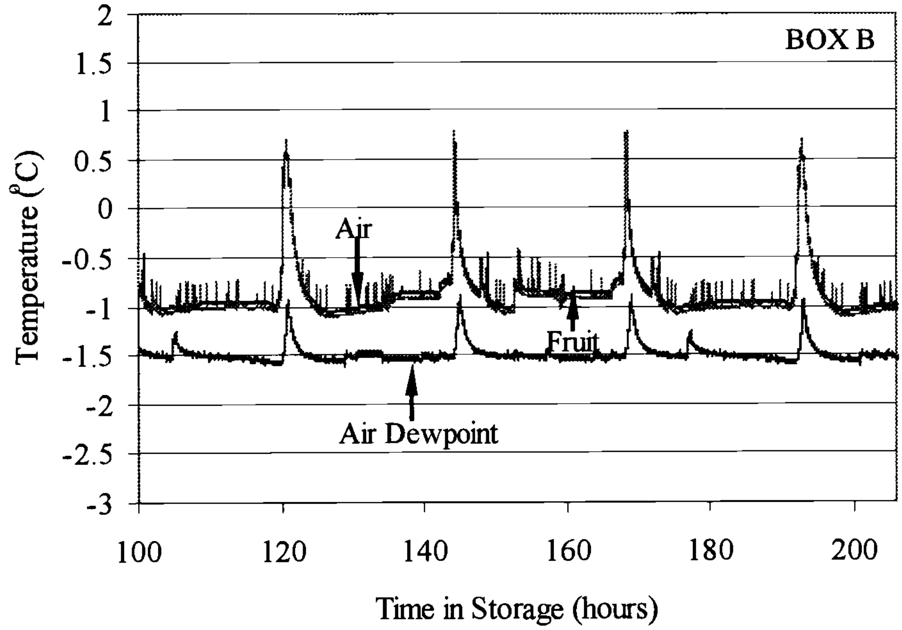

Figure B.23. Ambient air temperature history of Elliott blueberries stored in $5\%O_2$-$10\%CO_2$ in the 1998 storage season.

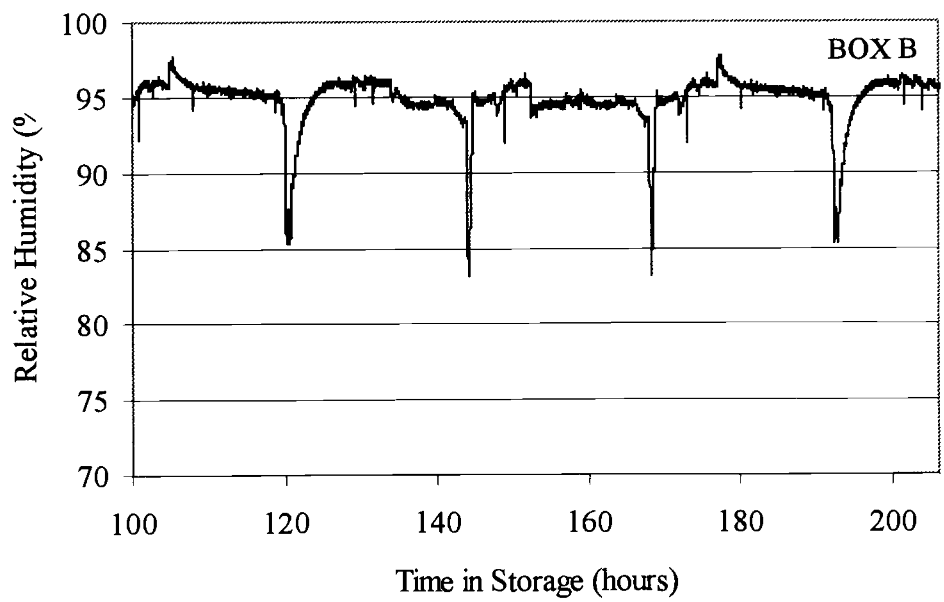

Figure B.24. Relative Humidity (%) of Elliott blueberries stored in $5\%O_2$-$15\%CO_2$ in the 1998 storage season.

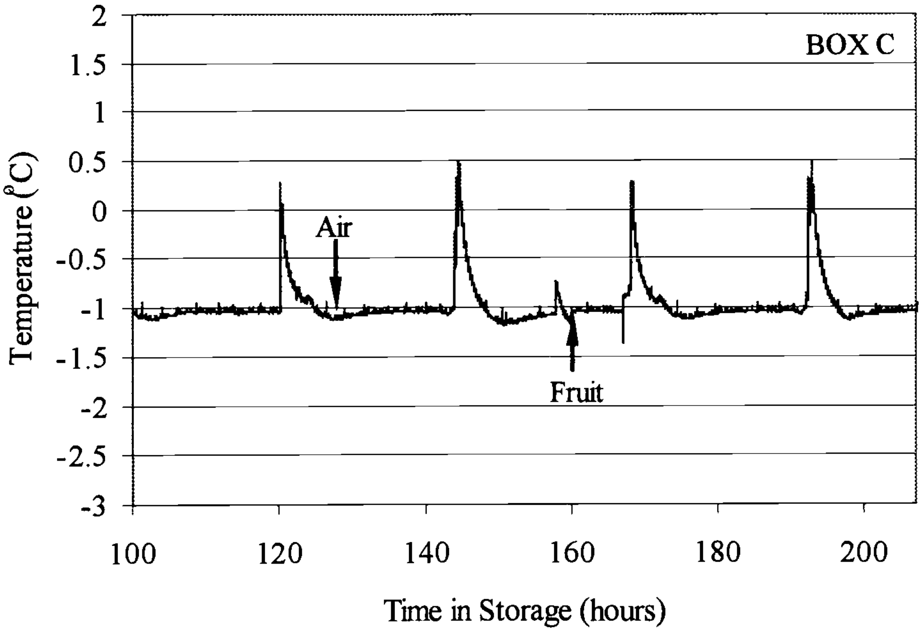

Figure B.25. Ambient air temperature history of Elliott blueberries stored in 2%O_2-10%CO_2 in the 1998 storage season.

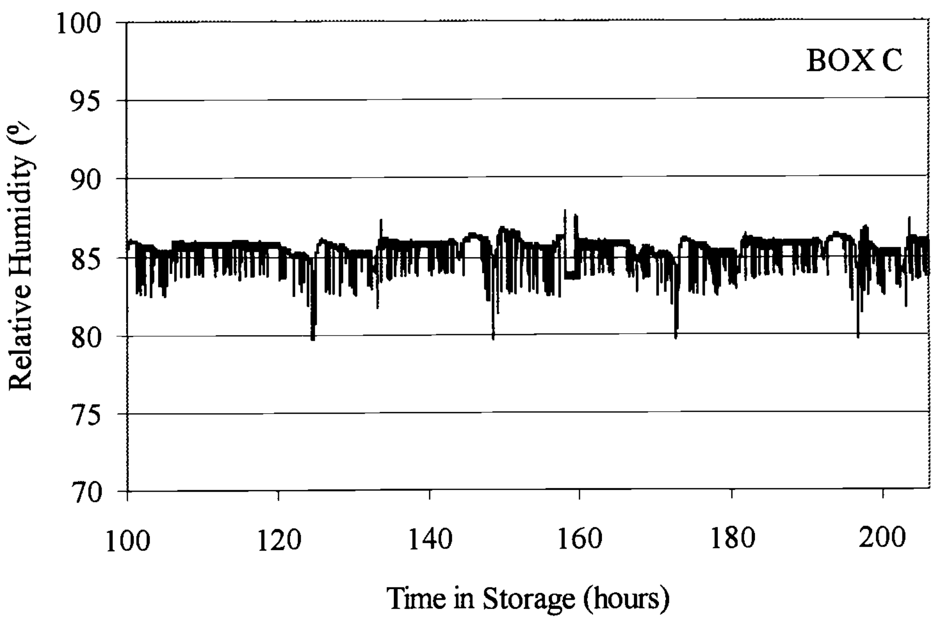

Figure B.26. Relative Humidity (%) of Elliott blueberries stored in 2%O_2-10%CO_2 in the 1998 storage season.

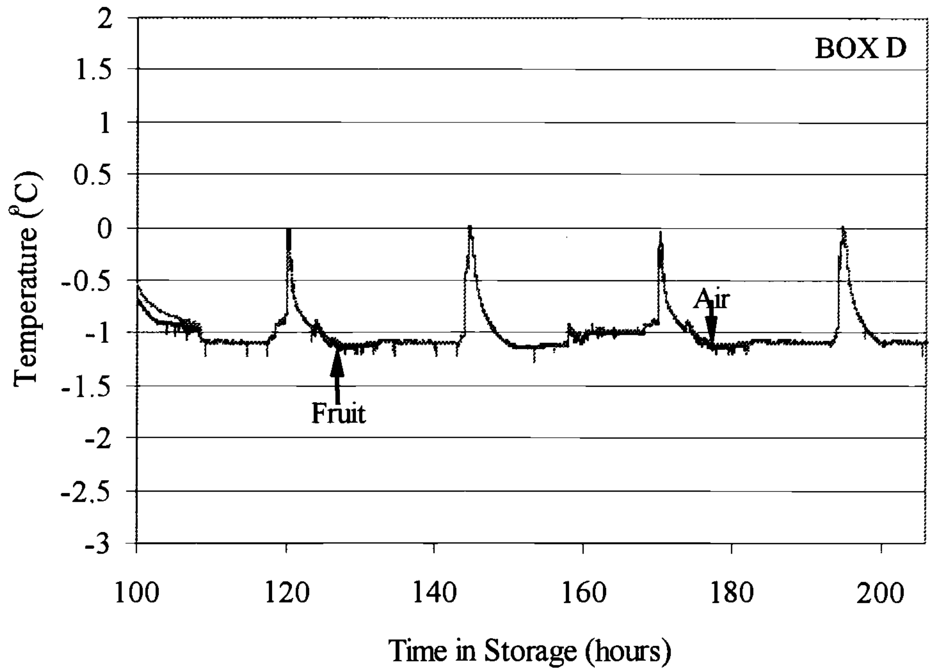

Figure B.27. Ambient air temperature history of Elliott blueberries stored in 5% O_2-15% CO_2 in the 1998 storage season.

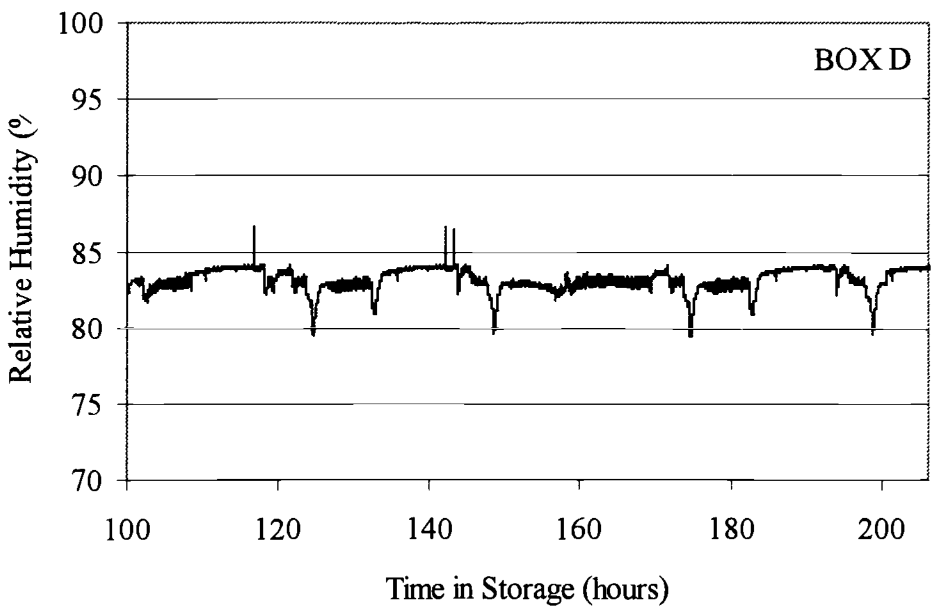

Figure B.28. Relative Humidity (%) of Elliott blueberries stored in 5% O_2-15% CO_2 in the 1998 storage season.