INFLUENCE OF CULTIVAR AND POST-HARVEST STORAGE ON THE QUALITY
OF VACUUM MICROWAVE-DRIED POTATO CHIPS

by

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ABSTRACT

As a healthy alternative to traditional oil-fried potato chips, microwaving potato slices under vacuum simulates puffing by deep-frying without the presence of oil. The main objective in this study was to determine how potato cultivar and post-harvest storage affected the quality of vacuum microwave-dried (VMD) potato chips, and to identify cultivars suitable for VMD chip processing.

Potato tubers from eighteen cultivars, harvested in 1998, were stored for (1) six months at 12°C; and (2) ten months at 4°C with reconditioning at 12°C for 2 weeks prior to VMD chip processing. VMD chip quality, in terms of texture (sensory and instrumental methods) and colour was evaluated. Observations of tuber specific gravity and moisture content were taken immediately prior to VMD chip processing.

In 1999-2000, tubers from six commercially important cultivars (Kennebec, Shepody, Russet Burbank, Norland, Warba, and White Rose) were stored at 4°C for 5 to 10 months followed by reconditioning at 12°C for 2 weeks prior to VMD chip processing. Monthly observations of VMD chip texture, tuber specific gravity and moisture, starch, amylose, reducing sugar and soluble carbohydrate contents were taken. Potato slices were dehydrated using three methods (air drying, freeze drying, and vacuum microwave drying) and the structural characteristics examined by scanning electron microscopy. VMD chips were rehydrated (at 100°C and 25°C) and their moisture absorption rates determined.

Specific gravity and starch content highly correlated with VMD chip sensory crispiness and instrumental peak force values. Cultivars with low dry matter content (Norland, Warba, and White Rose) produce chips that required less force for fracturing, compared to cultivars high in dry matter content (Kennebec, Shepody, and Russet Burbank). Tuber physiology
appeared in part to influence VMD chip puffing. Cultivars with low dry matter content produced chips with greater tissue porosity and/or expansion. From rehydration experiments, the rapid moisture absorption in cultivars with low dry matter content suggested a less dense chip tissue structure.

Changes in tuber specific gravity and moisture content during storage affected VMD chip quality. Tuber specific gravity, starch and moisture contents, and VMD chip peak force values did not significantly change over time when tubers were stored from 5 to 10 months at 4°C with reconditioning at 12°C for 2 weeks. However, tuber reducing sugar content did significantly increase during this storage treatment. Neither cultivar nor storage was found to significantly affect VMD chip Hunter L values.

Cultivars Norland, Warba, and White Rose (which are unsuitable for oil-fried chip production due to high sugar content) may be well suited for VMD chip production. From these cultivars, VMD chips of consistent quality were produced from tubers stored for up to 10 months.
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INTRODUCTION

A. The potato

The potato (*Solanum tuberosum* L.) originated in the highlands of South America. Prior to the arrival of the Spaniards in the New World, indigenous tribes had cultivated the potato plant for hundreds of years, and therefore the origins of the wild species of the potato are unknown (Burton, 1989). The Spaniards brought the potato to Europe at the end of the 16th century. From there the cultivation of potato spread throughout the Old and New Worlds. With few exceptions, all cultivated potatoes in the world are of the same species.

The portion of the plant that is used for consumption is the tuber, which in fact is a modified underground stem. During plant growth, numerous underground lateral shoots (stolons) emerge from the base of the stem and spread horizontally through the soil. At a late stage of plant growth, the stolons cease to elongate and begin to swell at their ends. This swelling, caused by the translocation of sugars from the leaves leads to the formation of the tuber. The tuber serves as the reserve of the plant’s energy, stored in the form of the polysaccharide starch. The potato plant can also be propagated vegetatively via the tuber.

As early as the 17th century, tubers from different cultivars were classified by their colour, shape, taste, and time of maturity (van Es and Hartmans, 1987a). For modern potato growers, these remain some of the most important characteristics. Although each cultivar has a unique genotype, the phenotype of individual tubers may be affected by growing conditions. Some known factors which can influence tuber phenotype include spacing of the potato plants, irrigation, fertilizer, soil type, light, temperature, and disease (Burton, 1989).
B. Anatomy of the tuber

The tuber exterior is comprised of the skin (periderm), lenticels, and eyes. The tuber is asymmetrical, with a bud end and a stem end (attachment site to the stolon). Moving inward from the skin is the cortex, followed in turn by the vascular ring, perimedullary zone, and the pith. The pith forms a small central core, extending through the tuber from the stem end (attachment site of stolon) to the bud end. Narrow branches called medullary rays radiate from the pith connecting to the eyes.

During the onset of tuberization, layers of cells constituting the periderm are formed. The skin is usually 6 to 8 cell layers thick, depending on cultivar and growing conditions (van Es and Hartmans, 1987a). When the tuber is young, this skin layer can easily be separated or peeled from the inner tuber tissues. By the time the tuber reaches maturity, cell division ceases in the periderm and the skin is firmly attached to the inner tissues. Skin colour and texture are inheritable cultivar traits. Skin colour can range from brown to yellow to red. Skin colour is caused by the presence of anthocyanins in the cells of the periderm and cortex. Rough-skinned (russet) potatoes have skin cells that are partially detached from the surface, while smooth-skinned tubers completely retain the outer cell layers of the periderm (Beukema and Van der Zaag, 1990).

Lenticels are the regions on the tuber skin where the stolon stomata had originally been. Tuber respiration occurs through the lenticels, as very little carbon dioxide or oxygen can pass directly through the skin itself (van Es and Hartmans, 1987a). The eyes of the tuber are homologous to the buds on the stolon. Within each eye is a main bud and several axillary buds, all surrounded by two scale leaves (“eyebrow”). If the main bud in an eye is damaged or removed, sprouting may still occur through the axillary buds (Burton, 1989).
The majority of tuber flesh consists of parenchyma cells, which contain starch granules. Starch granules comprise most of the dry matter of a potato tuber and are used as a reserve material for sprouting and respiration. Starch granules are located in the cell cytoplasm and are bound by a membrane. The size of starch grains range from 1 to 120 μ (Burton, 1989). The starch content increases with tuber growth, both by the number and size of grains.

The cortex is a narrow layer of starch-rich parenchyma cells between the periderm and vascular ring. The vascular ring is comprised of narrow bundles of xylem and phloem. The vascular ring is discontinuous around the tuber (the xylem connects the stem end to the eyes). The perimedullary zone forms from cell division on the inside of the vascular ring. Expansion of the perimedullary zone through cell division is the primarily factor for tuber growth (van Es and Hartmans, 1987a). The cells of the perimedullary zone also contain the largest starch grains. The cells of the pith and medullary rays contain few starch granules, and appear translucent. Tissue flesh colour, like skin colour is an inheritable cultivar trait. The abundance of carotenoids in the cells will give the flesh a yellow appearance.

The cell walls of the tuber consist of cellulose and hemicelluloses, linked together by a middle lamella comprised of pectin. Often, the suitability of cultivars for potato processing depends on the degree of separation of the middle lamella and the solubility of pectin during processing (Smith, 1975). The middle lamella is periodically interrupted by intercellular spaces, which provide areas for gas exchange for respiration. Tubers differ in the volume of intercellular spaces (Burton, 1989) which may be significant when calculating tuber dry matter.

C. Chemical composition and analysis of the tuber

The biochemistry of the tuber is primarily genetic and is mostly determined by cultivar. However, many other factors can significantly influence tuber composition including fertilizer
application, climate, soil type, growing season, and tuber maturity (Burton, 1989). For the purposes of marketing, processing, and storing potatoes, the quantity of dry matter is determined among batches of tubers. Potatoes generally have between 18-27 % dry matter (Toma et al., 1978). Tuber dry matter is commonly estimated by determining its specific gravity. Specific gravity refers to the ratio of the tuber weight in air divided by the weight of water displaced by the tuber. The relationship between dry matter content and specific gravity ($r = 0.912$) determined by Schippers (1976) was:

$$\% \text{ dry matter} = -217.2 + 221.2 \ (\text{specific gravity})$$

Cultivars differ in dry matter contents, as do batches of tubers of the same cultivar. Typically, larger tubers have lower dry matter contents than smaller tubers. Larger tubers may have greater intercellular spaces and/or medullary tissue which have greater water capacity (van Es and Hartmans, 1987a). Small immature tubers, however, have lower dry matter contents than mature tubers. Dry matter content also differs within the tubers from the bud end to the stem end (Weaver et al., 1978a).

Apart from water, the main chemical component of the tuber is starch, which comprises 55-80 % of the dry matter content. Starch is present in the cells as two polymers of $\alpha$-D-glucose, amylose and amylopectin. Amylose exists as long unbranched chains of monosaccharide units connected by $\alpha$-(1.4) linkages. Amylopectin is highly branched, containing $\alpha$-(1.4) glucosidic linkages and $\alpha$-(1.6) branching points every 24-30 residues. Potato starch amylopectin content is typically 3 to 5 folds greater than the amylose content.

The principle sugars in the tuber are the reducing sugars glucose and fructose, and the non-reducing sugar sucrose. Transitional sugars, such as glucose-1-phosphate, glucose-6-phosphate, and fructose-6-phosphate comprise the remainder of the total sugar (soluble carbohydrate) content. Factors that highly influence sugar content are cultivar, tissue, tuber
maturity, and storage (Beukema and van der Zaag, 1990). Tuber sugar content can range from 0.1 to 5.0 % of the tuber fresh weight.

Some other important compounds in the tuber are derived from nitrogen in various forms. These include proteins (albumin, globulin, prolamin, and glutelin), non-protein organic compounds (free amino acids and glycoalkaloids), and inorganic nitrogen (nitrate and nitrite). Together, nitrogen compounds make up 2.2 to 5.5 % of the tuber fresh weight. Minerals (ash) comprise 0.6 to 1.2 % of the tuber fresh weight, occurring in abundance in the layers of the cortex and periderm. Important minerals include phosphorus, calcium, and potassium. Vitamins are found mostly in the perimedullary tissue. The major vitamins in potatoes are the C and B group vitamins. Lipids (fats) account for only about 0.1 % of the tuber fresh weight.

D. Sugar:starch reactions and tuber storage

Sugars are produced in the leaves of the potato plant during photosynthesis. The sugars arrive in the growing tuber as sucrose. In the cell cytoplasm, much of the sucrose is cleaved into glucose and fructose by the enzyme invertase. Through a series of further reactions in the cytosol and then within the starch granule membrane, the product becomes starch.

\[
sucrose \leftrightarrow fructose + glucose \quad \leftrightarrow \quad \text{starch} \quad \text{glucose} \leftrightarrow \text{starch}
\]

The sugar:starch reactions are reversible, although the majority of the product remains in the form of starch.

Post-harvest storage of potato tubers can have an effect on the sugar-starch ratio, altering the proportion of one product to another. Storage temperature affects the activity of
enzymes that control the conversion processes. Cunningham (1973) found equilibrium between starch and sugar reactions of Russet Burbank tubers at 45°F (7.2°C). When tubers are stored below this temperature, the conversion of starch into sugars (in particular reducing sugars) is favoured. Tubers stored at high temperatures (ie. 12-30°C) will convert sugars into starch. High temperature storage is only useful for tubers stored for the short-term (a few weeks). Loss of dry matter, sprouting, and rotting is associated with long-term high temperature storage (Beukema and van der Zaag, 1990). Changes in the sugar:starch ratio, due to storage temperature, are reversible. Tubers stored at low temperatures can be reconditioned by placing them in high temperature storage to reconvert accumulated sugars back into starch. Following a brief initial increase, sugar content falls back towards pre-storage concentrations (Burton, 1989).

Storage duration also affects the sugar:starch ratio. During the early stages of tuber storage, reducing sugar content tends to increase for the first few weeks. After months of long-term storage, respiration leads to the eventual breakdown of starch, sprouting, and senescence. At this stage there is an irreversible accumulation of reducing sugars and degradation of starch. Potato starch degradation is controlled by the activity of enzymes α-amylase, β-amylase, and phosphorylase. α-Amylase degrades amylase and amylopectin by hydrolysis of non-terminal α-(1.4) linkages into α-dextrins, maltotriose and maltose units. β-Amylase cuts the linear α-(1.4) linkages from the reducing end into maltose units. The maltose units are split into glucose units by α-glucosidase. A specific α-(1.6) glucosidase is needed to cut the branches in amylopectin. Phosphorylase can degrade amylase, amylopectin, or the maltose units into glucose-1-phosphate. Glucose and glucose-1-phosphate are either converted into fructose-6-phosphate followed by fructose-1,6-phosphate and enter glycolysis, or converted to sucrose and translocated into the growing sprouts (van Es and Hartmans, 1987b).
E. Non-enzymatic browning reactions

During food processing or storage, non-enzymatic browning (Maillard) reactions can occur in the food material, significantly affecting the product quality. Browning reactions have a positive impact on certain food products, such as the baking of bread. However, for a large part of the food industry, browning reactions can be particularly problematic. Products that can be detrimentally affected by non-enzymatic browning reactions include milk powder, french-fries, and potato chips.

Sugars that exist in an acyclic or straight chain form (such as glucose and fructose) exhibit reducing power from their carbonyl end. During high temperature food processing, reducing sugars can react with amino acids or free amino groups of proteins in a series of steps to produce brown pigments. The Maillard reactions produce a variety of aromatic aldehydes (such as maltol and isomaltol), depending on the particular amino acid and sugar involved (Fellows, 2000). The first product of the Maillard reaction is an unstable aldose or ketose Schiff base, followed by rearrangement to a more stable Amadori product. The Amadori products can bond with adjacent amino groups or other protein to form advanced glycation end products (Friedman, 1996). Examples of some of these products include ε-pyrrolelysine (reaction between glucose and lysine) and fructoselysine (fructose and lysine). Further heating causes the production of dark brown melanoidins and a smoky or burnt aroma. Severe browning products such as (hydroxymethyl)furfural can develop at this stage.

The high temperature and low moisture content in the food tissue surface can also combine to caramelize the sucrose in the absence of amino acids. Extreme heating temperatures add numerous conjugated double bonds between carbons of adjacent molecules of glucose and fructose. As the number of double bonds increases, the darker the product
colour becomes. Further polymerization occurs between sucrose molecules, eventually forming high molecular weight compounds (caramelin).

F. Overview of potato chips and the snack food industry

Potato chips are a major component of the snack food industry around the world. The market for snack products continues to grow at a faster rate than most other areas of the food and beverage industry. In Canada, a 69% overall increase in the snack food market has been seen since 1988; with potato chip sales for the year 1999 totaling $266.7 million (Burn, 2000). North American sales of potato chips were $5.8 billion in the year 2000, and $14 billion worldwide (Combelles, 2001).

The trends of snack food purchasing often follow the personal income levels of today’s consumer. Disposable per capita income has been shown to have a positive effect on the potato chip market (Guenther et al., 1991). In the early 1990’s during economic recession, sales of potato snacks continued to rise slightly, due in part to sales of generic and sale-prices brands over private labels. In the late 1990’s, consumer confidence returned and sales of higher priced potato snacks further increased (Burn, 2000).

Although fat and cholesterol are two top concerns of today’s consumer, the purchasing decisions in snack foods are not reflective of this (Hammock, 1991). Many consumers, who had switched to no-fat and low-fat snacks, are again purchasing their former high-fat brands. Consumers rank taste and convenience as high priorities. So in which direction is the potato chip market heading? Much of the increase in snack food sales can be attributed to the movement towards healthier snack foods that do not sacrifice taste or texture (Burn, 2000). Consumers may be willing to pay premium price for a better, healthier potato chip.
G. Potato chip processing

Most potato chips are processed by one of two methods. The traditional version is by frying potato slices in edible oil. The second is by potato extrusion, forming dough or puree into a simulated potato slice, and then frying. Before any processing can begin, there are a number of factors to consider. The production line begins by the proper selection of potato cultivar. Potato chip producers generally choose cultivars with high specific gravity or dry matter content. This allows for a high yield of chips, along with lower oil absorption during frying (Matz, 1993).

Since it is not possible to have a freshly harvested supply of potato tubers throughout the year, potatoes must be stored. Tubers are placed in a well-ventilated cold storage facility with high humidity to prevent sprouting and moisture loss. At cold temperatures however, reducing sugars accumulate in the tuber. During processing, Maillard browning reactions may lead to unacceptable dark colored chips. The tubers must be reconditioned at higher temperatures for a period of time before processing in order to reconvert reducing sugars back into starch (Smith, 1975).

Once the tubers are ready for processing, the next steps include washing, peeling, and slicing. The slices, approximately 1.5-2.0 mm thick, are washed with water to remove surface starch and sugars, and fried in oil at a temperature of 175-195°C. Oil absorption replaces the moisture in the slices, and the steam within the slices expands the structure producing a puffed, crispy chip. The final moisture content of the chip is between 1.5-3 % (w/w). The absorbed oil however, accounts for 60 % of the caloric content of potato chips (Gladwell, 2001). After frying, the chips are seasoned and packaged. The packaging includes barriers to light, oxygen, and moisture. Potato chips are of highest quality when fresh, with an average shelf life of about two months.
H. Potato chip texture

Texture is “the sensory manifestation of the structure of the food and the manner in which this structure reacts to applied forces, the specific senses involved being vision, kinesthesia, and hearing” (Szczesniak, 1971). The most important textural characteristic of a potato chip is crispiness (Vickers, 1988). The term crispiness however, is difficult to define. Crispiness is perceived during the fracturing of the potato chip as a snapping force, pressure and/or sound (Seymour and Hamann, 1988). Other terms closely associated with crispiness include brittleness, rigidity, hardness (Sczczesniak et al., 1963). Several instrumental methodologies have attempted to correlate sensory crispiness with instrumental methodology (Segnini et al., 1999a; Seymour and Hamann, 1988; Vickers, 1988).

Potato chip crispiness can be affected by a number of factors. The chip starch content, intercellular spaces, and cell wall constituents influence the puffing structure in oil-fried chips (Smith, 1975). Segnini et al. (1999b) found that stronger chips were produced from potatoes with high starch contents. Moisture content has negative impact on chip crispiness. Water softens the starch, which reduces the mechanical strength of the chip (Katz and Labuza, 1981). Chip crispiness increases as the moisture content is lowered. If the chip moisture content is brought extremely low (< 2 % w/w), the crispiness will decrease (Segnini et al., 1999b).

I. Microwaves in food processing

Microwaves are a band of electromagnetic radiation between radio waves and infrared radiation on the electromagnetic spectrum. Being close in frequency to television and radio waves, microwaves pose a potential for electromagnetic interference. Therefore food processors commonly use only two microwave frequencies, 915 and 2450 MHz.
Similar to light waves, microwaves are reflected by some substances and absorbed by others. When microwaves pass through a food substance, the molecules in the food attempt to align themselves with the direction of the electrical field and rotate around their axes. The oscillation of the molecules causes friction between the molecules, which in turn produces heat. The amount of heating is dependent on the extent of microwave penetration and reflectance in the food material. The degree of microwave penetration and reflectance is dependent on the dielectric properties of the food material and the wavelength of the microwave (Decareau, 1970). The dielectric properties are determined by the relative dielectric constant (\(\varepsilon'\)), and the dielectric loss factor (\(\varepsilon''\)). The dielectric constant is an indication of the polarizability of the food molecules and their ability to store electric energy (Bircan and Barringer, 1998). The dielectric loss factor represents the amount of electromagnetic energy absorbed by the food material (Fellows, 2000). Foods generally have high dielectric loss factors due to the presence of water and salt (Bircan and Barringer, 1998), and are therefore ideal materials for microwave heating.

Microwave heating of food has been around for over 50 years. In 1945, Dr. Percy Spencer patented the first microwave oven. Two years later, the Radarange™ was the first microwave oven available to the food service industry. The microwave oven has become a very popular, almost essential item in today's household. Yet, the use of microwave ovens in the food processing industry is diminutive by comparison. Companies involved in microwave processing are small and few in number, or are divisions of large parent companies (Schiffman, 1992). Successful uses for microwaves in the food industry have included meat thawing, blanching, baking, pasteurization, and thermal sterilization. Perhaps the most effective use of industrial microwaves involves food dehydration. Although the removal of bulk water in food is not economically viable, microwave heating is very efficient in removing moisture from
nearly dried food, such as in pasta drying (Buffler, 1993). When food tissue is without moisture, the dielectric loss factor is low. Therefore portions dried first no longer heat, whereas moisture-containing portions continue to heat, resulting in even drying.

J. History of the microwave potato chip (finish drying) industry

During the 1960’s, potato chip manufactures became the first large-scale users of microwave for food processing. The microwave finish-drying process solved the problem of potato chip browning; caused by excessive reducing sugars in tubers stored for a long-term. The darkening of potato chips could be avoided if the chips were removed from the oil just before the onset of darkening and finish-dried in a microwave oven. During the late 1960’s and early 1970’s there were over 100 such operating systems around the world (O’Meara, 1973).

From an economic point of view, the chip producer could save money in many ways. Potato cultivars high in sugars but low in cost could be purchased for use in chip production. Storing tubers at lower temperatures to reduce respiration and loss of solids could increase the quantity of processed chips. Another economic benefit resulted from reduced oil absorption during chip processing, which in turn would increase the shelf life of packaged chips (Aref, 1968).

The problems that caused the downfall of the microwave chip finish-drying industry can be partially attributed to mechanical failures, such as microwave arcing, and a short and unpredictable life span of microwave generators (magnetrons). Another difficulty was final product quality control. The low dielectric loss factor of nearly dry chips, and the differences in drying rates among chips, made it difficult to achieve the desired low final moisture content.
(O'Meara, 1973). The microwave potato chip drying industry became obsolete as quickly as it began. Today there are no facilities currently in operation.

**K. Vacuum microwave (VM) technology**

Vacuum microwave (VM) drying is an alternate way to improve the quality of dehydrated products by microwaves. Potential heat and oxidative damage can occur in food materials when processed at high temperatures. This may affect product quality in terms of texture, colour, nutrients, and overall acceptability (Fellows, 2000). Dehydration of food materials in a vacuum can be accomplished at lower drying temperatures. Under one atmosphere of pressure, the boiling point of water is reduced. At 3.6 kPa (the pressure applied during this study), the boiling point of pure water is approximately 28°C. As long as there is sufficient moisture in the product, the boiling point will remain at or near this level. The low processing temperature of VM-drying minimizes thermal damage to the food material (Erle and Shubert, 2000). The absence of air within a vacuum also reduces potential oxidative reactions (Lin et al., 1998; Yongsawatdigul and Gunasekaran, 1996a).

Another advantage of combining microwave and vacuum drying is the greater speed and efficiency at which products can be dehydrated. This is accomplished by reducing the energy required for vaporization and by increasing the mass transfer rate of vapor from the product. The energy required to evaporate tissue moisture is equal to the sensible heat (the amount of energy required to raise the water temperature to the boiling point) plus the latent heat of evaporation (the energy required to change the liquid into vapor). By lowering the boiling point of water in a partial vacuum, less sensible heat is needed to reach the boiling point. Although the lower temperature slightly increases the latent heat of vaporization, there is an overall reduction of energy required for vaporization. The vacuum also confers a faster
rate of mass transfer of vapor by reducing the concentration of water molecules above the food material. Therefore, the rate and efficiency of dehydration is improved by VM drying.

The design of the VM oven is similar to conventional microwave ovens with the exception of a pump connected directly to the drying chamber to create the vacuum. Microwave energy is produced by the magnetrons at atmospheric pressure. The microwaves are guided through a translucent plastic window. The window serves as a waveguide, reflecting the electric field internally into the drying chamber (Fellows, 2000). The drying chamber is a stainless steel drum equipped with a rotating basket for the food product. In the case of continuous batch vacuum microwave dryers, the food product could pass through the drying chamber on a conveyor belt.

There are many benefits to the food industry for using vacuum microwave drying technology. Flavour, aroma, and nutrient retention of food products are superior compared to other drying methods (Yousif et al., 2000; Yongsawatdigul and Gunasekaran, 1996b). Colour is preserved in VM-dried food products (Litvin et al., 1998). VM dehydrated foods reconstitute (ie. reabsorb moisture) at faster rate (Yousif et al. 1999). Also, labour and operating costs are lower compared to other high quality drying methods, such as spray-drying or freeze-drying (Owusu-Ansah, 1991). To date, VM technology has been successfully employed in drying a variety of plant materials, such as oregano (Yousif et al., 2000), apples and strawberries (Erle and Schubert, 2000), carrots (Litvin et al., 1998), bananas (Drouzas and Schubert, 1996), and cranberries (Yongsawatdigul and Gunasekaran, 1996a,b).

L. Vacuum microwave-dried (VMD) potato chips and research objectives

Vacuum microwave dehydration can simulate the puffing effects of deep-frying in certain food materials, without the presence of oil. Low pressure within the drying chamber
rapidly converts water to steam, which expands the food structure. Subjecting potato slices to vacuum microwave dehydration can produce fat-free potato chips with crispy texture (Durance and Liu, 1996).

When producing traditional oil-fried potato chips, it is well known that tuber physiology can affect the quality of chips (Smith, 1975; Coffin et al., 1987; Herman et al., 1996; Pritchard and Adam, 1994). To the chip producer, selection of cultivar and tuber storage conditions are critical for quality control. Factors affecting the quality of VMD chips are not known.

The overall objective of this study was to determine how cultivar and post-harvest storage affect the quality of VMD potato chips. Specifically, the goals were to (1) identify potato cultivars suitable for VMD chip production, (2) investigate the structure of VMD chips from commercially important cultivars, and (3) monitor post-harvest changes in tuber physiology and VMD chip quality from these cultivars during long-term storage.

M. Experimental hypotheses

H₀₁: Cultivar and post-harvest storage do not affect VMD chip quality.
H₁₁: Cultivar and post-harvest storage affect VMD chip quality.

H₀₂: Chip textural differences are not reflected in chip physical structure.
H₁₂: Chip textural differences are reflected in chip physical structure.

H₀₃: Long-term storage from 5 to 10 months at 4°C followed by reconditioning at 12°C for 2 weeks does not significantly change tuber starch, sugar, or moisture contents.
H₁₃: Long-term storage from 5 to 10 months at 4°C followed by reconditioning at 12°C for 2 weeks does significantly change tuber starch, sugar, and moisture contents.
CHAPTER I

EFFECTS OF CULTIVAR AND STORAGE TREATMENT ON VMD POTATO CHIP QUALITY
1a. INTRODUCTION

Traditional potato chips are produced by frying tuber slices in edible oil. Unfortunately for health conscious consumer, these chips contain up to 39 % oil, which accounts for 60 % of the calories (Gladwell, 2001). Microwaving under vacuum can simulate the puffing effect of deep-frying without adding oil to the chips. During vacuum microwaving of potato slices, low pressure within the dryer chamber rapidly converts water in the slices to steam, which expands the tissue producing chips with crispy texture (Durance and Liu, 1996). Vacuum microwave-dried (VMD) potato chips have no added calories from oil.

The quality of potato chips can be ascertained by evaluating two chip parameters: texture and colour (Smith, 1975). Texture evaluation can be performed with sensory or instrumental methodology (Szczesniak et al., 1963). Difficulties often exist in attempting to correlate data obtained using these two approaches. Perhaps the most important sensory attribute of potato chip texture is crispiness (Vickers, 1988). Instrumental measurements that correlate with sensory assessment of chip crispiness include acoustic sounds, water activity monitoring, and mechanical deformation (Seymour and Hamann, 1988). In mechanical deformation, potato chips are fractured and the work involved is recorded and graphed into a force-deformation curve as seen in Figure 1.1. Bourne et al. (1966) reported the slope of the curve to be the best measure of chip crispiness, and thereby a good predictor of its texture. However, due to large variations in slope among samples, the measurement of the peak force of chip breakage has proven to be a more reliable measure of crispiness (Katz and Labuza, 1981; Demetriades et al., 1995).

Potato chip texture and colour are affected by tuber composition (Smith, 1975). Potato cultivars differ in their dry matter content and biochemistry (Burton, 1989). For oil fried chips, the starch to sugar ratio is very important for chip colour (Smith, 1975). A high reducing sugar
Figure 1.1. Instrumental measurement of VMD potato chip texture. (A) Apparatus used to measure texture and (B) force-deformation curve representing data quantified by the TA.XT2 Texture Analyzer.
(glucose and fructose) content is generally undesirable because reducing sugars interact with amino acids, ascorbic acid, and other organic compounds during deep-frying to produce an undesirable burned (caramelized) flavour and a dark coloration (Beukema and van der Zaag, 1990). Chip quality can also be affected by changes in tuber physiology during storage. During low temperature storage (<8°C) the reducing sugar content of potato tubers increases due to starch hydrolysis. Alternatively, storage at relatively higher temperatures (10-20°C) decreases reducing sugar concentration by increasing starch synthesis (Burton, 1989). Tubers with a high reducing sugar concentration, due to low storage temperatures, can be "reconditioned" by storage at high temperatures for two weeks, which converts sugars back to starch (Peshin, 2000). Long-term storage of tubers results in tuber sweetening due to rapid sugar production from starch breakdown (Davies and Ross, 1984).

Thus, while a significant amount of information regarding the factors affecting the quality of oil-fried chips is available, we know practically nothing about the factors affecting the quality of vacuum microwave-dried (VMD) chips. The objectives of this research were to (1) correlate sensory and instrumental methodologies for assessing VMD chip texture (2) determine how potato tuber characteristics and storage duration influence the quality of VMD potato chips, and (3) identify cultivars suitable for VMD chip production.

1b. MATERIALS AND METHODS

Cultivar selection and storage conditions

Tubers of 18 potato cultivars (Binje, Chieftain, Desiree, Epicure, Kennebec, Norchip, Norland, Norgold Russet, Nooksack, Red Lasoda, Red Pontiac, Rhinegold, Russet Burbank, Russet Norkotah, Shepody, Warba, White Rose, and Yukon Gold), grown in the Fraser Valley of British Columbia, were harvested in October 1998 and used over 10 months. Tubers were
stored in two controlled temperature rooms (800 ft³ capacity) in the Department of Food Science at the University of British Columbia. Two storage treatments for the tubers were employed: (1) short-term storage (0, 2, and 4 months) at 12°C; and (B) long-term storage (6, 8, and 10 months) at 4°C followed by reconditioning at 12°C for 2 wks. In 1999, 6 cultivars (Kennebec, Shepody, Russet Burbank, Norland, Warba, and White Rose) harvested in October were used for studying the effect of long-term storage (5, 6, 7, 8, 9, and 10 months) at 4°C followed by reconditioning at 12°C for 2 wks.

**Production of VMD potato chips**

Tubers were manually washed, peeled, and cut into 2.5-3.0 mm thick slices with a hand-held mandoline (Bron Co., Paris, France). The slices were soaked for 30 min in 5% NaCl to increase the dielectric loss factor ($\varepsilon''$) of the tissue, which results in more efficient conversion of microwave energy to heat (Bircan and Barringer, 1998). The potato slices were blanched in 1.5% NaCl for 10 min at 85°C and immediately rinsed with cold water to remove free starch. The slices were surface-dried on a Vers-a-belt (Wal-Dor Industries, New Hamburg, ON) air drier at 75°C, with an air rate of 1.5 m³/s and 15% RH. Starch granules partially gelatinized at this stage, raw potato flavour was eliminated, and moisture content was reduced to 50% (w/w). The slices were stored in plastic bags at 12°C for 24 h to equilibrate water concentrations among chips. A 2450 MHz vacuum microwave dryer (EnWave Corp., Vancouver, BC), equipped with a horizontally orientated rotating basket, was operated at 1.5 kW for chip production. The internal chamber pressure of the vacuum microwave dryer was 3.6 kPa. The basket was rotated at 8 rpm. Final moisture content of the finished potato chips was between 2-3% (w/w) following 8-10 min of vacuum microwave drying. The finished
chips were sealed in metallized polyester bags and stored at room temperature until further analysis.

**VMD chip texture measurement**

Texture of the chips was evaluated instrumentally using a TA.XT2 Texture Analyzer (Texture Technologies Corp., Scarsdale, NY/ Stable Micro Systems, Godalming, Surrey, UK). Chips were mounted on a metal plate above an open cylinder 3 cm high and 3 cm in diameter. A round-based probe (6 mm diameter) was used to break the chips (Fig. 1.1a), which produced a force-deformation curve (Fig. 1.1b). The mean peak force (g), slope (g/mm), and distance (mm) of the force-deformation curve were calculated from 12 replications per cultivar.

A trained sensory panel of four judges from the Department of Food Science, University of British Columbia assessed VMD chip texture. Two sessions were used to train panelists to assess differences in snack food crispiness, crunchiness, and hardness. One session was used to train panelists to evaluate potato chip crispiness from 4 store-bought potato chip brands. Sensory testing was performed in a red-lighted room. A randomized complete block design with each panelist as a block was used (Poste et al., 1991). Panelists evaluated chip “crispiness” on an unstructured line scale from 0-5. The control chip, Nalley ‘Thin and Crispy’ (Old Dutch Ltd., Calgary, AB), was anchored at “0” and a rating of “5” denoted “too crispy”. Mean sensory ratings were calculated from the panelists’ evaluations taken at each time period. Results from sensory and instrumental texture analysis from VMD chip of 18 cultivars, processed over 10 months, were compared (1998-1999).

**Determination of chip color**

VMD chips were fractured and placed into petri dishes to a depth of 1 cm. A Hunter LabScan II Spectrocolorimeter (Hunter Lab., Reston, VA) was used to evaluate the color
intensity of VMD potato chips. The instrument was equipped with a D_65 illuminant and a 2° observer optical position. The results from six replications per cultivar were expressed as mean Hunter L values ranging from 100 (white) to 0 (black). Hunter L values of 40 or greater were considered to have acceptable colour (Maga, 1973).

**Physical analysis of tubers**

Specific gravity was calculated as the ratio of tuber weight in air to the weight of the volume of water displaced by the tuber, for 6 tubers for each cultivar (Appendix 1b). Tuber moisture content (w/w) was determined by air-drying samples (triplicate replications from 4 tubers per cultivar) at 70°C for 48 h (AOAC, 1995) until a constant weight was achieved. Moisture content was expressed as a percentage of the total sample weight.

**Biochemical analysis**

Longitudinal and traverse sections from 4 tubers of each cultivar were finely chopped and collected in 20 ml plastic vials. The samples were frozen, freeze-dried, and stored at -85°C (Forma Scientific bio-freezer, Marietta, OH) until further analysis. Duplicate samples from each tuber were used for biochemical analysis.

Starch content was determined by extracting 25 mg of ground, lyophilized tuber tissue in 4 ml of 80 % ethanol (v/v) for 20 min. The extract was centrifuged at 1640 g for 20 min and the supernatant decanted. The extraction was repeated. The pellet was re-suspended in water and boiled for 1 h to gelatinize the starch. Aliquots of 10 µl were incubated with 400 µl amyloglucosidase (E.C. 3.2.1.3) reagent for 1 h at 55°C (Davies and Ross, 1984). 2 ml of a glucose oxidase reagent made from 30 mg glucose oxidase (E.C. 1.1.3.4), 3 mg horseradish peroxidase (E.C. 1.11.1.7), and 10 mg o-dianisidine dihydrochloride in a Tris-phosphate-
glycerol buffer (Lloyd and Whelan, 1969) was added to the mixture and incubated at 37°C for 45 min. HCl (5N, 2ml) was combined, mixed, and A525 recorded using a UV160u spectrophotometer (Shimadzu Corp., Kyoto, Japan).

The supernatant extracted from the ethanol was assayed colorimetrically for reducing sugars (Nelson [1944] and Somogyi [1952] procedure) and total soluble carbohydrates (Dubois et al., 1956). Three reagents were prepared for reducing sugar analysis. Copper reagent A was made from 4 g CuSO4•5H2O, 24 g Na2CO3, 12 g Rochelle salt, and 18 g Na2SO4 in 1000 ml H2O. Copper reagent B was made from 15 % CuSO4•5H2O. An arsenomolybdate colour reagent was prepared from 21 ml H2SO4 added to 25 g of ammonium molybdate in 450 ml H2O, and incubated at 37°C for 24 h. 1 ml of supernatant was added to 960 µl of copper reagent and 40 µl of copper reagent B. The solution was mixed and heated for 20 min in a boiling water bath. 1 ml of arsenomolybdate reagent was added and A500 was recorded. Total soluble carbohydrates were quantified by adding 50 µl phenol (80 % w/w) to 2 ml of supernatant. 5 ml of H2SO4 was rapidly pipetted into the mixture. The mixture was vortexed and placed into a 30°C water bath for 10 min and A480 was read. Both reducing sugars and total soluble carbohydrates were quantified using a glucose standard.

Amylose content (as a percentage of total starch) was determined by extracting 25 mg of freeze-dried tuber samples in 0.5 ml of 45 % perchloric acid. After 4 min, 8 ml of H2O was added. 4 ml of the solution was stained with 5 ml of a diluted (1:2 v/v) I2-KI solution (Merk, 2 g KI + 1 g I2 in 300 ml H2O). A618 and A350 were measured simultaneously. The amylose content was estimated from a formula (Hovenkamp-Hermelink et al., 1988) which accounts for the specific absorbencies of amylose and amylopectin at two wavelengths: [amylose content = (3.5 – 5.1 R) / (10.4 R –19.9); where R = the ratio of absorbances at 618 and 550 nm].
Statistical Analysis

Data was subjected to analysis of variance and regression analysis (P = 0.05) using the SYSTAT 7.0 (SPSS, Evanston, IL) software. Cultivar and storage treatment means were compared using Tukey's HSD post-hoc test (P = 0.05).

1c. RESULTS AND DISCUSSION

Quantification of VMD chip texture

Mean sensory ratings of VMD chip texture by a trained panel of judges were compared with the instrumental textural parameters of peak force, slope, and distance (Fig. 1.2a-c) for 1998-1999. A high correlation (r = 0.752) was found between the sensory ratings and peak force (Fig. 1.2a). Mean peak force of cultivars ranged between 455 g and 900 g, compared to 395 g for the control chip. VMD chips with high sensory ratings that were deemed “too crispy” typically had a high mean peak force.

The slope also correlated with the sensory rating (r = 0.201), but the values were widely dispersed around the regression line (Fig. 1.2b). This high variance amongst slope measurements has also been reported in other potato chip force-deformation studies (Segnini et al., 1999a; Katz and Labuza, 1981). Distance did not correlate with sensory ratings (Fig. 1.2c).

Segnini et al. (1999b) postulated that potato chips with uniform thickness and moisture content show variation in the texture values obtained by instrumental analysis due to uneven dry matter distribution and structural differences within a chip. The puffing effect of VMD chips can causes many structural irregularities, and it is not surprising to find variation in the values obtained using instrumental analysis. Nonetheless, this study suggested that the peak
Figure 1.2. Relationship between mean sensory panel ratings of VMD chip texture with instrumental parameters (A) peak force, (B) slope, and (C) distance (1998-1999 data).

\( \star = \text{Mean (n = 36) instrumental measure of the control chip.} \)
force obtained from force-deformation analysis is a good instrumental parameter to assess VMD chip texture.

**Tuber storage and VMD chip quality**

Cultivars were placed into 5 groups (Table 1.1) based on tuber physical characteristics such as rough skin texture (Russet), skin colour (red), or flesh colour (yellow and white). Significant differences were found between cultivar groups for specific gravity and moisture contents during storage at 12°C for 4 months (Table 1.2). Yellow flesh cultivars had significantly higher specific gravity (1.1045-1.1120) and lower moisture content (75.0-76.1 %) than red skin (specific gravity 1.0723-1.0863; moisture content 80.1-80.2 %) and white flesh cultivars with low specific gravity (1.0783-1.0890; moisture content 78.6-79.0 %). Yellow flesh cultivars also had higher mean chip sensory values (4.1-4.6) than red skin (2.1-2.4) and white flesh cultivars with low specific gravity (1.4-1.7) after 2 and 4 months storage. White flesh cultivars with low specific gravity and red skin cultivars had significant decreases in tuber specific gravity over time. No significant changes were observed in chip sensory and peak force values over time for any given cultivar group. Beyond 4 months of 12°C storage, tuber post-harvest deterioration, loss of turgidity, and sprouting prevented VMD chip processing.

When tubers were stored for long-term at 4°C followed by reconditioning at 12°C (Table 1.3), differences similar to the short-term storage treatment were observed in tuber specific gravity and moisture content among particular cultivar groups. Yellow flesh cultivars differed significantly in tuber characteristics from red skin cultivars from 6 to 10 months storage, and from white flesh cultivars with low specific gravity after 8 and 10 months storage. Mean chip sensory ratings of yellow flesh cultivars (4.3-4.7) were also significantly different
Table 1.1. Classification of cultivar groups on the basis of physical characteristics.

<table>
<thead>
<tr>
<th>Yellow flesh</th>
<th>Red skin</th>
<th>Russet skin</th>
<th>White flesh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>low s.g. (^1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>high s.g. (^1)</td>
</tr>
<tr>
<td>Binje</td>
<td>Chieftain</td>
<td>Norgold Russet</td>
<td>Nooksack</td>
</tr>
<tr>
<td>Desiree</td>
<td>Norland</td>
<td>Russet Burbank</td>
<td>Warba</td>
</tr>
<tr>
<td>Rhinegold</td>
<td>Red Lasoda</td>
<td>Russet Norkotah</td>
<td>White Rose</td>
</tr>
<tr>
<td>Yukon Gold</td>
<td>Red Pontiac</td>
<td></td>
<td>Norchip</td>
</tr>
</tbody>
</table>

\(^1\) s.g. = specific gravity
Table 1.2. Comparison of tuber characteristics (specific gravity and moisture content) and chip qualities (sensory rating, peak force, and colour) from tubers stored for 0, 2, and 4 months at 12°C.

<table>
<thead>
<tr>
<th>Storage treatment (months)</th>
<th>Tuber specific gravity (s.g.)</th>
<th>Tuber moisture content (%)</th>
<th>Sensory rating of chip texture (0-5)</th>
<th>Chip peak force (g)</th>
<th>Chip colour (Hunter L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow flesh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1.1083 ± 0.0128</td>
<td>76.0 ± 1.8</td>
<td>3.0 ± 0.9</td>
<td>701 ± 115</td>
<td>73.9 ± 0.5</td>
</tr>
<tr>
<td>2</td>
<td>1.1120 ± 0.0233</td>
<td>75.0 ± 2.4</td>
<td>4.6 ± 0.7</td>
<td>739 ± 110</td>
<td>75.7 ± 1.5</td>
</tr>
<tr>
<td>4</td>
<td>1.1045 ± 0.0076</td>
<td>76.1 ± 1.5</td>
<td>4.1 ± 0.8</td>
<td>702 ± 117</td>
<td>75.5 ± 2.0</td>
</tr>
<tr>
<td>White flesh (high s.g.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1.0986 ± 0.0082</td>
<td>76.0 ± 0.8</td>
<td>3.8 ± 0.9</td>
<td>705 ± 93</td>
<td>74.0 ± 1.1</td>
</tr>
<tr>
<td>2</td>
<td>1.1002 ± 0.0035</td>
<td>76.6 ± 0.7</td>
<td>2.5 ± 0.7</td>
<td>670 ± 105</td>
<td>77.0 ± 2.2</td>
</tr>
<tr>
<td>4</td>
<td>1.0948 ± 0.0112</td>
<td>76.7 ± 1.8</td>
<td>2.7 ± 0.6</td>
<td>679 ± 117</td>
<td>76.2 ± 2.0</td>
</tr>
<tr>
<td>White flesh (low s.g.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1.0890 ± 0.0054</td>
<td>78.6 ± 0.6</td>
<td>2.7 ± 0.4</td>
<td>618 ± 95</td>
<td>74.1 ± 0.9</td>
</tr>
<tr>
<td>2</td>
<td>1.0853 ± 0.0023</td>
<td>79.0 ± 0.1</td>
<td>1.4 ± 0.1</td>
<td>573 ± 86</td>
<td>75.8 ± 1.1</td>
</tr>
<tr>
<td>4</td>
<td>1.0783 ± 0.0035</td>
<td>78.8 ± 0.1</td>
<td>1.7 ± 0.1</td>
<td>499 ± 77</td>
<td>74.9 ± 2.7</td>
</tr>
<tr>
<td>Russet skin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1.0966 ± 0.0074</td>
<td>77.5 ± 2.2</td>
<td>3.4 ± 0.5</td>
<td>687 ± 85</td>
<td>72.6 ± 2.5</td>
</tr>
<tr>
<td>2</td>
<td>1.0993 ± 0.0165</td>
<td>78.6 ± 1.1</td>
<td>3.1 ± 0.5</td>
<td>676 ± 93</td>
<td>75.4 ± 2.7</td>
</tr>
<tr>
<td>4</td>
<td>1.0863 ± 0.0092</td>
<td>79.0 ± 1.6</td>
<td>2.4 ± 0.7</td>
<td>564 ± 75</td>
<td>75.0 ± 1.6</td>
</tr>
<tr>
<td>Red skin</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1.0863 ± 0.0073</td>
<td>80.1 ± 0.6</td>
<td>2.9 ± 0.4</td>
<td>612 ± 60</td>
<td>73.9 ± 1.4</td>
</tr>
<tr>
<td>2</td>
<td>1.0791 ± 0.0082</td>
<td>80.2 ± 0.3</td>
<td>2.4 ± 1.3</td>
<td>597 ± 90</td>
<td>75.7 ± 1.9</td>
</tr>
<tr>
<td>4</td>
<td>1.0723 ± 0.0068</td>
<td>80.2 ± 0.7</td>
<td>2.1 ± 0.6</td>
<td>669 ± 107</td>
<td>75.2 ± 1.2</td>
</tr>
</tbody>
</table>

1 Means ± SE (n ≥ 16) not followed by the same letter (a-c) are significantly different (P = 0.05) for cultivar groups at a given time of storage.

2 Means ± SE (n ≥ 16) in the same column not followed by the same letter (y-z) are significantly different (P = 0.05) for the storage duration of a given cultivar group.

See Table 1.1. for classification of cultivar groups.
Table 1.3. Comparison of tuber (specific gravity and moisture content) and chip (sensory rating, peak force, and colour) characteristics from tubers stored for 6, 8, and 10 months at 4°C followed by reconditioning for 2 wks at 12°C.

<table>
<thead>
<tr>
<th>Cultivar group¹</th>
<th>Storage treatment² (months)</th>
<th>Tuber specific gravity (s.g.)</th>
<th>Tuber moisture content (%)</th>
<th>Sensory rating of chip texture (0-5)</th>
<th>Chip peak force (g)</th>
<th>Chip colour (Hunter L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yellow flesh</td>
<td>6</td>
<td>1.1020 ± 0.0139 az</td>
<td>75.7 ± 1.9 az</td>
<td>3.1 ± 0.3 by</td>
<td>749 ± 91 az</td>
<td>73.7 ± 2.7 az</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.0955 ± 0.0138 az</td>
<td>74.9 ± 2.2 az</td>
<td>4.3 ± 0.8 az</td>
<td>759 ± 96 az</td>
<td>73.8 ± 1.6 az</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.0953 ± 0.0079 az</td>
<td>76.3 ± 1.7 az</td>
<td>4.7 ± 0.3 az</td>
<td>810 ± 96 az</td>
<td>74.2 ± 2.4 az</td>
</tr>
<tr>
<td>White flesh</td>
<td>6</td>
<td>1.1026 ± 0.0048 az</td>
<td>75.4 ± 1.6 az</td>
<td>3.9 ± 0.3 ay</td>
<td>704 ± 90 abz</td>
<td>75.1 ± 1.1 az</td>
</tr>
<tr>
<td>(high s.g.)</td>
<td>8</td>
<td>1.0950 ± 0.0072 az</td>
<td>76.4 ± 0.8 az</td>
<td>3.7 ± 0.8 ay</td>
<td>758 ± 72 az</td>
<td>74.7 ± 1.0 az</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.0924 ± 0.0082 az</td>
<td>76.4 ± 1.9 az</td>
<td>4.6 ± 0.3 az</td>
<td>789 ± 69 az</td>
<td>76.5 ± 1.1 az</td>
</tr>
<tr>
<td>White flesh</td>
<td>6</td>
<td>1.0855 ± 0.0035 az</td>
<td>77.5 ± 0.7 az</td>
<td>1.7 ± 0.2 cz</td>
<td>593 ± 72 bz</td>
<td>76.3 ± 0.4 az</td>
</tr>
<tr>
<td>(low s.g.)</td>
<td>8</td>
<td>1.0875 ± 0.0015 az</td>
<td>77.7 ± 0.5 az</td>
<td>1.7 ± 0.7 bz</td>
<td>652 ± 104 abz</td>
<td>75.2 ± 1.0 az</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.0750 ± 0.0046 by</td>
<td>78.9 ± 0.7 az</td>
<td>2.2 ± 0.4 bz</td>
<td>629 ± 61 bz</td>
<td>76.9 ± 0.5 az</td>
</tr>
<tr>
<td>Russet skin</td>
<td>6</td>
<td>1.0910 ± 0.0106 abz</td>
<td>77.4 ± 1.8 az</td>
<td>2.5 ± 0.3 bz</td>
<td>658 ± 91 abz</td>
<td>76.3 ± 2.4 az</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.0860 ± 0.0107 abz</td>
<td>77.7 ± 2.7 abz</td>
<td>3.0 ± 0.9 az</td>
<td>664 ± 108 abz</td>
<td>70.5 ± 4.5 az</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.0877 ± 0.0083 abz</td>
<td>78.8 ± 2.4 az</td>
<td>3.9 ± 1.3 az</td>
<td>707 ± 92 abz</td>
<td>74.7 ± 2.0 az</td>
</tr>
<tr>
<td>Red skin</td>
<td>6</td>
<td>1.0815 ± 0.0048 bz</td>
<td>80.6 ± 0.8 bz</td>
<td>1.8 ± 0.6 cy</td>
<td>572 ± 73 bz</td>
<td>75.0 ± 1.0 az</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1.0783 ± 0.0087 bz</td>
<td>80.6 ± 1.7 bz</td>
<td>2.4 ± 1.0 byz</td>
<td>587 ± 69 bz</td>
<td>75.9 ± 1.0 az</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.0780 ± 0.0086 bz</td>
<td>79.7 ± 1.5 az</td>
<td>3.0 ± 1.3 az</td>
<td>669 ± 87 abz</td>
<td>75.4 ± 1.8 az</td>
</tr>
</tbody>
</table>

¹ Means ± SE (n ≥ 16) not followed by the same letter (a-c) are significantly different (P = 0.05) for cultivar groups at a given time of storage.

² Means ± SE (n ≥ 16) in the same column not followed by the same letter (y-z) are significantly different (P = 0.05) for the storage duration of a given cultivar group.

See Table 1.1. for classification of cultivar groups.
from red skin (2.4-3.0) and white flesh cultivars with low specific gravity (1.7-2.2) at 8 and 10 months storage. No significant changes were observed in tuber characteristics or chip quality over time for any given cultivar group.

Mean Hunter L values for chip cultivar groups varied in range from 70.5-76.9 over the entire 10 month study (Tables 1.2 and 1.3). No significant differences in chip colour were determined for either cultivar group or storage duration. All cultivars produced chip samples with acceptable colour.

There were significant cultivar x time interactions during storage for tuber specific gravity and moisture content (Table 1.4). This would imply that changes in tuber physiology during storage varied among different cultivars, (see Appendix Ia and Ib), which may be attributed to their differences in the rates of tuber respiration and evaporation (van Es and Hartmans, 1987c). As also observed in Table 1.4, VMD chip texture (sensory ratings and peak force) was shown to change significantly over time. Scanlan (1996) suggested that during tuber storage, post-harvest changes affecting tissue structural components (cell wall, middle lamella) and/or tissue turgor pressure could manifest themselves as textural changes in potato chips. VMD chip texture appears to be influenced in part by factors other than the proportion of tuber dry matter. This would account for the differences between chip texture and the proportion of tuber dry matter.

Neither cultivar nor time significantly affected VMD chip Hunter L colour values (Table 1.4). Typically, when tubers are stored at low temperatures for a prolonged duration off colours become evident in oil-fried potato chips, due to non-enzymatic browning reactions (Coffin et al., 1987). However, in vacuum microwave drying, non-enzymatic browning is minimized due to low heating temperatures (Yousif et al., 1999). Another factor could be that during blanching, much of the reducing sugar content was leached from the potato slices.
Table 1.4. Sources of variation and the probability of their influence on tuber specific gravity, moisture content, chip sensory ratings, peak force, and colour.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Tubers stored for 0, 2, and 4 months at 12°C</th>
<th>Tubers stored for 6, 8, and 10 months at 4°C followed by reconditioning at 12°C for 2 wks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tuber specific gravity</td>
<td>Tuber moisture content</td>
</tr>
<tr>
<td>Cultivar (C)</td>
<td>0.005*</td>
<td>0.001*</td>
</tr>
<tr>
<td>Time (T)</td>
<td>0.034*</td>
<td>0.407</td>
</tr>
<tr>
<td>Replication</td>
<td>0.562</td>
<td>0.835</td>
</tr>
<tr>
<td>C x T</td>
<td>0.021*</td>
<td>0.929</td>
</tr>
</tbody>
</table>

* = significant at P = 0.05
(see Table 1.7), reducing the substrate(s) required for non-enzymatic browning.

**Effects of tuber composition, cultivar, and long-term storage on VMD chip texture**

The long-term storage treatment (4°C followed by reconditioning at 12°C for 2 wks) was repeated during 1999-2000 employing only 6 cultivars. Norland, Warba, and White Rose were chosen based on the 1998-1999 results from VMD chip textural analysis (Appendix Ic,d). These cultivars produced VMD chips with less rigid texture (similar to the control chip as was seen in Fig. 1.2). Cultivars Kennebec, Shepody, and Russet Burbank were chosen because they are important commercial varieties for oil-fried chips and french-fries. Generally these cultivars are used for chip processing due to their high specific gravity and storage qualities (Barichello *et al.*, 1991; Coffin *et al.*, 1987).

Analysis from 1999-2000 showed significant effects of tuber composition on chip peak force (Table 1.5). Peak force correlated significantly with tuber specific gravity and starch, moisture, reducing sugar, and soluble carbohydrate contents (Table 1.5). The tuber amylose content did not have a significant effect on peak force. Multiple analysis of variance (Table 1.6) showed that specific gravity (P = 0.002) and starch content (P = 0.017) contributed to the majority of the variation in peak force measurements. Specific gravity has been calculated as an accurate measure of tuber dry matter content (Schippers, 1976). Specific gravity is also highly correlated with tuber starch content, since starch is the principle component of tuber dry matter (Burton, 1989).

Cultivars Norland, Warba, and White Rose were significantly lower in VMD chip peak force than Kennebec, Shepody, and Russet Burbank (Fig. 1.3a). The former group of cultivars had lower tuber specific gravity and starch content, and higher moisture content than the latter (Fig. 1.3b-d). Long-term (up to 10 months) tuber storage did not significantly change chip
Table 1.5. Sources of variation and their influence on VMD chip peak force.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Effect on peak force</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F-ratio</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>47.7*</td>
</tr>
<tr>
<td>Starch content</td>
<td>31.9*</td>
</tr>
<tr>
<td>Soluble carbohydrate content</td>
<td>61.2*</td>
</tr>
<tr>
<td>Reducing sugar content</td>
<td>50.4*</td>
</tr>
<tr>
<td>Moisture content</td>
<td>46.9*</td>
</tr>
<tr>
<td>Amylose content</td>
<td>0.1</td>
</tr>
</tbody>
</table>

* = Significant at $P = 0.05$.  

$n \geq 180$.  

Table 1.6. Multiple analysis of variation (MANOVA) on VMD chip peak force and the proportion of the variation attributed to each source.

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Effect on peak force (probability)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>0.002*</td>
</tr>
<tr>
<td>Starch content</td>
<td>0.017*</td>
</tr>
<tr>
<td>Soluble carbohydrate content</td>
<td>0.118</td>
</tr>
<tr>
<td>Reducing sugar content</td>
<td>0.168</td>
</tr>
<tr>
<td>Moisture content</td>
<td>0.876</td>
</tr>
<tr>
<td>Amylose content</td>
<td>0.726</td>
</tr>
</tbody>
</table>

* = Significant at P = 0.05.

n ≥ 180.
Figure 1.3. Changes in chip peak force (A), tuber specific gravity (B), moisture (C), starch (D), reducing sugar (E), and soluble carbohydrate (F) contents during storage: (■) Norland, Warba, White Rose; (●) Kennebec, Shepody, Russet Burbank. Error bars represent standard error of the mean.
peak force, tuber specific gravity, starch or moisture contents over time. Norland, Warba, and White Rose also differed from Kennebec, Shepody, and Russet Burbank in reducing sugar and soluble carbohydrate content. Reducing sugar content of all cultivars increased over time (Fig. 1.3e). The increase in tuber sugar content resulted from the breakdown of starch, due to long-term storage (van Es and Hartmans, 1987a). The increase in tuber soluble carbohydrate content was not possible due to the breakdown of some soluble carbohydrates for respiration. The overall increase in tuber sugars, which constitute a relatively small percentage of tuber dry matter, was not proportionate to a significant decline in tuber starch content.

Effect of blanching on the dry matter content of potato slices

Potato solids lost during the blanching stage of chip processing were analyzed (Table 1.7). Blanching removed 65.7-91.3 % of the reducing sugar content and 45.8-88.5 % of the soluble carbohydrate content from potato slices. Similar results on reducing sugar losses from potato strips during blanching have been reported by Kayman and Kincal (1994). Loss of soluble carbohydrates during blanching could account for up to 5 % loss of the total dry matter content of the slice (Fig. 1.4b). Approximately 1.4-2.7 % of the starch and 1.3-9.3 % of the amylose were also leached during blanching.

1d. CONCLUSIONS

High quality VMD potato chips were produced from tubers stored short-term (4 months) at 12°C and long-term (up to 10 months) at 4°C followed by reconditioning at 12°C for 2 weeks. Chip colour was not affected by cultivar or storage treatment. Cultivar and storage may however affect chip texture, as determined by sensory panelists and peak force instrumental measurement. Chip texture was highly influenced by tuber specific gravity and starch content.
Table 1.7. Loss of starch, amylose, reducing sugars, and soluble carbohydrates from potato slices during the blanching stage of VMD potato chip processing\(^1\).

<table>
<thead>
<tr>
<th>Tuber component</th>
<th>Cultivar</th>
<th>Kennebec</th>
<th>Shepody</th>
<th>Russet Burbank</th>
<th>Norland</th>
<th>Warba</th>
<th>White Rose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch</td>
<td></td>
<td>1.8 %</td>
<td>2.2 %</td>
<td>2.7 %</td>
<td>1.7 %</td>
<td>1.4 %</td>
<td>1.8 %</td>
</tr>
<tr>
<td>Amylose</td>
<td></td>
<td>1.3 %</td>
<td>5.6 %</td>
<td>2.7 %</td>
<td>3.7 %</td>
<td>3.9 %</td>
<td>9.3 %</td>
</tr>
<tr>
<td>Reducing sugar</td>
<td></td>
<td>91.3 %</td>
<td>70.0 %</td>
<td>65.7 %</td>
<td>70.4 %</td>
<td>73.3 %</td>
<td>72.9 %</td>
</tr>
<tr>
<td>Soluble carbohydrate</td>
<td></td>
<td>88.5 %</td>
<td>66.4 %</td>
<td>87.5 %</td>
<td>46.0 %</td>
<td>51.8 %</td>
<td>45.8 %</td>
</tr>
</tbody>
</table>

\(^1\) Mean (n = 16) percent loss calculated from tubers at 7 and 10 months storage (1999-2000).
Cultivars typically low in specific gravity and starch content (such as Norland, Warba, and White Rose) may be better suited for VMD chip production, due to their crispy, but less rigid texture.
CHAPTER II

EVALUATION OF VACUUM MICROWAVE-DRIED POTATO CHIP STRUCTURE
2a. INTRODUCTION

Microwaving in a vacuum is a rapid and efficient method for the dehydration of food materials. In a vacuum, the reduced pressure lowers the boiling point of water, resulting in an increased rate of evaporation. Reduced pressure in the vacuum also lowers the concentration of water surrounding the food, thereby increasing the rate of mass transfer of vapour from the tissue (Gunasekaran, 1999). When applied to potato slices, this method can rapidly convert cellular water to steam, which in turn create an outwards pressure making the chip puff (Durance and Liu, 1996). The tissue layers are expanded to produce chips with a puffed structure similar to oil-fried chips. Vacuum microwave-dried (VMD) chips are a fat-free snack alternative to traditional high caloric oil-fried chips.

The method for dehydrating potatoes can have a significant influence on the colour (Krokida et al. 2001), nutrient content (Fellows, 2000), and texture of the final product (Krokida and Maroulis, 1999). VMD products, such as carrots and cranberries, have been shown to have superior colour, nutrient retention, and textural properties compared to conventional drying methods (Lin et al., 1998; Yongsawatdigul and Gunasekaran, 1996b). The effects of vacuum drying and microwave drying on dehydrated potato texture and structure have previously been reported. In an early experiment, Collins and McCarty (1969) found that sensory panelists were unable to differentiate the texture of potatoes cooked in water and those cooked by microwaves. Bouraoui et al. (1994) compared microwave drying to convective drying of potatoes. Microwaved potatoes showed no evidence of case-hardening (accumulation of solutes on food surface during heating, which forms a hard impermeable layer), less tissue shrinkage, and greater rehydration potential than air-dried potatoes. Microwave drying has been reported to increase potato tissue porosity, while vacuum drying can decrease bulk density of dried potatoes (Krokida and Maroulis, 1997). The effects of
vacuum-microwave drying on the physical structure of dehydrated potatoes, however, have not been reported.

Starch and water, the two major constituents of potato tubers, have significant impacts on the physical properties of processed potatoes (Smith, 1975). Starch and starch derivatives have been used for many years as functional ingredients to achieve various textural attributes in foods. Starch is comprised of two compounds of glucose, amylopectin (branched) and a smaller quantity of amylose (linear). For puffed snacks, combinations of high-amylose and high-amylopectin starches can achieve the desired structural or textural characteristics (Huang, 1995). The objective of this study was to investigate the physical structure and puffing of VMD potato chips produced from cultivars varying in tuber starch and moisture contents.

2b. MATERIALS AND METHODS

Preparation of dried potato slices

Tubers from 6 cultivars (Kennebec, Shepody, Russet Burbank, Norland, Warba, and White Rose), harvested in 1999, were sliced (2.5-3.0 mm thick), and the slices dried using three procedures: vacuum microwave drying, partial air drying, or freeze drying (See Chapter 1c, Materials and Methods, for VMD chip production procedure). Slices were partially air-dried to 50 % moisture (w/w) on a Vers-a-belt air-drier (Wal-Dor Industries, New Hamburg, ON) at 75°C with an air rate of 1.5 m³/s and 15 % RH. Partially air-dried slices were stored at -85°C until further use. Slices were freeze-dried (Model 4451 F, Labconco Corp., Kansas City, MO) for 72 h. The freeze dryer was operated at 1.6 mm Hg with a condenser temperature of -55°C.

Scanning Electron Microscopy (SEM)

Each of the three drying treatments (vacuum microwave-dried, air-dried, and freeze-
dried) were examined using a scanning electron microscope from three slices of different tubers for each cultivar. Fragments (approximately 1 cm²) of slices were glued to SEM stubs, coated with gold using the Nanotech SEMPREP II Sputter Gold Coater, and examined by SEM (Stereoscan 250, Cambridge Instruments Ltd., Cambridge, U.K.).

Rehydration

The rehydration potential of dried potato slices was evaluated by immersing 10 g samples into water insulated at 100°C or 25°C. Samples were drained and weighed at 10, 20, 30, 40, 50, 60, and 70 min for the samples rehydrated at 25°C and at 1, 2, 4, 6, 8, 10 min for those rehydrated at 100°C. Moisture absorbed during rehydration was expressed as a percentage of the initial moisture content of the sample. Rehydration rate (slope of the rehydration curve was calculated.

2c. RESULTS AND DISCUSSION

Analysis of tuber physiology

The contents of tuber starch, moisture, and amylose from cultivars used in this study are listed in Table 2.1. Russet Burbank had the highest starch concentration (815 mg/g dry wt.) and the lowest moisture content (73.2 % w/w) of all cultivars. Kennebec, Shepody, and Russet Burbank had a significantly higher starch content compared with Norland, Warba, and White Rose. Amylose content was highest in White Rose (20.3 %) and Russet Burbank (20.3 %), and lowest in Shepody (18.7 %) and Norland (17.2 %).

Results of scanning electron microscopy

Scanning electron micrographs of cross-sections of potato slices processed from the
Table 2.1. Starch, moisture, and amylose contents of 6 potato cultivars$^1$.

<table>
<thead>
<tr>
<th>Cultivar$^1$</th>
<th>Kennebec</th>
<th>Shepody</th>
<th>Russet Burbank</th>
<th>Norland</th>
<th>Warba</th>
<th>White Rose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch (mg/g dry wt.)</td>
<td>$815 \pm 59$ $^a$</td>
<td>$827 \pm 49$ $^a$</td>
<td>$832 \pm 21$ $^a$</td>
<td>$707 \pm 20$ $^b$</td>
<td>$705 \pm 41$ $^b$</td>
<td>$710 \pm 21$ $^b$</td>
</tr>
<tr>
<td>Moisture (% w/w)</td>
<td>$77.2 \pm 1.8$ $^b$</td>
<td>$76.9 \pm 2.4$ $^b$</td>
<td>$73.2 \pm 0.4$ $^a$</td>
<td>$80.2 \pm 0.6$ $^c$</td>
<td>$79.4 \pm 1.1$ $^{bc}$</td>
<td>$80.2 \pm 1.2$ $^{bc}$</td>
</tr>
<tr>
<td>Amylose (% of total starch)</td>
<td>$16.4 \pm 0.3$ $^c$</td>
<td>$18.7 \pm 0.4$ $^b$</td>
<td>$20.3 \pm 0.4$ $^a$</td>
<td>$17.2 \pm 0.5$ $^c$</td>
<td>$19.6 \pm 0.6$ $^{ab}$</td>
<td>$20.3 \pm 0.5$ $^a$</td>
</tr>
</tbody>
</table>

$^1$ Values are means ± SE (n ≥ 16). Values for cultivars not followed by the same letter (a-c) are significantly different (P = 0.05).
three drying methods showed differences in structural characteristics (Fig 2.1-2.6). VMD chips, as a result of puffing, showed increased tissue expansion relative to partially air-dried and freeze-dried samples from like cultivars (freeze-dried slices retained their original thickness, while partially air-dried slices had varying degrees of tissue shrinkage).

Norland VMD chips (Fig. 2.1a-b) appeared highly expanded and porous. The large intercellular spaces may be attributed in part to low dry matter content in the tuber (Burton, 1989) and the solubilization of pectin in the middle lamellas of cells during processing, which can lead to cell separation (Huang et al., 1990). Intercellular spaces and tissue porosity seemed evident in air-dried and freeze-dried slices of Norland (Fig. 2.1c-d).

VMD chips produced from Warba (Fig. 2.2a-b) and White Rose (Fig. 2.3a-b) had large rotund pores as a result of puffing. These chips were highly expanded. Few intercellular spaces were seen in the layers of tissue where puffing did not occur. Minimal tissue shrinkage was observed in air-dried samples of White Rose (Fig 2.3c) compared to air-dried samples from other cultivars. Freeze-dried slices of White Rose also appeared extremely porous (Fig. 2.3d) in comparison with freeze-dried samples of other cultivars.

Kennebec (Fig. 2.4a-b) and Shepody (Fig.2.5a-b) produced chips with minimal puffing and tissue expansion. Chip tissue structure appeared dense and compressed. Structural damage to the tissue layers seemed evident in Kennebec air-dried samples (Fig. 2.4c). Shepody air-dried slices (Fig. 2.5c) had a dense and compact tissue structure compared with samples from other cultivars. There appears to be a relationship between the degree of tissue shrinkage resulting from air-drying with the amount of tissue expansion during vacuum microwave drying. Cultivars that produced VMD chips with poor puffing also had compacted and/or damaged tissue structures from air-drying.
Figure 2.1. Scanning electron micrographs of a cross-section of slices from Norland tubers; (A,B) VMD chip, (C) air-dried, (D) freeze-dried.
Figure 2.2. Scanning electron micrographs of a cross-section of slices from Warba tubers; (A,B) VMD chip, (C) air-dried, (D) freeze-dried.
Figure 2.3. Scanning electron micrographs of a cross-section of slices from White Rose tubers; (A,B) VMD chip, (C) air-dried, (D) freeze-dried.
Figure 2.4. Scanning electron micrographs of a cross-section of slices from Kennebec tubers; (A,B) VMD chip, (C) air-dried, (D) freeze-dried.
Figure 2.5. Scanning electron micrographs of a cross-section of slices from Shepody tubers;

(A,B) VMD chip, (C) air-dried, (D) freeze-dried.
Figure 2.6. Scanning electron micrographs of a cross-section of slices from Russet Burbank tubers; (A,B) VMD chip, (C) air-dried, (D) freeze-dried.
Russet Burbank produced VMD chips with highly puffed structure (Fig. 2.6a-b) despite having high tuber starch content. Air-dried and freeze-dried tissues (Fig. 2.6c-d) were also porous and undamaged. It may be possible that puffing in VMD chips could be influenced not only by the starch quantity but also by the ratio of amylose:amylopectin. Weak association between amylose and amylopectin (Appelqvist and Debet, 1997) could lead to increased separation of starch layers in amylose-rich tissues. The intense outward pressure caused by steam during vacuum microwaving could increase puffing in this region. This may explain why Russet Burbank, which was high in starch and amylose contents, produced chips with good puffing.

The surface structure of VMD chips is seen in Fig. 2.7. The cell wall structure can be seen and appears to remain mostly intact (Fig. 2.7a-b). Regions of cell wall damage or roughness on the chip surface (Fig. 2.7c-d) may have resulted from the rapid escape of tissue steam during VMD processing (Durance and Liu, 1996). Surface roughness did not seem to be cultivar specific.

**VMD chip rehydration**

Rehydration of plant materials is partially affected by the presence of internal spaces (Yousif *et al.*, 2000). VMD chips from cultivars Norland, Warba, and White Rose rehydrated at a faster rate and had a greater capacity for absorbing moisture than chips from cultivars Kennebec, Shepody, and Russet Burbank (Fig. 2.8). Tissue structures that are more porous and less dense are able to rehydrate more completely and a faster rate than more dense structures (Pappas *et al.*, 1999). The results suggest that VMD chips from cultivars Norland, Warba, and White Rose have a less dense tissue structure.
Figure 2.7. Scanning electron micrographs of VMD chip surface; (A) Norland, (B) Russet Burbank, (C) White Rose, (D) Shepody.
Figure 2.8. Rehydration (n = 12) of VMD potato chips at (A) 100°C and (B) 25°C:

(■) Norland, Warba, White Rose; (○) Kennebec, Shepody, Russet Burbank.
2d. CONCLUSIONS

The structural characteristics of VMD chips could be influenced by tuber physiology. VMD chip puffing, expansion, and porosity may be related to the quantity, composition, and distribution of tissue starch. VMD chips from cultivars with low starch content (Norland, Warba, White Rose) appear in part to have some greater expansion, puffing, and porosity than chips from cultivars with high starch content. In turn, it may be possible to predict certain textural properties of VMD chips from prior knowledge of tuber composition.
CHAPTER III

EFFECTS OF LONG-TERM STORAGE AT 4°C FOLLOWED BY RECONDITIONING AT 12°C ON CULTIVAR PHYSIOLOGY
3a. INTRODUCTION

Consumer demands for fresh and processed potatoes require the potato industry to provide a continuous supply of tubers throughout the year. In regions where cultivation occurs for only part of the year, and alternate suppliers are not available, potatoes must be stored. Physiological changes that occur in the tubers during storage can be detrimental to product quality. Therefore, it is a concern of the potato industry to determine optimal storage methods. Although advances in storage treatments and facilities have allowed the storage life of potatoes to be extended beyond a few months, unpredictable changes in tuber physiology can occur under long-term storage (Hermann et al., 1996).

Despite available literature regarding tuber physiological post-harvest changes, comparison of results is often difficult due to experimental differences in storage temperatures and duration. Tuber composition varies with cultivar, storage temperature, and duration. Typically, low temperature storage (2-6°C) limits loss of tuber dry matter due to respiration and inhibits sprouting (Ratovski, 1987; Boe et al., 1974). Low temperature storage also causes the accumulation of reducing sugars from starch hydrolysis (van Es and Hartmans, 1987a). For oil-fried potato chip production, tubers are typically stored at a low temperature followed by reconditioning at a higher temperature prior to processing (Pereira et al., 1992). Reconditioning converts sugars accumulated during the low temperature storage back into starch, minimizing dark colours in the chips due to non-enzymatic browning reactions (Beukema and van der Zaag, 1990). Long-term storage of tubers beyond a few months results in senescence sweetening, characterized by the irreversible accumulation of sugars (Burton, 1989).

Cultivars Kennebec, Shepody, and Russet Burbank are widely used for production of potato chips and french fries, and their storage characteristics are well known (Liu et al., 1990;
Gichohi and Pritchard, 1995). However, very little information is available regarding the storage characteristics of cultivars that are susceptible to reducing sugar accumulation, such as Norland, Warba, and White Rose. VMD chips produced from these cultivars have textural characteristics that make them well suited for VMD potato chip production, regardless of their reducing sugar content (Chapter I). The objective of this study was to determine how long-term storage at 4°C followed by reconditioning at 12°C affects tuber composition of some cultivars used in VMD and oil-fried chip production.

3b. MATERIALS AND METHODS

Six cultivars (Kennebec, Shepody, Russet Burbank, Norland, Warba, White Rose), grown in the Fraser Valley of British Columbia, were harvested in 1998 and 1999 and stored from 1998-1999 and 1999-2000, respectively. Two controlled temperature rooms (800 ft$^3$; 4°C and 12°C) in the Department of Food Science, The University of British Columbia, were employed. Storage treatment was 4°C followed by reconditioning at 12°C for 2 wks. Tuber specific gravity and moisture content were measured after 6, 8, and 10 months of storage in 1998-1999 and from 5-10 months in 1999-2000. Tuber starch, amylose, reducing sugar, and soluble carbohydrate contents were determined after 5, 6, 7, 8, 9, and 10 months storage (1999-2000).

Refer to “Chapter Ic. Materials and Methods” for experimental methodology on physical and biochemical procedures of tuber analysis.

3c. RESULTS

Kennebec, Shepody, Russet Burbank, Norland, Warba, and White Rose tubers stored for 10 months during 1998-1999 did not show any sprouting or post-harvest deterioration. No
significant changes occurred in tuber specific gravity (Table 3.1) or moisture content (Table 3.2) during storage in these cultivars. Significant differences, however, were observed in specific gravity and moisture content between certain cultivars. Based on these results, it was decided to further analyse these cultivars in the following year.

From results obtained in 1999-2000, analysis of variance (Table 3.3) showed that the year of production, cultivar, and storage duration had significant effects on tuber composition. Tubers produced in consecutive years had significant differences in terms of specific gravity and moisture contents. Cultivars differed significantly from each other in terms of specific gravity and moisture, starch, reducing sugar, and soluble carbohydrate contents. The duration of storage significantly affected tuber reducing sugar and soluble carbohydrate contents.

Specific gravity and moisture contents

During 1999-2000, Norland, Warba, and White Rose tubers were significantly lower in specific gravity than Russet Burbank during every month in storage (Fig.3.1). Norland, Warba, and White Rose also differed significantly from Russet Burbank in tuber moisture content (Fig. 3.2). Kennebec, Shepody, and Russet Burbank tubers had a substantially lower specific gravity during 1999-2000 than compared to the tubers stored in the previous year (1998-1999, Table 3.1). During both years of production, no significant changes over time for mean specific gravity or moisture content were observed for any given cultivar.

Starch and amylose contents

Cultivars Russet Burbank, Shepody, and Kennebec contained significantly higher concentrations of starch than cultivars Norland, Warba, and White Rose (Figure 3.3). High variation in starch content was observed for all cultivars, especially in Kennebec and Shepody.
Table 3.1. Specific gravity of 6 cultivars after 6, 8, and 10 months storage (1998-1999) at 4°C followed by reconditioning at 12°C for 2 wks.

<table>
<thead>
<tr>
<th>Storage duration</th>
<th>Cultivar</th>
<th>Kennebec</th>
<th>Shepody</th>
<th>Russet Burbank</th>
<th>Norland</th>
<th>Warba</th>
<th>White Rose</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 months</td>
<td></td>
<td>1.1047 ± 0.0062 a</td>
<td>1.1038 ± 0.0054 a</td>
<td>1.0984 ± 0.0068 a</td>
<td>1.0746 ± 0.0057 c</td>
<td>1.0866 ± 0.0075 bc</td>
<td>1.0891 ± 0.0067 b</td>
</tr>
<tr>
<td>8 months</td>
<td></td>
<td>1.1063 ± 0.0095 a</td>
<td>1.0982 ± 0.0099 ab</td>
<td>1.0981 ± 0.0087 ab</td>
<td>1.0649 ± 0.0082 c</td>
<td>1.0882 ± 0.0044 b</td>
<td>1.0875 ± 0.0088 b</td>
</tr>
<tr>
<td>10 months</td>
<td></td>
<td>1.1030 ± 0.0102 a</td>
<td>1.0849 ± 0.0111 ab</td>
<td>1.0935 ± 0.0082 a</td>
<td>1.0680 ± 0.0088 c</td>
<td>1.0714 ± 0.0067 bc</td>
<td>1.0798 ± 0.0070 bc</td>
</tr>
</tbody>
</table>

1 Means ± SE (n = 4). Values in a row followed by a different letter (a -c) are significantly (P = 0.05) different.

2 The effect of storage duration was not significant (P = 0.05) for any cultivar.
Table 3.2. Moisture content (% w/w) of 6 cultivars after 6, 8, and 10 months storage (1998-1999) at 4°C followed by reconditioning at 12°C for 2 wks.

<table>
<thead>
<tr>
<th>Storage duration</th>
<th>Kennebec</th>
<th>Shepody</th>
<th>Russet Burbank</th>
<th>Norland</th>
<th>Warba</th>
<th>White Rose</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 months</td>
<td>75.6 ± 1.9 c</td>
<td>76.0 ± 1.8 bc</td>
<td>76.5 ± 1.3 bc</td>
<td>80.7 ± 0.7 a</td>
<td>78.1 ± 1.0 b</td>
<td>76.8 ± 0.7 bc</td>
</tr>
<tr>
<td>8 months</td>
<td>75.4 ± 2.0 c</td>
<td>76.8 ± 2.2 bc</td>
<td>74.9 ± 1.5 d</td>
<td>82.9 ± 0.9 a</td>
<td>77.2 ± 1.1 b</td>
<td>78.2 ± 1.0 b</td>
</tr>
<tr>
<td>10 months</td>
<td>74.3 ± 2.4 d</td>
<td>77.0 ± 2.2 c</td>
<td>75.7 ± 1.6 d</td>
<td>81.5 ± 0.8 a</td>
<td>79.6 ± 1.4 b</td>
<td>78.2 ± 1.1 bc</td>
</tr>
</tbody>
</table>

1 Means ± SE (n = 4). Values in a row followed by a different letter (a-c) are significantly (P = 0.05) different.

2 The effect of storage duration was not significant (P = 0.05) for any cultivar.
Table 3.3. Sources of variation and their probability of influencing tuber specific gravity and moisture, starch, amylose, reducing sugar, and soluble carbohydrate contents (1999-2000).

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>D.F.</th>
<th>Specific Gravity</th>
<th>Moisture</th>
<th>Starch</th>
<th>Amylose</th>
<th>Reducing sugar</th>
<th>Soluble carbohydrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year of production</td>
<td>1</td>
<td>0.047*</td>
<td>0.024*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cultivar (C)</td>
<td>5</td>
<td>0.050*</td>
<td>0.010*</td>
<td>0.012*</td>
<td>0.906</td>
<td>0.028*</td>
<td>0.047*</td>
</tr>
<tr>
<td>Time (T)</td>
<td>5</td>
<td>0.387</td>
<td>0.329</td>
<td>0.116</td>
<td>0.676</td>
<td>0.044*</td>
<td>0.025*</td>
</tr>
<tr>
<td>Replication ¹</td>
<td>1, 3, 7, 11</td>
<td>0.270</td>
<td>0.757</td>
<td>0.602</td>
<td>0.134</td>
<td>0.137</td>
<td>0.058</td>
</tr>
<tr>
<td>C x T</td>
<td>25</td>
<td>0.733</td>
<td>0.450</td>
<td>0.352</td>
<td>0.783</td>
<td>0.131</td>
<td>0.655</td>
</tr>
</tbody>
</table>

* = Significant at the 0.05 probability level

¹ Degrees of freedom for replication = 1 for year of production, 3 for specific gravity; 7 for starch, amylose, reducing sugars, and soluble carbohydrates; 11 for moisture content.
Figure 3.1. Specific gravity of cultivars during 5-10 months storage (1999-2000) at 4°C followed by reconditioning at 12°C for 2 wks.

1 Means for cultivars (n =6) not having a common letter (a-d) on top are significantly (P = 0.05) different at a given storage duration. Error bars represent standard error of the mean.
Figure 3.2. Moisture content (% w/w) of cultivars during 5-10 months storage (1999-2000) at 4°C followed by reconditioning at 12°C for 2 wks.

¹Means for cultivars (n =12) not having a common letter (a-d) on top are significantly (P = 0.05) different at a given storage duration. Error bars represent standard error of the mean.
Figure 3.3. Starch content of cultivars during 5-10 months storage (1999-2000) at 4°C followed by reconditioning at 12°C for 2 wks.

1 Means for cultivars (n = 8) not having a common letter (a-c) on top are significantly ($P = 0.05$) different at a given storage duration. Error bars represent standard error of the mean.
tubers. There were no significant changes in tuber starch content over time for any given cultivar. Amylose content in different cultivars ranged from 14.0-20.3 % of their total starch content (Figure 3.4). White Rose and Russet Burbank had the highest mean amylose contents of the cultivars. There were no significant changes in mean amylose content over time, although the amylose content varied by as much as 3 % per cultivar.

**Reducing sugar and soluble carbohydrate contents**

The reducing sugar concentrations in all cultivars increased significantly over time (Figure 3.5). Russet Burbank and Shepody had significantly lower concentrations of reducing sugars than cultivars Norland, Warba, and White Rose. Dramatic increases in reducing sugars began after 9 months for Russet Burbank and Shepody, and after 6 months for Kennebec. Cultivars Norland, Warba, and White Rose contained high reducing sugar concentrations at 5 months and the sugar concentration continued to rise up to 10 months.

Cultivars Norland and Kennebec significantly increased in soluble carbohydrate contents over time (Figure 3.6). Kennebec soluble carbohydrates increased rapidly after 6 months storage, similar to changes in its reducing sugar content at the same time period. Shepody and Russet Burbank had significantly lower concentrations of soluble carbohydrates than Norland, Warba, and White Rose.

**3d. DISCUSSION**

Tuber composition has been reported to vary within the part and the tissue of a tuber (Weaver, 1978a,b), within a cultivar population (Kleinkopf et al., 1987), and between the years of production (Sinha et al., 1992; Zulu and Pritchard, 1987). Smith (1975) recommended random sampling from at least 100 tubers to accurately measure specific gravity.
Figure 3.4. Amylose content (% of total starch) of cultivars during 5-10 months storage (1999-2000) at 4°C followed by reconditioning at 12°C for 2 wks.

¹Means for cultivars (n = 8) not having a common letter (a-c) on top are significantly ($P = 0.05$) different at a given storage duration. Error bars represent standard error of the mean.
Figure 3.5. Reducing sugar content of cultivars during 5-10 months storage\(^2\) (1999-2000) at 4\(^\circ\)C followed by reconditioning at 12\(^\circ\)C for 2 wks.

\(^1\)Means for cultivars (n = 8) not having a common letter (a-c) on top are significantly (P = 0.05) different at given storage duration. 
\(^2\)Means for each storage duration not having a common letter (x-z) on top are significantly (P = 0.05) different for a given cultivar. 
Error bars represent standard error of the mean.
Figure 3.6. Soluble carbohydrate content of cultivars during 5-10 months storage\(^2\) (1999-2000) at 4°C followed by reconditioning at 12°C for 2 wks.

\(^1\)Means for cultivars (n =8) not having a common letter (a-d) on top are significantly (P = 0.05) different at a given storage duration.

\(^2\)Means for each storage treatment not having a common letter (y-z) on top are significantly (P = 0.05) different for a given cultivar. Error bars represent standard error of the mean.
Variation in tuber composition may affect the quality of the final chip product. Chips sliced from a single tuber differ in their dry matter composition, as do chips sliced from different tubers. Therefore, to ensure consistent chip quality, it is important for a batch of stored tubers to have uniformity in dry matter composition within each tuber and among different tubers. Kennebec and Shepody had greater variation in terms of specific gravity and moisture content than the cultivars, which could significantly affect their final chip quality.

Storage losses are defined as losses in tuber weight and quality, caused by respiration, evaporation, sprouting, and changes in chemical composition (Rastovski, 1987). Hence, a storage treatment is considered effective when tubers do not significantly change in composition over time, along with minimal variance between sampled tubers. No significant changes over time were determined in specific gravity or starch content for any cultivar. Therefore, the loss of solids due to tuber respiration during storage was minimized, although changes in the weights of individual tubers were not recorded. Changes in tuber moisture content were also insignificant over time for all cultivars. Any gain in tuber moisture content due to respiration may have been balanced out by moisture lost through evaporation (van Es and Hartmans, 1987b).

Amylose content of potato starch has been reported as high as 33-39 % (O'Donoghue et al., 1996; Weaver et al., 1978a) when quantified by iodine colorimetric methodology. The maximum absorbancies of amylose and amylopectin are not clearly separated (Hovenkamp-Hermelink et al., 1988; Garcia et al., 1995) and should be taken into account when calculating the relative amount of each compound. McCready and Hassid (1943) separated potato starch into amylose and amylopectin by diffusion analysis and reported 19.0 % amylose content in potato starch, which corresponds closely to our results (Fig. 3.4).
Smith (1975) reported that tubers should have no more than 0.25% (fresh wt.) reducing sugar content for production of oil-fried chips. Pritchard and Adam (1994) reported that reducing sugar accumulation in Russet Burbank and Shepody tubers stored at 8°C for 9 months led to unacceptably colored french-fries. Russet Burbank and Shepody contained the least amount of reducing sugars among the cultivars (Fig. 3.5), and would have been acceptable for oil-fried chip production until 8 months storage. Reconditioning of tubers at 12°C for 2 weeks did not sufficiently minimized reducing sugars for Kennebec, Norland, Warba, or White Rose to be used for oil-fried chipping. Liu et al. (1990) reported that Kennebec tubers required 4 weeks of reconditioning at 20-25°C to produce acceptable colored oil-fried chips, after being stored for 9 months at low temperatures.

Soluble carbohydrate content of tubers mainly includes reducing (glucose and fructose) and non-reducing (sucrose) sugars. The proportion of tuber soluble carbohydrates to reducing sugars was observed to vary slightly over time in each cultivar. Changes in this proportion could be due to fluctuations in sucrose and transitional sugar content during starch-sugar conversions (van Es and Hartmans, 1987b). Monitoring changes in the ratio of tuber sugars could be useful as an indicator of increased tuber respiration or the onset of sprouting.

In conclusion, tuber storage at 4°C followed by reconditioning at 12°C for 2 wks was effective in extending tuber longevity, by sufficiently minimizing loss of tuber dry matter and moisture content due to respiration, evaporation, and sprouting. This storage treatment would have been ineffective for oil-fried chip processing, due to high reducing sugar concentrations in all cultivars. Considering that VMD chip colour was not significantly affected by cultivar or storage treatment (Chapter I), it may be possible to employ low temperature storage without a reconditioning treatment for tubers used in VMD chip production. Storage of tubers at one temperature could save substantial costs for the VMD chip processor.
CONCLUSIONS AND RECOMMENDATIONS

The quality of VMD chips was assessed by colour and texture analyses. Cultivar did not significantly affect chip colour. However, it did have a significant influence on the chip texture, as greater force was required to fracture chips produced from cultivars with high specific gravity and starch content. Chip texture was reflected in part by the physical structure of the chip. Chips with less rigid textures appeared to have greater tissue expansion and porosity.

Likewise, post-harvest storage did not affect chip colour, but had an influence on chip texture and tuber physiology. Tubers stored at 12°C were unprocessable beyond 4 months due to deterioration, turgor loss, and sprouting. In order to extend tuber longevity, the 18 cultivars employed in this study were stored for up to 10 months at 4°C followed by reconditioning for 2 weeks at 12°C. Chip textural changes over time occurred in both storage treatments. These results led to a final study (1999-2000) focusing on 6 commercially important cultivars (Kennebec, Shepody, Russet Burbank, Norland, Warba, and White Rose) stored from 5-10 months at 4°C followed by reconditioning. The results for these cultivars showed no significant changes in either chip texture, tuber specific gravity, or starch and moisture contents. Tuber sugar content did significantly increase with storage time.

VMD potato chips may have marketing potential in the snack food industry, as an alternative crispy-textured potato snack with no added calories or ingredients other than salt. The future commercial success of this product is dependent on three key areas: research and development, market testing, and cost of production.
Research and development should focus on improving VMD chip texture and mouthfeel. Chip nutritional components, such as minerals and vitamin C content, should be evaluated (advertisement of nutritional benefits could serve as a strong marketing tool). Optimum storage conditions specific for cultivars employed in VMD chip production should then be determined. Market testing would be comprised of large-scale hedonic evaluations to determine consumer preferences for chip crispiness, flavour, and overall acceptability. Also important is the development of a proper marketing strategy (ie. healthy fat-free snack). For large-scale production of VMD chips, the processing equipment must remain reliable and the technology should be accepted with confidence by the food industry and the consumer. Production costs will need to be minimized. The cost of raw materials could be reduced by bulk purchasing of potato tubers and low-temperature storage to increase longevity. VMD chips may also have a longer potential shelf life than oil-fried chips, since there would be no rancidity due to the oxidation of fatty acids.

Whether this novel snack food product will be marketed in the near future is yet to be determined. Perhaps oil-fried chip producers could incorporate VMD chip technology in order to lower the fat content of their current brands (much like the microwave potato chip finishing industry of the 1960’s). Either way, there is potential for the VMD potato chip.
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APPENDIX I

Analysis of VMD chips and tuber physiology from 18 potato cultivars

(1998-1999)
Table A. Mean tuber specific gravity.

<table>
<thead>
<tr>
<th></th>
<th>Kennebec</th>
<th>Norgold</th>
<th>Russet</th>
<th>Red Pontiac</th>
<th>Rhinegold</th>
<th>Shepody</th>
<th>Warba</th>
<th>Yukon Gold</th>
<th>Binje</th>
<th>Chiefteen</th>
<th>Desiree</th>
<th>Epicure</th>
<th>Nooksack</th>
<th>Norchip</th>
<th>Russet Burbank</th>
<th>Russet Norkotah</th>
<th>White Rose</th>
</tr>
</thead>
<tbody>
<tr>
<td>* 1 month</td>
<td>1.074</td>
<td>1.079</td>
<td>1.067</td>
<td>1.061</td>
<td>1.063</td>
<td>1.066</td>
<td>1.067</td>
<td>1.067</td>
<td>1.067</td>
<td>1.068</td>
<td>1.097</td>
<td>1.095</td>
<td>1.108</td>
<td>1.092</td>
<td>1.093</td>
<td>1.089</td>
<td>1.077</td>
</tr>
<tr>
<td>* 2 months</td>
<td>1.099</td>
<td>1.081</td>
<td>1.112</td>
<td>1.109</td>
<td>1.106</td>
<td>1.095</td>
<td>1.081</td>
<td>1.125</td>
<td>1.142</td>
<td>1.082</td>
<td>1.103</td>
<td>1.103</td>
<td>1.105</td>
<td>1.099</td>
<td>1.110</td>
<td>1.076</td>
<td>1.065</td>
</tr>
<tr>
<td>* 4 months</td>
<td>1.099</td>
<td>1.078</td>
<td>1.074</td>
<td>1.079</td>
<td>1.094</td>
<td>1.099</td>
<td>1.080</td>
<td>1.112</td>
<td>1.112</td>
<td>1.078</td>
<td>1.095</td>
<td>1.095</td>
<td>1.087</td>
<td>1.113</td>
<td>1.089</td>
<td>1.096</td>
<td>1.082</td>
</tr>
<tr>
<td>** 6 months</td>
<td>1.104</td>
<td>1.074</td>
<td>1.066</td>
<td>1.087</td>
<td>1.081</td>
<td>1.119</td>
<td>1.103</td>
<td>1.102</td>
<td>1.119</td>
<td>1.084</td>
<td>1.103</td>
<td>1.104</td>
<td>1.109</td>
<td>1.088</td>
<td>1.089</td>
<td>1.089</td>
<td>1.089</td>
</tr>
<tr>
<td>** 8 months</td>
<td>1.106</td>
<td>1.064</td>
<td>1.072</td>
<td>1.083</td>
<td>1.087</td>
<td>1.109</td>
<td>1.098</td>
<td>1.078</td>
<td>1.078</td>
<td>1.096</td>
<td>1.109</td>
<td>1.097</td>
<td>1.096</td>
<td>1.090</td>
<td>1.098</td>
<td>1.098</td>
<td>1.087</td>
</tr>
<tr>
<td>** 10 months</td>
<td>1.103</td>
<td>1.068</td>
<td>1.076</td>
<td>1.085</td>
<td>1.088</td>
<td>1.098</td>
<td>1.084</td>
<td>1.093</td>
<td>1.106</td>
<td>1.071</td>
<td>1.107</td>
<td>1.104</td>
<td>1.105</td>
<td>1.090</td>
<td>1.093</td>
<td>1.094</td>
<td>1.079</td>
</tr>
</tbody>
</table>

* tubers stored @ 12 degrees  
** tubers stored @ 4 degrees and reconditioned @ 12 degrees for 2 weeks  

n = 6

Table B. Mean moisture content (% w/w).

<table>
<thead>
<tr>
<th></th>
<th>Kennebec</th>
<th>Norgold</th>
<th>Russet</th>
<th>Red Pontiac</th>
<th>Rhinegold</th>
<th>Shepody</th>
<th>Warba</th>
<th>Yukon Gold</th>
<th>Binje</th>
<th>Chiefteen</th>
<th>Desiree</th>
<th>Epicure</th>
<th>Nooksack</th>
<th>Norchip</th>
<th>Russet Burbank</th>
<th>Russet Norkotah</th>
<th>White Rose</th>
</tr>
</thead>
<tbody>
<tr>
<td>* 1 month</td>
<td>76.9</td>
<td>81.1</td>
<td>80.4</td>
<td>80.0</td>
<td>74.1</td>
<td>76.3</td>
<td>78.2</td>
<td>74.5</td>
<td>76.9</td>
<td>79.3</td>
<td>78.4</td>
<td>76.5</td>
<td>74.6</td>
<td>75.5</td>
<td>77.0</td>
<td>75.0</td>
<td>77.0</td>
</tr>
<tr>
<td>* 2 months</td>
<td>77.3</td>
<td>80.2</td>
<td>80.5</td>
<td>80.4</td>
<td>79.7</td>
<td>75.7</td>
<td>77.5</td>
<td>75.3</td>
<td>71.2</td>
<td>80.5</td>
<td>77.8</td>
<td>76.4</td>
<td>75.7</td>
<td>76.1</td>
<td>76.9</td>
<td>78.5</td>
<td>79.1</td>
</tr>
<tr>
<td>* 4 months</td>
<td>78.3</td>
<td>81.2</td>
<td>81.2</td>
<td>79.7</td>
<td>79.4</td>
<td>76.0</td>
<td>77.6</td>
<td>76.7</td>
<td>73.7</td>
<td>80.6</td>
<td>77.8</td>
<td>74.9</td>
<td>75.4</td>
<td>74.1</td>
<td>77.3</td>
<td>78.5</td>
<td>78.7</td>
</tr>
<tr>
<td>** 6 months</td>
<td>75.6</td>
<td>80.7</td>
<td>80.0</td>
<td>81.5</td>
<td>76.3</td>
<td>76.0</td>
<td>78.1</td>
<td>75.4</td>
<td>72.9</td>
<td>79.2</td>
<td>78.2</td>
<td>75.6</td>
<td>77.2</td>
<td>72.5</td>
<td>76.5</td>
<td>75.8</td>
<td>76.8</td>
</tr>
<tr>
<td>** 8 months</td>
<td>75.4</td>
<td>82.9</td>
<td>81.3</td>
<td>81.5</td>
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* tubers stored @ 12 degrees  
** tubers stored @ 4 degrees and reconditioned @ 12 degrees for 2 weeks  

n = 6

Table C. Mean sensory panel ratings1 of VMD chip texture.

<table>
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<tr>
<th></th>
<th>Kennebec</th>
<th>Norgold</th>
<th>Russet</th>
<th>Red Pontiac</th>
<th>Rhinegold</th>
<th>Shepody</th>
<th>Warba</th>
<th>Yukon Gold</th>
<th>Binje</th>
<th>Chiefteen</th>
<th>Desiree</th>
<th>Epicure</th>
<th>Nooksack</th>
<th>Norchip</th>
<th>Russet Burbank</th>
<th>Russet Norkotah</th>
<th>White Rose</th>
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1 scale 0-5; control chip = 0  
* tubers stored @ 12 degrees  
** tubers stored @ 4 degrees and reconditioned @ 12 degrees for 2 weeks  

n = 4

83
Table D. Mean force-deformation values of VMD chip texture.

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<th>Pontiac</th>
<th>Redgold</th>
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<th>Warba</th>
<th>Yukon Gold</th>
<th>Binje</th>
<th>Chieftain</th>
<th>Desiree</th>
<th>Epicure</th>
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<th>Norchip</th>
<th>Russet Burbank</th>
<th>Russet Norkotah</th>
<th>White Rose</th>
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* tubers stored @ 12 degrees
** tubers stored @ 4 degrees and reconditioned @ 12 degrees for 2 weeks
n = 12
Table E. Mean HunterLab values of VMD chip colour.

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</tbody>
</table>

Hue

\[\tan^* (b/a)\]

| 0 months | -80.4 | -82.9 | -82.2 | -83.7 | -81.3 | -89.6 | -79.1 | 89.5 | -85.3 | -86.0 | -85.6 | -87.8 | -86.3 | -84.7 | -86.1 | -83.4 | -88.3 | 89.7 |
| 1 month  | -80.2 | -82.8 | -82.9 | -81.5 | -80.8 | -82.2 | -84.9 | -84.0 | -80.0 | -76.0 | -81.8 | -80.1 | -78.4 | -78.8 | -80.8 | -81.8 | -81.1 |     |
| 2 months | -84.0 | -83.4 | -83.1 | -86.7 | -78.0 | -83.5 | -86.5 | -84.0 | -81.5 | -82.6 | -79.5 | -84.3 | -84.5 | -78.4 | -83.9 | -80.9 | -80.8 | -77.6 |
| 4 months | -86.2 | -86.2 | -83.8 | -86.1 | -85.1 | -89.4 | -86.0 | -85.0 | -87.0 | -83.7 | -81.5 | -87.9 | -85.8 | -84.2 | -86.3 | -86.5 | -86.4 | -88.7 |
| 6 months | -81.5 | -83.1 | -84.1 | -85.2 | -80.6 | -87.4 | -81.1 | -88.8 | -83.2 | -87.5 | -82.9 | -86.9 | -85.0 | -83.1 | -85.5 | -84.4 | -86.3 | -89.3 |
| 8 months | -80.7 | -84.3 | -86.3 | -83.3 | -79.5 | -85.3 | -84.2 | -87.5 | -80.6 | -84.4 | -80.4 | -82.1 | -83.6 | -80.4 | -83.9 | -82.9 | -82.7 | 88.9 |
| 10 months| -85.2 | -83.7 | -84.0 | -84.6 | -79.8 | -85.5 | -87.5 | 89.4 | -82.3 | -85.1 | -79.1 | -85.6 | -82.7 | -78.1 | -84.2 | -86.4 | -80.1 | -86.7 |

Chroma

\[\sqrt{a^2 + b^2}\]

| 0 months | 11.6  | 13.8  | 11.0  | 13.4  | 13.6  | 20.0  | 13.2  | 14.4  | 19.4  | 14.2  | 13.3  | 17.5  | 17.3  | 15.3  | 17.2  | 13.6  | 15.1  | 15.2  |
| 1 month  | 12.6  | 11.0  | 10.2  | 13.8  | 11.3  | 18.5  | 14.3  | 13.0  | 17.1  | 14.0  | 10.7  | 21.7  | 17.5  | 14.5  | 15.7  | 13.3  | 15.2  | 14.6  |
| 2 months | 12.7  | 12.1  | 9.6   | 13.0  | 9.7   | 11.9  | 12.0  | 11.3  | 12.5  | 9.2   | 10.1  | 12.2  | 12.9  | 10.0  | 13.2  | 10.5  | 10.4  | 8.6   |
| 4 months | 17.7  | 15.2  | 13.2  | 16.7  | 15.4  | 26.5  | 14.4  | 13.8  | 21.3  | 17.2  | 12.2  | 21.9  | 17.0  | 13.6  | 16.2  | 14.8  | 15.4  | 15.6  |
| 6 months | 15.3  | 12.7  | 9.9   | 15.7  | 14.9  | 21.3  | 16.7  | 15.1  | 16.4  | 15.8  | 19.6  | 21.7  | 16.0  | 12.9  | 14.9  | 11.9  | 13.6  | 12.2  |
| 8 months | 14.4  | 16.4  | 11.9  | 12.4  | 10.4  | 20.2  | 11.7  | 12.9  | 17.5  | 11.1  | 13.8  | 12.2  | 13.8  | 11.5  | 15.4  | 12.4  | 12.9  | 10.4  |
| 10 months| 18.3  | 17.9  | 14.7  | 16.2  | 11.5  | 24.1  | 17.8  | 15.3  | 19.2  | 16.3  | 17.3  | 21.9  | 16.1  | 13.9  | 16.9  | 13.8  | 13.6  | 13.7  |

* Tubs stored @ 12 degrees
** Tubs stored @ 4 degrees and reconditioned @ 12 degrees for 2 weeks

n = 6