MEASUREMENT OF PHYSICAL PROPERTIES DURING PROCESSING OF FRENCH FRIES

A Thesis

Submitted to the Faculty of Graduate Studies

The University of Manitoba

by

Amewushika Agblor

In Partial Fulfilment of the

Requirements for the Degree

of

Doctor of Philosophy

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FACULTY OF GRADUATE STUDIES

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ABSTRACT

Colour and texture are the two most important quality attributes of the french fry processing industry. Achieving optimal colour and texture in french fries requires control of the unit process operations that convert raw potatoes into french fries. This, in turn, necessitates precise measurement of the effect of a given unit operation. A puncture test was used to measure the effects of blanching, drying and frying conditions on the mechanical properties (peak force, peak deformation and post-puncture energy consumption) of french fries. Potato cultivars (Russet Burbank and Shepody) grown at Portage and Carberry, Manitoba in 1994 and 1995, and stored for 11 months were used. For texture, a high peak force, a large peak deformation and a low post-puncture energy consumption were assumed to be associated with improved quality. French fry colour was also measured using the lightness (L) scale on a Hunterlab colorimeter. A high L value was indicative of improved colour quality. For a given unit operation, french fries processed by the standard conditions, which mimic industrial french fry operations, were compared to fries processed by a low-temperature long-time (LTLT) and a high-temperature short-time (HTST) regime. Processing conditions were found to have varying effects on french fry quality. With the exception of the LTLT blanching conditions, which improved both colour and textural quality, and the LTLT drying conditions which decreased these physical properties, a compromise has to be made between improved colour and improved textural quality. French fry quality was influenced by storage period, cultivar and site. French fries processed from potatoes at 11 months storage had improved colour and textural quality compared to potatoes at 9 months storage whereas fries processed at 3 months were darker in colour but firmer in texture than french fries processed from

potatoes at 1 month. For cultivar, no significant differences ($p \leq 0.05$) were found in peak force of fries made from Russet Burbank and Shepody potatoes but fries processed from Shepody potatoes were darker than those made from Russet Burbank potatoes. For site, fries made from Portage potatoes were darker in colour but firmer in texture than fries processed from Carberry potatoes.

Strip position within the tuber was a major source of variation for mechanical properties. Because mechanical properties vary widely within a given tuber and between tubers, it was necessary to compare the efficacy of two processing regimes using strips taken from as close a position as possible within the tuber. Peak force, peak deformation and post-puncture energy consumption were greater for blanched french fry strips located in the pith of the tuber (inner strips) than for outer strips taken from the cortex of the tuber. Examination of the microstructure of these french fry strips revealed that parenchyma cells in the outer strips had a "balloon-like" appearance due to the magnitude of starch swelling pressure generated by swollen granules. For inner strips, this "balloon-like" appearance was less evident. Such appearance is in support of the starch swelling pressure hypothesis. High swelling pressure induces deformation in the cell walls leading to tissue failure when an external stress is applied (such as in the puncture test). The measured volume of cell agglomerate obtained upon maceration of strips was significantly higher ($p \leq 0.001$) for outer strips than for inner strips and implies greater friability for outer strips. This is consistent with the swelling pressure hypothesis. It was concluded that because uniformity in product texture is crucial to product quality, a differential blanching treatment should be used, in which inner strips are blanched by HTST conditions and outer strips by LTLT conditions. To obtain optimal french fry quality, this differential blanching operation should be used in conjunction with the standard drying conditions

and the LTLT finish fry conditions.

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DEDICATION

To the Creator and Sustainer of the universe, the Lord God Almighty.

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1. INTRODUCTION

The potato is one of the world's staple food crops with an annual production estimated at 280 million metric tons (FAO, 1995). Recent trends in the global consumption of potato indicate that french fries are becoming increasingly popular (Anon, 1988). In Manitoba, french fries account for approximately 80% of all processed potato products (Manitoba Agriculture, 1995). It is currently estimated that french fries contribute up to 66 million dollars in revenue of which 11 million dollars is from frozen french fry exports (Manitoba Agriculture, 1995).

French fry quality is critical to consumer acceptability. The three main attributes that describe french fry quality are colour, texture and flavour (Talburt et al., 1987a) of which colour and texture are the most significant (Burton, 1989). The desirable textural attributes of a french fry are a crisp outer crust and a soft mealy interior (Talburt et al., 1987a; Du Pont et al., 1992). A mealy texture is one in which the cells are friable and lack cellular integrity (Böhler et al., 1986). More importantly, a french fry should be firm and break evenly when bent (Burton, 1989). Fry colour, on the other hand, must be light cream to golden-brown to be of acceptable quality, and a uniform colour is highly desirable (Talburt et al., 1987a). The extent to which a food processor can achieve these quality attributes is dependent on a number of factors.

The structure and composition of parenchyma cells play a crucial role in determining french fry quality. Parenchyma cells make up the principal tissue constituting potato tubers and their structure and composition is determined by a number of factors such as cultivar, climatic conditions and edaphic factors (Iritani, 1981; Faulks and Griffiths, 1983). The three most abundant components of

parenchyma cells are water, starch and pectin (Jarvis et al., 1981). Through interactions with other tuber components these three components contribute significantly to potato texture (Linehan and Hughes, 1969a). The reducing sugars, namely glucose and fructose, resulting from the biochemical degradation of starch during storage are of prime importance to fry colour (Roe et al., 1990). At high processing temperatures these sugars react with amino acids in a non-enzymatic browning reaction, called the Maillard reaction, to produce undesirable brown colouration and bitter flavour compounds (Baltes, 1982). Sucrose, a non-reducing sugar, participates in other non-enzymatic browning reactions and contributes to the brown discolouration (Leszkowiat et al., 1990).

French fry quality is also determined by compositional and anatomical variations evident within the tuber (Sharma et al., 1959b; Sayre et al., 1975). Potato flesh is comprised of various tissue types, namely the cortex, located below the periderm or skin, the vascular storage parenchyma and the pith which is located in the centre of the tuber (Talburt et al., 1987b). A vascular ring consisting mainly of xylem and phloem conducting vessels separates the cortex from the vascular storage parenchyma. Dry matter distribution within the tuber varies from one tissue type to another, with pith tissue containing relatively few starch granules and cortical tissue packed with starch granules (Reeve, 1967). Compositional variations are also evident from the stem to the bud end of the tuber: the stem end, the point of attachment of the tuber to the plant, is higher in dry matter than the bud end (Artschwager, 1924; Reeve et al., 1970). These intrinsic variations are crucial to french fry quality, especially texture (Mohr, 1972).

Storage conditions play a vital role in determining the processing quality of

potato tubers. In Manitoba, processing grade french fry potatoes are stored at 8°C (Pritchard and Adam, 1992). During prolonged storage at this temperature cell membranes disintegrate and tuber components degrade. These events have implications on french fry colour and texture (Brierley and Cobb, 1992; Pritchard and Adam, 1992; Turnbull and Cobb, 1992). Storage of tubers at 8°C requires the use of chemical sprout suppressants but with increasing concerns about food safety and the environment, tubers are sometimes stored at lower temperatures (4-5°C) (Gichohi and Pritchard, 1995). However, accumulation of reducing sugars in potato tubers at low storage temperatures is detrimental to fry colour. By exposing tubers to high temperatures prior to processing, a process known as reconditioning, reducing sugars are reconverted to starch (Isherwood, 1973).

Processing conditions are also of critical importance to french fry quality. French fry processing is comprised of several unit operations, namely blanching, drying, parfrying, freezing and finish frying (Lingle, 1988). These unit operations induce structural changes in potato tissue which significantly influence both colour and texture (Kawabata et al., 1976; Kaymak and Kincal, 1994).

As frozen french fries continue to become an item of economic importance and as trade opportunities in international markets become available, there is an increasing need to ensure optimal french fry quality. Control of the various unit operations is therefore crucial to achieving optimal colour and texture in french fries. This, in turn, necessitates efforts to develop methods for precise measurement of the effect of a given process operation.

This study was therefore undertaken to determine the effects of unit process operations on the mechanical properties and colour of french fries as a means to

optimizing product quality. Because the textural properties of french fries are largely determined by compositional and anatomical variations inherent in potato tubers, this research also sought to examine ways to minimize this variability to attain uniformity in product quality.

2. LITERATURE REVIEW

2.1 The Structural Components Of The Parenchyma Cell

The structural components of parenchyma cells are fundamental to french fry quality. These components provide structure and organization to the cell and impart mechanical strength to the tissue thereby maintaining cellular integrity (Ilker and Szczesniak, 1990). Parenchyma cells consist of a primary cell wall and a membrane-bound protoplasm. The cell wall represents 1-3% of the fresh weight of the tuber (Hoff and Castro, 1969) and consists of cellulose, hemicellulose and pectic polysaccharides (Ryden and Selvendran, 1990). Glycoproteins and phenolic substances are also present. The cell walls are linked together by the middle lamella which is often interrupted creating intercellular air spaces. The air spaces account for about 1-3% of the total volume of the tuber and permit gaseous exchange with the atmosphere (Fedec et al., 1977). The protoplasm consists primarily of a nucleus, cytoplasm and vacuoles. Starch and water are the predominant components of the cytoplasm. Vacuoles contain cell sap which exert turgor pressure maintaining a state of turgor in the cells of raw potato (Newcomb, 1980).

2.1.1 Cellulose

Cellulose consists of linear chains of ß(1,4)-linked glucose molecules stabilized by intra- and intermolecular hydrogen bonds. Cellulose occurs naturally as microfibrils. The microfibrillar structure contains crystalline regions in which the cellulose molecules are closely packed. The amorphous regions of the macromolecule are less organized (Bacic et al., 1988) and may contain xylose and arabinose sugars (Ring and

Selvendran, 1978). Cellulose represents approximately 30% of the dry weight of the cell wall (Jarvis et al., 1981) and provides mechanical strength to the cell wall (Shomer and Levy, 1988).

2.1.2 Hemicellulose

Xyloglucan is the major hemicellulosic polymer of the potato cell wall (Ring and Selvendran, 1981). It consists of a cellulose backbone to which xylose sugars are attached at the C-6 position. The xylose sugars in turn are attached to arabinose and galactose sugars at the C-2 position. Through its strong attachment to cellulose by hydrogen bonds, xyloglucan provides a foundation upon which the microfibrils are embedded in the amorphous matrix (Ryden and Selvendran, 1990). Arabinogalactans and arabinoxylans are other hemicellulosic polymers present in the potato cell wall. Hemicellulose comprises 7-10% of the dry weight of the potato cell wall (Hoff and Castro, 1969; Jarvis et al., 1981).

2.1.3 Pectic polysaccharides

The pectic polysaccharides consist of a main backbone and pectin sidechains (Jarvis, 1984). The main backbone of pectin is comprised of linear chains of α(1,4)-linked galacturonic acid units containing α(1,2)-linked rhamnose sugars. Insertion of rhamnose sugars into the pectin backbone confers flexibility to the chain (Jarvis, 1984). A variable number of the carboxyl groups in the galacturonic acid chain contain methyl esters, acetyl or phenolic groups (Fry, 1986). The presence of these groups promote solubility and gelling of pectin by preventing cross-linking of the polymer (Jarvis, 1984). The pectin sidechains, which consist mainly of galactose, arabinose

and xylose sugars, act as bridges connecting the rhamnogalacturonan backbone to hemicellulose and cellulose (Jarvis, 1984).

The pectic polysaccharides are located in the cell wall and middle lamella. Cell wall pectin comprises approximately 55% of the dry weight of the wall (Hoff and Castro, 1969; Jarvis et al., 1981) and plays a role in providing mechanical strength to the cell wall. The pectic substances in the middle lamella, on the other hand, act as intercellular adhesives (Jarvis, 1984) and occur mainly as salts of calcium and magnesium (Warren and Woodman, 1973). Calcium has a stabilizing effect on pectin structure (Jarvis, 1984).

2.1.4 Glycoproteins

Glycoproteins constitute approximately 2% of the dry weight of the cell wall (Ring and Selvendran, 1978) and are attached to the rhamnogalacturonan backbone of pectin through the pectin sidechains (Fry, 1986). Extensin, a structural protein found in potato tissue, is thought to play a role in determining the rate of growth, size and shape of parenchyma cells (Taiz, 1984; Cassab and Varner, 1988). Hydroxyproline is the major amino acid of the protein fraction although other amino acids, such as serine and lysine, are present (Leach et al., 1982). The carbohydrate fraction is composed of arabinose and galactose sugars (Cassab and Varner, 1988).

2.1.5 Phenolics

Through cross-linking with cell wall polymers, the phenolic substances play a structural role in the cell wall (Jarvis, 1984). Tyrosine and chlorogenic acid are the main phenolic constituents of parenchyma cells (Reeve et al., 1969; Sosulski et al.,

1982) that are responsible for undesirable discolouration in uncooked and cooked potato tissue (Hughes and Swain, 1962). Tyrosine is found mainly as a constituent of cell wall proteins (Fry, 1983) while chlorogenic acid is coupled through ester linkages to the rhamnogalacturonan backbone (Fry, 1986). Ferulic and coumaric acids, also present in potato tissue (Sosulski et al., 1982), may play a role in the maintenance of cell wall integrity during processing (Parker and Waldron, 1995).

2.1.6 Water

Water constitutes approximately 70% of the parenchyma cell wall (Northcote, 1972) and plays a number of roles in the cell. Firstly, as a major component of the pectin gel network, water is a structural component of the amorphous matrix of the cell walls. The amount of water in the cell influences the consistency of pectin gels. Secondly, penetration of water into the microfibrillar structure causes disruption of linkages between the cell wall components, reducing the extent of cohesion between cellulose molecules and adhesion between the matrix polysaccharides and cellulose microfibrils. Consequently, the mechanical properties of the cell wall are altered (Northcote, 1972).

Water is an important cytoplasmic component. As part of the starch granule, water confers stability to the starch granule (Imberty et al., 1991). Water is also an important component of the vacuole. The vacuole contains a highly concentrated solution of salts and sugars known as the cell sap. Entry of water into the vacuole creates a turgor pressure which causes expansion of the vacuole and pressing of the cytoplasmic contents against the cell wall thereby stiffening the cellular structure as a whole (Niklas, 1989).

2.1.7 Starch

Located in amyloplasts, starch comprises 15-20% of the fresh tuber weight (Jarvis et al., 1981). Starch occurs naturally as round and oval-shaped granules (Fedec et al., 1977). The macromolecule consists mainly of the glucose polymers amylose and amylopectin and minor components such as lipid, protein and ionic substances (Biliaderis, 1989). Amylose is largely a linear α(1,4)-linked glucan comprising approximately 25% of the starch while amylopectin, constituting about 75%, is highly branched and consists of an amylose backbone with α(1,6) branch points.

Within the granule, the starch chains are intertwined into a compact structure of densely-packed double helices arranged in a hexagonal pattern. The double helices also occur in pairs and are held together by inter- and intramolecular hydrogen bonds (Imberty et al., 1991). Hydrogen bonding and the close association of starch chains provide mechanical stability to the granule (Biliaderis et al., 1980).

The starch molecule consists of crystalline and armorphous regions (Blanshard, 1987). The principal component of the crystalline region is amylopectin. The armorphous region, which is rich in amylose, contains less ordered polymer chains and is more susceptible to enzymatic hydrolysis (Blanshard, 1987). The sidechains of amylopectin, found predominantly in the amorphous regions, promote swelling and solubility of starch (Biliaderis, 1992).

2.1.8 Lipids

Lipids comprise approximately 0.1% of the tuber's fresh weight (Galliard, 1973) and the majority act as structural components of cell membranes. These tuber lipids are present mainly as phospholipids and glycolipids of which linoleic (18:2) and

linolenic (18:3) acids account for 42% and 17%, respectively, of the total fatty acid composition. Palmitic (16:0) and stearic (18:0) acids account for 27% and 9%, respectively of the fatty acid composition (Knowles and Knowles, 1989).

2.2 Biochemical And Physiological Changes In Cell Structure During Storage

2.2.1 Tuber sweetening

Potato tubers have the propensity for sugar accumulation during storage, a phenomenon known as tuber sweetening. Tubers harvested at chemical immaturity are more susceptible to sugar accumulation during storage (Pritchard and Adam, 1992), although the genetic constitution of the tuber is also an important factor (Barichello et al., 1990). Tuber sweetening during storage results from two main events: firstly, from prolonged storage of tubers, a condition known as senescent sweetening, and secondly, from storage of tubers at low temperatures (4-5°C) referred to as low-temperature sweetening (Van der Plas, 1987). While sugar accumulation due to low-temperature sweetening can be reversed by exposing the tubers to higher storage temperatures, a process known as reconditioning, senescent sweetening is irreversible (Isherwood, 1973).

The biochemical pathway for the conversion of starch to sugars in stored tubers occurs in three major steps, namely starch degradation, sucrose synthesis and hexose accumulation (Sowokinos, 1990). Starch degradation begins with the phosphorylation of starch by inorganic phosphate in the amyloplast resulting in the production of glucose-1-phosphate (G-1-P). Transportation of G-1-P across the amyloplast membrane into the cytoplasm takes place by specific translocators, such as inorganic phosphate, located in the inner amyloplast membrane (Sowokinos, 1990). In the

cytoplasm, G-1-P is first converted to glucose-6-phosphate (G-6-P) by phosphoglucomutase and subsequently to fructose-6-phosphate (F-6-P) by hexose isomerase. Sucrose synthesis involves the conversion of the hexose phosphates to sucrose by sucrose synthase. Sucrose is transported to the vacuole and growing sprouts (Davies, 1990). Hexose accumulation involves the conversion of sucrose to reducing sugars by invertase (Richardson et al., 1990).

It is currently hypothesized that the activation of a cyanide-resistant electron transport pathway in the mitochondrion of the cell might play a vital role in low-temperature sweetening in potato tubers (Duplessis et al., 1996). Increases in respiration rates accompanied by an increase in sugar concentrations in the tuber were observed during storage at low temperatures (4°C) (Amir et al., 1977). This rise in respiration rates was attributed to an increase in oxygen (O_2) solubility in the cell which activated the cyanide-resistant pathway leading to sucrose accumulation in tubers (Duplessis et al., 1996). Subsequent conversion of sucrose by invertase results in accumulation of reducing sugars and darkening in fry colour during processing (Duplessis et al., 1996). Sherman and Ewing (1982) noted that low levels of O_2 in the tuber suppressed the cyanide-resistant pathway and prevented sugar accumulation at low temperatures. However, it is currently unclear whether this pathway plays a role in tuber sweetening at 8°C (Duplessis et al., 1996). According to Sherman and Ewing (1982), the cyanide-resistant pathway is inactive at storage temperatures above 5°C.

2.2.2 Changes in starch granule size

Golachowski (1985) observed an increase in the total number of small-sized granules during a 12-week storage period at 8°C. Starch granules 20-30 μm and <

20 μm in diameter increased from 39% to 43% and from 16% to 20%, respectively whereas the number of large-sized granules >35 μm in diameter decreased from 45% to 37% during the same time period. This increase in the total number of small granules was attributed to enzymatic hydrolysis of large granules during storage. Reeve (1967) noted that the length of starch granules decreased from 32 to 28 μm as storage temperature decreased from 10 to 4°C. This decrease in length of large granules was also attributed to the susceptibility of large granules to enzymatic hydrolysis during storage. Changes in starch granule size during storage have been reported to influence gelling properties of starch (Golachowski, 1985).

2.2.3 Cell membrane disintegration

The vacuolar membrane is more susceptible to disintegration during senescence than the amyloplast membrane (Turnbull and Cobb, 1992) because while the latter consists of a double lipid bi-layer, the former is made up of a single bi-layer (Sowokinos et al., 1987). Lipolytic acyl hydrolase (LAH), an enzyme in potato tubers, catalyzes the breakdown of membrane lipids to polyunsaturated fatty acids, such as linoleic and linolenic acids, which in turn become substrates for lipoxygenase (Turnbull and Cobb, 1992). By catalyzing the incorporation of oxygen into these fatty acids, lipoxygenase initiates membrane disintegration. LAH exists in an inactive form in the vacuole (Galliard and Matthew, 1973). Increases in the activity of LAH after 3 months storage at 10°C (Turnbull and Cobb, 1992) and decreases in fatty acid content of tubers over a 10-month period at 9°C (Spychalla and Desborough, 1990) were indicative of disintegration of the vacuolar membrane.

Loss of vacuolar membrane integrity has several implications for french fry

quality. Firstly, the vacuole is a storage site for sucrose. Disruption of the vacuolar membrane results in accumulation of sucrose in the cytoplasm. The subsequent conversion of sucrose to reducing sugars is detrimental to fry colour (Spychalla and Desborough, 1990). Secondly, the vacuole is a storage site for excess inorganic phosphate (Sowokinos, 1990). Elevated levels of inorganic phosphate in the cell increase the rate of starch phosphorolysis and transfer of G-1-P across the amyloplast membrane into the cytoplasm (Sowokinos, 1990). Thirdly, loss of vacuolar membrane integrity during storage has implications on the turgidity of parenchyma cells (Brusewitz et al., 1989). The integrity of the amyloplast membrane, on the other hand, was found to be relatively unchanged during a nine-month storage period at 9°C (Sowokinos et al., 1987).

2.2.4 Tuber sprouting

Sprouting is one of the physiological changes occurring in potato tubers during storage. It involves the mobilization of starch reserves to the growing sprouts resulting in the production of reducing sugars in the tubers (Davies, 1990) which are detrimental to processing quality. Early sprout emergence during storage can be prevented by applying sprout suppressants such as chloro-isopropyl carbamate (CIPC) during storage or maleic hydrazide during the growing season (Gichohi and Pritchard, 1995). High levels of carbon dioxide (CO_2) gas arising in the storage facility at the time of application of CIPC is suggested to have adverse effects on fry colour (Mazza and Siemens, 1990) due to its effect on increased permeability of the amyloplast membrane (Workman et al., 1976) and high levels of nitrogenous compounds in the tuber (Seetharaman and Mondy, 1991). However, according to Pritchard and Adam

(1996), increased levels of CO_2 in the storage facility during application of CIPC did not have any detrimental effects on fry colour. These authors noted that darkening of fries was dependent on the chemical maturity of tubers prior to application of CIPC.

2.2.5 Moisture loss

Moisture loss in tubers occurs naturally during storage due to the physiological processes of respiration and transpiration (Braue et al., 1983). Excessive moisture loss after harvest is usually prevented by preconditioning of tubers. During preconditioning, tubers are exposed to conditions of high temperatures (15°C) and high relative humidity (85-90%) for approximately 14 days (Pritchard and Adam, 1992). Formation of suberin in the periderm acts as a barrier against excessive moisture loss (Braue et al., 1983).

2.2.6 Changes in other tuber components

Although changes in the cell wall components during long-term storage are reported to be negligible (Van der Plas, 1987; Burton, 1989), Sharma et al. (1959a) observed a decrease in the hemicellulose and pectic contents of potato tubers. During an 8-week storage period at 21°C, hemicellulose and pectin decreased from 1.9 to 1.3% and from 1.4 to 1.0 % fresh weight, respectively. Cellulose, however, remained relatively unchanged at 0.4% fresh weight. Changes in tuber proteins have also been observed. Brierley and Cobb (1992) reported that the ratio of free amino acids to soluble proteins in Pentland Dell tubers increased almost four-fold during an 8-month storage period at 10°C. Increases in the free amino acid content, comprised mainly of aspargine and glutamine, were attributed to degradation of tuber proteins during

storage.

2.3 Changes In Cell Structure During Processing

2.3.1 Blanching

In commercial french fry operations blanching is a brief heat treatment usually performed by immersing potato strips in hot water (Lingle, 1988). The objectives of blanching in french fry processing are firstly, to inactivate enzymes such as peroxidase which cause undesirable discolouration of potato tissue, and secondly to leach out surface sugars which have adverse effects on fry colour (Kaymak and Kincal, 1994). A third objective of the blanching operation is to gelatinize starch present in the surface tissue in order to prevent excessive oil uptake during frying (Lamberg et al., 1990) and fourthly, to facilitate moisture removal during drying by increasing the permeability of cell membranes (Van Arsdel, 1973). Blanching can also be performed in a two-stage operation involving a low-temperature long-time (LTLT) blanch followed by a high-temperature short-time (HTST) blanch. The HTST blanch is used to inactivate undesirable enzymes (Canet et al., 1984). The benefits of LTLT blanching in promoting desirable structural changes in frozen vegetables have been well-documented (Steinbuch, 1976; Canet et al., 1984; Fuchigami et al., 1995).

The application of heat during blanching induces several physical and chemical changes in the parenchyma cell (Katsaboxakis, 1984). The mode of heat transfer is by convection from the blanch water to the potato tissue and by conduction within the tissue (Califano and Calvelo, 1983). Mass transfer occurs concomitantly with heat transfer. One of the initial changes in the cell is the thermal expansion and expulsion of intercellular air due to entry of blanch water (Loh et al., 1982). The force with

which the air escapes creates mechanical stresses in the intercellular spaces which cause a weakening in cell structure (Loh et al., 1982). Loss of cell membrane integrity, due to protein denaturation (Katsaboxakis, 1984), results in loss of turgor pressure (Jarvis et al., 1992) and entry of water into the cytoplasm. Although the cellulosic and hemicellulosic components of the cell wall are relatively stable to heat (Fedec et al., 1977), increases in cell wall thickness due to hydration of the pectic polysaccharides have been reported (Kawabata et al., 1976).

During blanching, diffusion of sugars and other water-soluble substances such as minerals and vitamins out of the cells and into the blanch water occurs (Sullivan et al., 1985). The amount of sugars leaching out from potato tissue is dependent upon the blanching time and temperature (Kaymak and Kincal, 1994). Kaymak and Kincal (1994) observed an increase in sugars leached from tubers from 23% to 61% of total solids as blanching time increased from 10 to 40 min. Blanching temperature was 70°C. Likewise, as blanching temperature was raised from 70 to 80°C an increase in leached-out sugars from 23% to 31% of total solids was reported. Blanching time was 10 min. Garrote et al. (1984) reported that apparent glucose diffusivity increased from 2.3 to 8.2 x 10^{-10} m^2 s^{-1} as temperature increased from 55 to 65°C. Subsequent increase in temperature to 85C resulted in an increase in the apparent glucose diffusivity to 12.8 x 10^{-10} m^2 s^{-1}. According to Garrote et al. (1984), sudden increase in apparent glucose diffusivity between 55 and 65°C was caused by disintegration of cell membranes during thermal processing. Califano and Calvelo (1983) reported that during blanching at temperatures below 75°C there is an increase in reducing sugar content of potato tissue by approximately 20%. A similar mechanism has been reported to occur in sweet potato roots during cooking (Damir, 1989) who noted that

enzymatic hydrolysis of starch by amylase, between 60-70°C, may explain this increase in reducing sugar content during blanching.

Another change which occurs during blanching is a non-enzymatic discolouration known as after-cooking darkening. After-cooking darkening is due to a reaction between chlorogenic acid and iron (Hughes and Swain, 1962). Oxidation of the colourless chlorogenic acid-ferrous iron complex to the ferric iron complex produces the grey discolouration which becomes evident soon after blanching. After-cooking darkening is usually controlled by immersing potato strips in a solution of sodium acid pyrophosphate (SAPP) (Smith and Davis, 1960). SAPP forms complexes with iron thereby rendering it unavailable for the reaction.

2.3.2 Drying

The drying operation in french fry processing involves the gradual removal of moisture from the surface tissue to attain a moisture content of 62-66% (Lingle, 1988). Reduction in moisture content during drying minimizes fat uptake during frying (Lamberg et al., 1990). The mode of heat transfer to the outer layers of the french fry strip during drying is by convection (Crapiste et al., 1988). Within the tissue, heat transfer is by conduction. Mass transfer during drying is characterized by moisture removal from the tissue (Bouraoui et al., 1994) and deposition of dissolved substances such as sugars on the surface layer (Van Arsdel, 1973). Moisture transport within the potato occurs primarily by diffusion (Yusheng and Poulsen, 1988) along the cell walls (Molz and Ikenberry, 1974; Crapiste et al., 1988).

Changes in cellular structure during drying are due to shrinkage of cells (Ratti, 1994), formation of air-pores in the cell structure (Marousis and Saravacos, 1990) and

moisture re-distribution within the tissue (Van Arsdel, 1973). Wang and Brennan (1995) used light microscopy to study changes in cell structure during drying. Examination of horizontal and vertical tissue sections indicated that changes in cell structure were negligible. The drying regime was 70°C for 1h. Case hardening, another structural change occurring at high drying temperatures (above 100°C) (Van Arsdel, 1973), is a condition that arises when the rate of moisture removal from the surface tissue occurs faster than the rate of moisture migration from the interior tissue to the surface. The formation of a rigid surface layer retards further moisture removal (Ratti, 1994; Wang and Brennan, 1995). At high drying temperatures, approximately 103°C, precursors of the Maillard reaction are formed in the tissue which predisposes french fries to darkening during subsequent frying (Aguilera et al., 1975; Talley and Eppley, 1985).

2.3.3 Freezing

The rate of freezing significantly affects cellular integrity (Kawabata et al., 1976). Canet and Espinosa (1984) studied the effects of freezing rate on the shear rupture force of blanched potato tissue. The effect of quick freezing was found to be non-significant compared to the cooked control, 9.7 and 9.4 N, respectively, whereas slow freezing was found to cause a significant reduction (at the 1% level) in the shear rupture force to 5.2 N. Similar observations were made by Kawabata et al. (1976) who used light microscopy to study the effects of freezing rates on the cell structure of fully-fried french fries. While extensive disruption of cellular integrity was evident during slow freezing, in quick frozen tissue, cell integrity was maintained. Changes in cellular structure during slow freezing (freezing at a rate of less than 1°C/min)

(Fennema, 1989) were attributed to the formation of large extracellular ice crystals whereas changes during fast freezing were attributed to the production of small uniform ice crystals formed in intra- and extracellular regions (Kawabata et al., 1976; Canet and Espinosa, 1984).

2.3.4 Frying

2.3.4.1 Crust formation

Crust formation is a major structural change occurring during frying. The modes of heat transfer during frying are by convection from the heated oil to the product and by conduction within the product (Singh, 1995). The crust acts as a diffusion barrier preventing excessive moisture loss from the interior tissue (Reeve et al., 1968). Changes in cellular structure of the interior tissue were found to be minimal during frying (Reeve et al., 1968) whereas the cells in the crust layer appeared to be clumped together (Rose and Southcombe, 1987) due to excessive dehydration of the surface layer (Lamberg et al., 1990). Mass transfer during frying is dominated by moisture removal, oil uptake (Saguy and Pinthus, 1995) and migration of soluble substances from the interior tissue to the surface (Jiang and Ooraikul, 1989; Blumenthal, 1991). Moisture removal and oil uptake occur simultaneously (Kozempel et al., 1991). Oil uptake is reported to occur along the cell walls and void spaces in the tissue (Reeve et al., 1968) and is confined to the crust region (Keller et al., 1986; Lamberg et al., 1990) which is approximately 2 mm-thick after 6 min of frying at 190°C (Singh, 1995).

Time and temperature are important parameters governing the frying process (Rose and Southcombe, 1987; Blumenthal, 1991). Du Pont et al. (1992) reported that

increasing the frying time from 2 to 4 min resulted in an increase in crust thickness of fully-fried french fries from 0.4 mm to 0.9 mm, respectively. The frying temperature was kept constant at 187°C. An increase in crust thickness was also observed as the frying temperature increased from 155°C to 200°C (Pravisani and Calvelo, 1986).

2.3.4.2 The Maillard reaction

Under conditions of high temperatures and low moisture content the Maillard reaction proceeds with the development of undesirable coloured compounds (Aguilera et al., 1975; Talley and Eppley, 1985). The Maillard reaction occurs in several stages beginning with the reaction between a free amino group and an aldose or ketose group of a reducing sugar to form a glycosylamine (Baltes, 1982). This stage is reversible and the equilibrium depends on the moisture content of the product (Baltes, 1982). At lower moisture contents, the reaction proceeds at a faster rate (Aguilera et al., 1975). The next stage in the reaction involves the rearrangement of the glycosylamine by an Amadori rearrangement to yield an aldoseamine or ketoseamine. The third stage in the reaction involves further rearrangement of aldoseamine or ketoseamine to produce diamino or diketoseamine sugars which are then degraded to yield amino compounds. The amino compounds then undergo condensation to form furfurals and melanoidins, the brown pigments (Baltes, 1982). The intermediary products of the Maillard reaction are not visible during the initial stages of the reaction (Talley and Eppley, 1985). Glycosylamine, formed in the first stage of the reaction, can also undergo the Strecker degradation reaction resulting in the production of brown pigments and bitter flavour compounds.

2.4 Changes In The Molecular Structure Of Starch During Processing

2.4.1 Starch swelling pressure

Potato starch has the propensity for extensive swelling during thermal processing (Leach et al., 1959). Swelling begins in the amorphous regions and occurs in a radial pattern due to the orientation of starch chains in the granule (Sterling, 1974). Starch behaves as a weak-acid ion-exchanger in solution (Oosten, 1982). The presence of negatively charged phosphate groups, found abundantly on amylopectin (Swinkels, 1985), induce repulsive forces which result in unfolding of the helical starch chains (Cooke and Gidley, 1992) and extensive swelling of the granules. Starch swelling pressure of the order of 300 kPa is suggested to initiate cell cleavage along the middle lamella (Jarvis et al., 1992) and contribute to mealiness, a desirable textural attribute in cooked potato (Linehan and Hughes, 1969a; Böhler et al., 1986).

2.4.2 Starch gelatinization and retrogradation

Starch gelatinization occurring within 2-3 minutes at temperatures between 62 to 66°C (Donovan, 1979; Lamberg and Olsson, 1989) is accompanied by a transformation from the helical coil in the native structure to a random structure (Cooke and Gidley, 1992) as a result of destabilization of hydrogen bonds (Sterling, 1974). Amylose leaching out of the granule during gelatinization (Hoover and Hadziyev, 1981) complexes with tuber lipids of the amyloplast membrane (Morrison, 1981). Evidence of the presence of amylose-lipid complexes was demonstrated by comparing samples of potato starch with a pure lipid-amylose complex. Close similarities were found between the X-ray diffraction patterns (Hoover and Hadziyev, 1981). Formation of amylose-lipid complexes is suggested to restrict excessive

swelling and provide rigidity to the starch gel (Biliaderis and Tonogai, 1991). Lipid molecules are present either as inclusion complexes in the helical chains of amylose or in spaces between amylose and amylopectin molecules (Morrison, 1981; Biliaderis et al., 1985).

Evidence of formation of amylose-cellulose complexes during processing was demonstrated by Linehan and Hughes (1969b) using model systems containing tuber cells in solutions of amylose or amylopectin. The compressive strength of cooked tissue, as measured with a tenderometer, was compared to the compressive strength of the tissue when cooked in water. The results indicated that in the presence of amylose the compressive strength increased by 45% compared to water. However, when a solution of amylopectin was used, the relative increase in compressive strength was negligible (5%). These results suggested that through complexation with cellulose, amylose had a strengthening effect on the potato cell wall.

Ionic substances such as magnesium have been reported to increase tissue firmness through formation of complexes with starch (Haydar et al., 1980). According to Haydar et al., (1980) as the magnesium concentration in the cooking medium increased, the penetration force of cooked potato tissue, measured using a 6.4 mm-diameter cylindrical probe, increased concomitantly.

Starch retrogradation is a phenomenon occurring during cooling of starch gels (Biliaderis, 1992). Starch retrogradation is due to the aggregation and re-crystallization of starch chains (Miles et al., 1985). Although retrogradation can occur at temperatures of 45-60°C, the process is faster at lower temperatures (Biliaderis, 1992). Starch retrogradation influences cooked potato texture (Jankowski, 1992). Jankowski (1992) measured fracturability, defined as the maximum force to fracture

cooked tissue using two compression plates, at 4 and 20°C and reported that maximum force to fracture was consistently lower at 4 than at 20°C. Although starch retrogradation cannot be precluded from participating in structural changes in potato tissue during processing, retrogradation is faster at lower temperatures and higher fracturability of cooled starch gels would be expected at 4°C due to an increase in rigidity of starch gels, as observed by McCafferty and Bourne (1995). These latter authors reported that cooked potato tissue was firmer at 2°C than at 20°C.

2.5 Changes In The Molecular Structure Of Pectin During Processing

During processing, pectin is degraded into small molecular weight fractions (Loh and Breene, 1982). Calcium ions released from gelatinized starch during processing (Bartolome and Hoff, 1972) diffuse from the cytoplasm to the cell walls (Van Marle et al., 1994) to form complexes with pectin, particularly at low temperatures (Fuchigami et al., 1995). Calcium stabilizes pectin structure resulting in an increase in tissue firmness (Haydar et al., 1980; Canet et al., 1984). According to Moledina et al. (1981) a cooling period is critical for stabilization of the calcium-pectate complex. These authors noted that the penetration force of cooked potato tissue increased from 416 to 751 g force when cooling was incorporated in the cooking procedure.

The neutral sugars of the pectin sidechains have been implicated in structural changes during processing (Quinn and Shafer, 1994). These neutral sugars are relatively stable to heat (Loh and Breene, 1982) and during processing are suggested to play a structural role in maintaining the integrity of the cell wall while the calcium-pectate complexes are being formed (Quinn and Schafer, 1994).

According to Bartolome and Hoff (1972), at temperatures below 70°C pectin

methyl esterase (PME) catalyzes the removal of methyl ester groups on the pectin backbone to produce free carboxyl groups which become accessible for attachment by diffusing calcium ions thus implicating PME in structural changes in potato tissue during processing. However, the role of PME in potato texture has been disputed (Moledina et al., 1981; Taguchi et al., 1991). According to Moledina et al. (1981), optimum PME activity occurred at pH 7.0. At pH 6.1, the pH of potato tubers, the activity of PME decreased by 40%. Taguchi et al. (1991) noted that increasing the temperature from 60°C to 75°C resulted in a three-fold increase in the compressive strength of cooked potato tissue. Since the optimum temperature of PME occurred at 60°C, by 75°C enzyme inactivation would have occurred (Moledina et al., 1981).

2.6 Instrumental Methods For Measurement Of The Mechanical Properties Of French Fries

Ross and Porter (1966) used a Kramer shear press for measurement of french fry quality. The shear press was equipped with a multiblade system in which each blade was approximately 3 mm apart. A layer of fries was placed on top of the lower blades. During testing, the upper blades were lowered onto the fries and the energy consumption, interpreted as compression and shear (Ross and Porter, 1968), was used to describe the textural properties of french fries. In subsequent studies the Kramer shear press was used to investigate the effects of storage time and processing conditions on french fry texture (Ross and Porter, 1969; 1971). According to Ross and Porter (1971), storage of potatoes over a nine-month period did not have any significant effects on the quality of french fries although uncooked tubers were found to soften during storage. Length of cooling period after frying was found to cause a

significant reduction in shear energy (Ross and Porter, 1966; 1971). According to Ross and Porter (1966), shear energy decreased almost two-fold after 30-min cooling period relative to a sample with no cooling. This decrease in shear energy was attributed to softening of the crust resulting from moisture re-distribution in fries (Ross and Porter, 1966).

Rose and Southcombe (1987) used a modified version of the Kramer shear press in which a single blade 1 to 2.5 mm in thickness was forced halfway into french fry samples. These authors found a strong correlation ($r=0.91$) between the maximum force measured by this method and the shear force measured by the Kramer shear press. Freeman et al. (1992) used a similar method to determine the effect of cooking time on the softness of potato tissue. Potato strips, 3 cm long and 1 cm^2 in cross-sectional area, were cooked for 5, 10 and 15 min. After making incisions with a blade across the sides of the french fry strips, they were cut halfway through with a stainless steel wire 0.28 mm in diameter and maximum force exerted in cutting was measured. Freeman et al. (1992) reported that as cooking time increased the resistance to cutting decreased due to cell separation.

The droopmeter is another instrument that measures french fry texture (Anon, 1966). The droopmeter operates on the cantilever principle whereby the product is held at one end and allowed to bend throughout its entire length. The amount of bending, measured by the distance the unsupported end moves or by the angle of deflection from a horizontal plane (Anon, 1966), was used as an index of textural quality. A more rigorous approach was developed by Kapsalis et al. (1972) to measure the bending of raw potato strips at a constant rate of curvature. Well-defined rheological properties such as bending rigidity were indicative of the strength of the

potato strip. These authors noted possible relationships between mechanical measurements obtained from the bending test and sensory limpness. Du Pont et al. (1992) measured well-defined rheological properties of fully-fried french fries using a portable pendulum. The frozen fries were fried at various times at 187°C and held securely onto a plate. Impact energy of a pendulum hitting the fries was measured. Impact energy was found to increase from 9 to 13 mJ as frying time increased from 2 to 5 min.

2.6.1 The puncture test

The puncture test has been used extensively to measure the mechanical properties of a variety of food materials (Bourne, 1979). The puncture test is performed by puncturing a material with a cylindrical probe to a specified depth. The maximum force exerted (peak force), the deformation at peak force (peak deformation) and the energy consumption during penetration, measured by the area under the load-deformation curve, are used as indices of textural quality (Finney, 1969). A large peak force would be interpreted as an increase in tissue firmness (Bourne, 1965) whereas a large peak deformation would be interpreted as softer tissue (Bourne, 1967). Low energy consumption is suggested to be indicative of softer tissue (Finney, 1969).

The puncture test is suitable for performing texture measurements in localized regions of the material (Böhler et al., 1987). However, these results are often influenced by the outer epidermis or skin tissue of horticultural crops (Bourne, 1965). For example, Thompson et al. (1992) reported that the skin tissue contributed 60% of the overall force required to puncture cucumber fruit whereas in tomato fruit, the skin was reported to contribute up to 70% of overall firmness during ripening (Jackman and

Stanley, 1994).

Puncture force is dependent upon the compressive and shear forces exerted during testing (Bourne, 1966). The compressive force is determined by the area under the probe and by the compression coefficient of the material whereas the shear force is determined by the perimeter of the probe and the shear coefficient of the material. Puncture force, compression and shear are related by the following equation:

$$F=K_cA+K_sP+C \quad (1)$$

where F= puncture force (N)

K_c = compression coefficient of the material (Ncm^{-2})

A = area of the probe or $(diameter)^2$ for circular probes (cm^2)

K_s = shear coefficient of the material (Ncm^{-1})

P = perimeter of the probe or diameter for circular probes (cm)

C = constant, usually equal to zero within the limits of experimental error (Bourne, 1975).

Using probes of different sizes Bourne (1966) demonstrated that a plot of F vs A was rectilinear with slope equal to K_c and intercept K_sP+C indicating that puncture force and area were directly related when the perimeter was constant. Likewise, a plot of F vs P was rectilinear with slope K_s and intercept K_cA+C. Bourne (1966) noted that equation (1) can be used to calculate the puncture force for a probe of any size.

Hawkins and Harvey (1919) were, perhaps, the first to use the puncture test to measure the mechanical properties of potato. These authors investigated the susceptibility of potato cultivars to infection by the fungus *Pythium debaryanum*. The probe, consisting of a needle approximately 69 microns in diameter, was allowed to

puncture the tuber at various puncture locations and the maximum force exerted during the test was indicative of tissue resistance to the fungus. Their results, supported by microscopic observations, provided evidence of the mechanism by which fungal hyphae infect tubers. During infection the hyphae penetrate along the cell walls. The measured mechanical parameters were therefore indicative of the susceptibility of tubers to infection.

Other early reports of puncture testing were made by Witz (1954) and Finney et al. (1964) who measured the susceptibility of potato cultivars to bruising during harvesting. According to these authors high puncture force was indicative of a firm potato and increased susceptibility to bruising. Soft potatoes were less susceptible to bruising. Finney et al. (1964) stated that potatoes were more susceptible to bruising immediately after harvest. During the preconditioning and storage periods, however, the potatoes became less susceptible to bruising because of changes occurring in the periderm during preconditioning. The puncture test was performed by puncturing the surface tissue with a 1.6 mm probe. Witz (1954) used a 4 mm probe to perform puncture tests on eight potato cultivars grown at four locations. Although the different cultivars showed varying susceptibility to bruising, the geographic location was the major determinant of bruise susceptibility. Voisey et al. (1969) used a puncture test to investigate the effect of geographic location and storage time on tuber quality. The test was performed by puncturing tubers at 28 different locations with a 3 mm probe during an eight-month storage period. Although storage period did not have a significant effect on puncture force, potatoes grown at different geographic locations had significantly different puncture force from each other.

Fedec et al. (1977) used a puncture test to investigate compositional

differences in steam-cooked potato tissue. Energy consumption during penetration was measured using a cylindrical probe 6.4 mm in diameter. Their results indicated that puncture energy was higher for pith tissue than for perimedullary or cortical tissue. Differences in puncture energy between pith and cortical tissue were attributed to extensive cell separation in the cortex due to breakdown of the middle lamella. Anzaldúa-Morales et al. (1992) determined the effect of compositional and anatomical variations in raw potato tissue by puncturing tubers of different cultivars at various puncture locations with a 2.5 mm probe. Their results consistently showed that cortical tissue had higher puncture force than pith tissue. Differences between the stem and bud ends of the tuber were, however, found to be inconsistent from one cultivar to another.

2.7 Methods For Measurement Of French Fry Colour

Measurement of fry colour can be accomplished by visual comparison of fries to a colour chart or by instrumental analysis. The most frequently used visual standard for french fries in the potato industry is the USDA colour chart (Francis and Clydesdale, 1972). Colour charts have the advantage of convenience and simplicity but are limited in that the colour receptors of the human eye are subject to variation and colour evaluation is highly dependent on the operator (Francis, 1983).

The Hunterlab colorimeter is one of the most widely used instruments for measuring french fry and potato chip colour (Francis and Clydesdale, 1975). The Hunterlab colorimeter is designed to duplicate perception of colour. The colorimeter consists essentially of a light source, filters and a photodetector (Hunter and Harold, 1987). The filters in the colorimeter are analogous to the three sets of cones in the

human eye which are sensitive to red, blue and green light. During operation, light reflected from the sample passes through these filters to a photodetector. Colour is recorded by the instrument in L, a and b scales. The L scale is indicative of the degree of lightness or darkness of the sample as determined by the human eye (Hunter and Harold, 1987). The higher the L value the lighter the fry colour (Habib and Brown, 1956; Smith, 1961). The a and b scales are the red-green and blue-yellow scales, respectively, and these scales mimic the way in which messages sent from the cones to the brain are interpreted (Francis, 1983). Of these three Hunterlab parameters the L value is the best indicator of french fry and chip colour (Habib and Brown, 1956; Jiang and Ooraikul, 1989). Habib and Brown (1956) noted that there was a strong correlation ($r^2=0.94$) between the Hunterlab L value of potato chips and the optical density of brown pigments extracted from the chips, measured using a spectrophotometer. Likewise, Jiang and Ooraikul (1989) indicated that the Hunterlab L value of potato chips and french fries strongly correlated ($P=0.01$) with colour scores using standard colour charts.

One of the earliest documented reports using the Hunterlab colorimeter was for measurement of the effect of cultivar and storage conditions on potato chip colour (Habib and Brown, 1956). The cultivar Red Pontiac consistently produced darker coloured chips during storage compared to three other cultivars (Katadhin, Russet Rural and Red Kote). Habib and Brown (1956) reported that after four weeks of storage at 4°C, the mean Hunterlab L value of all four cultivars decreased from 50 to 32. However, during reconditioning at a temperature of 24°C the Hunterlab L value increased, reaching a value of 58 after the fourth week of reconditioning.

Smith (1961) used the Hunterlab colorimeter to determine the effects of soil

conditions and harvest date on potato chip colour and reported that tubers harvested early in the season (September) were lighter in colour than tubers harvested later in the season (November). A decrease in soil temperature was reported to cause darkening in chip colour, perhaps due to changes in tuber composition. A similar observation was made by Walkof (1970) who used the Hunterlab colorimeter to monitor changes in chip colour during tuber growth and development. Walkof (1970) noted that in three consecutive years after the 11th week of growth, chip colour of Kennebec potatoes declined to unacceptable values (Hunterlab L values below 45) as soil temperature dropped to 10°C. However, for two experimental cultivars, Walkof (1970) observed that up until the 20th week of growth chip colour was above acceptable levels, even as soil temperature declined to 4°C.

Effects of processing conditions on french fry colour have been studied using the Hunterlab colorimeter (Marquez and Anon, 1986; Toma et al., 1986; Schwartz et al., 1987). Schwartz et al. (1987) used the Hunterlab colorimeter to monitor changes in colour of sweet potato french fries during frozen storage over a one-year period. The french fries were blanched, partially dried and frozen. At 3-monthly intervals the frozen fries were finish fried. These authors reported that although colour changes during frozen storage were not evident, frying resulted in darker-coloured french fries. Toma et al. (1986) examined the effects of partial freezing prior to blanching and parfrying on french fry quality and reported that the Hunterlab L value of the finish fries that had received a partial freezing treatment (-21°C for 25 min) was consistently higher by 2-12 units than fries that had not received the treatment. Partial freezing was suggested to cause cellular damage which facilitated leaching of soluble substances during blanching resulting in light-coloured french fries. Marquez and Anon

(1986), on the other hand, determined the effect of frying conditions on chip colour of Kennebec potatoes and reported that chip colour decreased significantly from a Hunterlab L value of 50 to 25 as frying time increased from 3 to 5 min. Further changes in chip colour with increased frying time were more gradual reaching a value of 21 after 15 min.

The Agtron reflectance meter has also been used to measure potato chip and french fry colour (Francis and Clydesdale, 1975). When used to measure fry colour the Agtron reflectance meter is used with a green filter (Iritani and Weller, 1974), while for potato chips, a red filter is used (Coles et al., 1993). The maximum wavelength for the Hunterlab L filter is approximately the same as that of the green filter in the Agtron (Hunter and Harold, 1987; Orr and Janardan, 1990). Mazza et al. (1983) examined the relationship between chip colour and other tuber components, such as sugars, ascorbic acid and protein content. These authors reported that reducing sugars were the major tuber components influencing chip colour and cautioned that predicting chip colour based on data from one given cultivar could be erroneous since tuber composition varies from one cultivar to another. The correlation coefficient between chip colour and reducing sugars was 0.81, 0.62 and 0.66 for Russet Burbank, Norchip and Kennebec potatoes, respectively, although the correlation coefficient between chip colour and dry matter of these three cultivars was similar ($r=0.8$).

Recently, there have been applications of computer image analysis for measurement of colour of processed potato products (Coles et al., 1993; Ritchie, 1994; Scanlon et al., 1994). Scanlon et al. (1994) compared chip colour measured using image analysis to chip colour measured by Agtron and Hunterlab and noted that there was good correlation between these instruments. The coefficient of

determination (r^2) between the image analysis system and the Agtron was 0.83 whereas between image analysis and Hunterlab an r^2 of 0.88 was reported (Scanlon et al., 1994). A major advantage of using image analysis for chip colour measurements is in its ability to measure colour of individual chips in contrast to Hunterlab and Agtron which require a composite sample of chips (Coles et al., 1993). Using image analysis, Coles et al. (1993) noted that tuber-to-tuber variability was a more important factor influencing chip colour measurements than within tuber variability. On-line measurement of fry colour during commercial processing, using image analysis, has also been reported (Ritchie, 1994). According to Ritchie (1994), image analysis eliminates operator subjectivity but more importantly, it is an effective tool for monitoring raw material quality prior to processing.

2.7.1 Factors influencing colour measurement

2.7.1.1 Instrument calibration

Instrument calibration is essential for accuracy and is performed using standard coloured tiles of known reflectance (Hunter and Harold, 1987). These standards provide the basis for colour measurement of a sample. For example, Mondy and Gosselin (1988) used a grey tile to calibrate the Hunterlab colorimeter to determine the effects of phenolic substances on after-cooking darkening in potatoes, whereas Parkin and Schwobe (1990) used a yellow tile for calibrating the instrument to determine the effects of modified atmospheres and low-temperature storage on chip colour. Habib and Brown (1956), on the other hand, used an ivory-coloured tile to calibrate the Hunterlab colorimeter and noted that it was the closest to the colour of a light-coloured potato. In comparing the lightness values of potato chips measured by various colour

measuring instruments, Scanlon et al. (1994) used black and white tiles to calibrate the Hunterlab colorimeter.

2.7.1.2 Method of sample presentation

The manner in which the specimen is presented to the instrument influences colour measurement (Francis and Clydesdale, 1975; Hunter and Harold, 1987). The method of sample presentation is extremely important for colour measurement because it influences the amount of light reflected from the sample which is recorded by the photodetector. Schwartz et al. (1987) placed two rows of french fry strips in a sample cell 5 cm x 4 cm for measurement of colour of sweet-potato french fries whereas Jiang and Ooraikul (1989) covered the sample cell containing fries with a black aluminum plate in which a hole, 4 cm in diameter, had been made and fry colour was measured at three different positions through the hole.

2.7.1.3 Averaging of colour readings

In evaluating colour, the human eye averages the colour of an entire sample (Hunter and Harold, 1987). Therefore, it is essential in instrumental analyses for colour measurements to be performed on a number of samples to obtain a reading that is representative of the whole sample (Hunter and Harold, 1987). Scanlon et al. (1994) described a procedure in which potato chip samples were poured out of the sample cell into a plastic bag and back again into the sample cell to obtain representative colour readings of potato chip samples. Parkin and Schwobe (1990), on the other hand, reported that three colour measurements were performed on each sample of crushed potato chips although no description of the procedure was recorded.

2.7.1.4 Changes in fry colour during cooling

Changes occur in fry colour immediately after removal from the fryer (Iritani and Weller, 1974; Scanlon et al., 1994). Iritani and Weller (1974) observed changes in fry colour beginning 3 min after removal of fries from the fryer up until 10 min whereas Scanlon et al. (1994) noted that the most significant change in chip colour occurred between 2 and 15 min. Change in chip colour was relatively steady up to 4 h (Scanlon et al., 1994). According to Iritani and Weller (1974) fry colour was relatively unchanged from 10 to 30 min.

3. MATERIALS AND METHODS

3.1 Materials

3.1.1 Potatoes

Processing grade potatoes (cvs. Russet Burbank and Shepody) were commercially grown at various sites in Manitoba from 1992 to 1996. The potatoes were supplied by Midwest Food Products (Nestlé-Simplot) in Carberry. The production sites, crop years and duration of storage are shown in Table 1.

The potatoes were harvested from August to October of each year and on arrival from the grower were preconditioned for 14 days at 15°C and 90% relative humidity (R.H.). The temperature was subsequently lowered to 8°C at the rate of 1°C/week (Pritchard and Adam, 1992). All tubers were stored at this temperature except for tubers grown at Graysville which separate lots were stored at 5°C and at 8°C. The tubers were sprout-inhibitor treated approximately four months after storage at a commercial facility by thermal fogging with iso-propyl N-(3-chlorophenyl carbamate) (CIPC).

3.1.2 Chemicals

Food grade sodium acid pyrophosphate (SAPP) and glucose were obtained from Albright and Wilson Amerique (Buckingham, PQ) and Aldrich Chemical Company (Milwaukee, WI), respectively. Glutaraldehyde and LR White Resin (medium grade) were purchased from Sigma Chemicals (St. Louis, MO) and Marivac Chemicals (Halifax, NS), respectively. Cellufluor was obtained from Polysciences, Inc. (Warrington, PA) and iodine and potassium iodide were procured from Mallinckrodt Inc. (Paris, TN).

Table 1. Production sites, crop years and storage periods for Russet Burbank (RB) and Shepody (SH) potatoes[1]

Crop year	Site	Cultivar	Maximum storage time (months)
1992	Graysville	RB, SH	11
1993	Winkler	SH	11
	Shilo	SH	11
	Carberry	RB, SH	11
	Portage	RB	11
	Carman	RB	11
1994	Shilo	RB	8
	Carberry	RB, SH	11
	Portage	RB, SH	11
	Carman	RB	6
1995	Shilo	RB	7
	Carberry	RB, SH	4
	Portage	RB, SH	7
1996	Shilo	RB	6
	Portage	RB	6

[1] All tubers were stored at 8°C and 90% R.H. except for tubers grown at Graysville which were stored at 5°C and at 8°C.

3.2 Methods

3.2.1 Overview

The study was comprised of four main parts.

Part I

Evaluation of methods for (i) processing of frozen french fries, (ii) measurement of french fry colour and, (iii) measurement of the mechanical properties of french fries.

Part II

Examination of methods to determine the source of variation associated with the measured mechanical parameters.

Part III

Quantification of differences between inner and outer french fry strips since strip position within a given tuber is a known major source of variation for the mechanical properties of french fries.

Part IV

Determination of the effects of various unit process operations on the colour and mechanical properties of fully-fried french fries and examination of microstructural changes in potato tissue during processing.

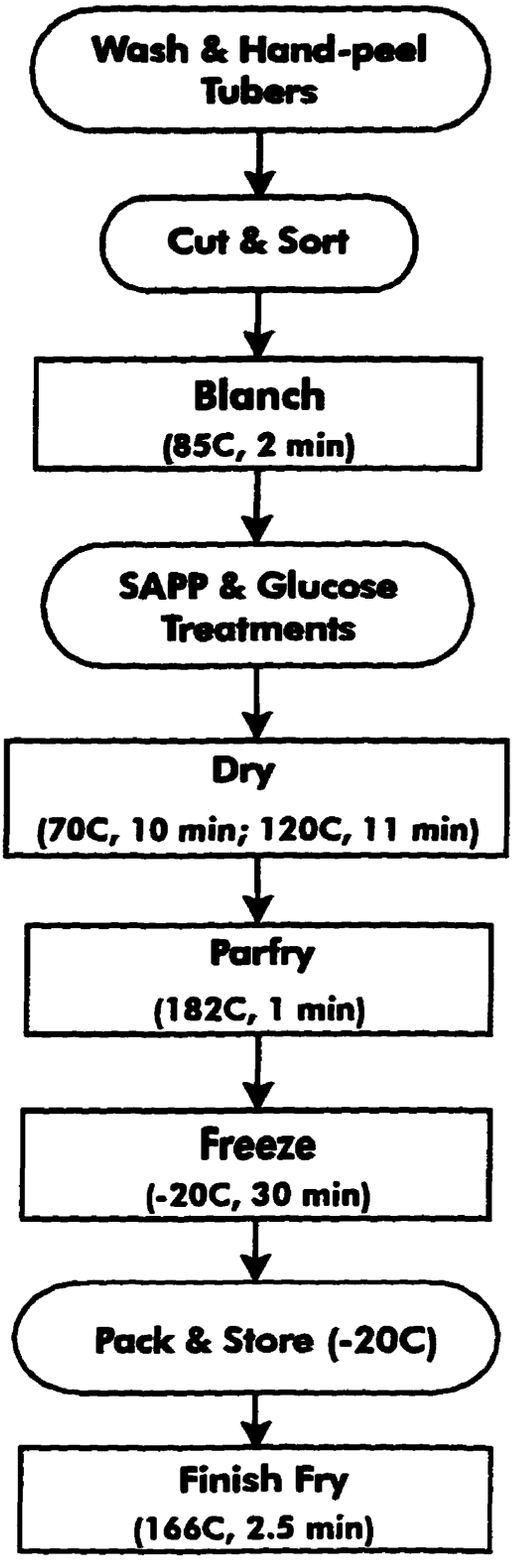
3.2.2 Procedure for french fry processing

Figure 1 is a flow diagram of the process operations that were used for french fry processing. These operations are based on industrial operations (Talburt et al., 1987a; Lingle, 1988) and are therefore similar to industrial operations used in Manitoba. Through preliminary experimentation, these continuous operation conditions were adapted to batch operations. Temperature was constantly monitored during each process operation using a thermocouple.

All tubers were removed from storage just prior to processing. Four tubers were processed at one time. The tubers were washed, hand-peeled and cut into strips using a french fry cutter (Bloomfield Industries, Chicago, IL). The strips were typically 1 cm^2 in cross-sectional area. The strips were sorted to remove small and defective pieces and placed in a mesh basket to facilitate transfer into and out of the blanch water. Blanching was performed in an open-jacketed thermostat-controlled steam kettle (Dover Corporation, Elk Grove Village, IL) by immersing the strips in hot water at 85 ± 2°C for 2 min. The blanched strips were subsequently immersed in a 0.5% (w/v) solution of sodium acid pyrophosphate (SAPP), maintained at room temperature (22 ± 1 °C), for 1 min. The strips were then arranged in a single layer, 0.5 cm apart, on a mesh tray and sprayed with a 1% (w/v) glucose solution (approximately 20 mL) using a wash bottle ensuring that all four sides received the glucose treatment. The tray was immediately transferred to the drying oven.

The drying operation was performed in a Moffat convection electric oven (Model ECO3, Deltarex Canada Inc., Orillia, ON). Drying was conducted in two phases as follows: 70 ± 5°C for 10 min and 120 ± 5°C for 11 min. It took approximately an additional 4 min to raise the temperature from 70°C to 120°C and the fries were kept

Figure 1. **Flow diagram of unit operations for french fry processing.**


Wash & Hand-peel Tubers
Cut & Sort
Blanch
(85C, 2 min)
SAPP & Glucose Treatments
Dry
(70C, 10 min; 120C, 11 min)
Parfry
(182C, 1 min)
Freeze
(-20C, 30 min)
Pack & Store (-20C)
Finish Fry
(166C, 2.5 min)

in the oven as the temperature was raised.

Immediately after drying, the french fries were placed in a frying basket and parfried in a thermostat-controlled deep-fat fryer (Garland Model 80-03, Mississauga, ON). The parfry operation was performed at 182±2°C for 1 min. To prevent fries from floating on top of the oil during frying, which leads to uneven colour development, one frying basket was stacked on top of the other prior to fully immersing the fries in oil. The frying oil, Crisco Professional Frying Oil (Proctor and Gamble, Toronto, ON), was a hydrogenated canola oil. The oil was changed after 150 h of frying (i.e. every 2-3 months prior to commencing processing experiments for a given storage period). Visual inspection of the oil was also conducted and the colour was observed to be golden-brown (not dark) at the time of change. After frying, the excess oil was removed from the fries by agitating the basket. The french fries were placed in a single layer on a metal tray and frozen in an air freezer (Model WTD, Coldstream Refrigerator Mfg. Ltd, Winnipeg, MB) at -20°C to attain a target temperature of -12°C. They were placed close to a fan to simulate conditions in a blast freezer. In preliminary experiments the time taken to attain a temperature of -12°C was 30 min. Subsequently, the fries were packaged in pre-labelled ziploc freezer bags, sealed and placed in frozen storage (-20°C). For finish frying, the french fries were taken directly out of frozen storage and fried with no thawing. The finish fry operation was performed at 166±2°C for 2.5 min. These finish fry conditions mimic the conditions used by fast-food outlets and restaurants.

3.2.3 Procedures for measurement of french fry colour

3.2.3.1 Instrumental measurement

Colour measurements were performed using a Hunterlab colorimeter (Model D25L-2, Hunter Associates Laboratory, Inc., Reston, VA). The instrument was calibrated with white and black tiles so that the Hunterlab L values were 92.4 and 0, respectively. Hunterlab L value (the lightness-darkness scale) was used as a measure of french fry colour (Jiang and Ooraikul, 1989).

3.2.3.2 Determination of method of sample presentation

Because the method of sample presentation influences the amount of light reflected from the surface of an object (Francis and Clydesdale, 1975; Hunter and Harold, 1987), five methods of sample presentation were investigated to determine the most suitable method for measurement of french fry colour. In presentation #1, ten fries were placed in a single layer at the bottom of the sample cell. (The dimensions of the cell were 10 cm x 10 cm x 5 cm). In presentation #2, four additional fries, two at each opposite end of the sample cell, were placed on top of, and perpendicular to, the bottom layer. The rationale for this presentation was to ensure that the ends of the bottom layer of fries were fully covered. Presentation #3 consisted of two layers of fries, each perpendicular to the other, while in presentation #4 a number of fries were heaped into the sample cell and shaken (not pressed) until the cell was full. Presentation #5 consisted of five layers of fries each perpendicular to the layer beneath it. The time taken to fill the sample cell was also recorded to aid in selecting the most suitable method.

3.2.3.3 Determination of effects of repacking and orientation on fry colour

The objective of this experiment was to select a suitable method for obtaining colour readings that were fully representative of the colour of a french fry sample (Hunter and Harold, 1987). Two procedures were investigated. In the first procedure (the repacking procedure), the french fries were emptied onto a tray after the initial colour reading, mixed together and repacked into the sample cell according to their given sample presentation method (3.2.3.2). Three repackings were performed for each sample presentation. In the second procedure (the orientation procedure), the sample cell containing french fries was rotated a quarter turn while on the window of the colorimeter. Colour measurements were recorded after each quarter turn. The sides of the sample cell were marked prior to the test.

3.2.3.4 Determining the effect of cooling on fry colour

The changes occurring in fry colour after finish frying (Iritani and Weller, 1974; Scanlon et al., 1994) were investigated. The rationale was to determine the extent to which fry colour was affected by cooling so that colour measurements could commence when change in fry colour was minimal. Colour measurements of fully-fried french fries were taken at predetermined time intervals beginning at 3 min after finish fry and then 2 min later. Thereafter, colour measurements were taken every 5 min for 30 min and every subsequent 15 min for 1 h.

3.2.4 Procedures for measurement of the mechanical properties of french fries

3.2.4.1 Determining the effect of cooling on mechanical properties

Because the mechanical properties of french fries change with standing time

(Ross and Porter, 1966; 1971; Bourne, 1982), it was necessary to determine when a change with time was minimal. Pre-washed and pre-peeled average-sized tubers were sliced longitudinally into 0.8 and 1.1 cm-thick samples using a Hobart food slicer (Model 410, Hobart Manufacturing Co., OH). The reason for using slices of various thicknesses was to determine whether the change in mechanical properties during cooling was independent of slice thickness. Three adjacent slices taken from as close as possible to the centre plane of each tuber were removed and marked. The rationale was to minimize tuber-to-tuber variations. The reason for using potato slices instead of fries was that while a potato slice has two major planes, a top and bottom plane, a french fry has more than two planes. Thus, during frying, heat transfer to the potato slice occurs through the top and bottom planes only, whereas in french fries heat transfer occurs in more than one plane (i.e. multidirectional). Potato slices were chosen to minimize the effect of this multidirectional heat transfer on mechanical properties. The slices were fried for 5 and 15 min at 177 ± 2°C to determine whether the changes in the mechanical properties during cooling were influenced by the thickness of the crust. The slices were cooled to room temperature for 15 min. The time taken for the samples to cool to room temperature was determined prior to the experiment by inserting a thermocouple into the centre of the slice. Mechanical testing commenced immediately after the cooling period. Thereafter, measurements were taken every subsequent 15 min for 45 min.

3.2.4.2 Measurement of the mechanical properties of the crust and fry interior

This experiment was aimed at measuring the mechanical properties of the individual components that comprise french fry texture, namely the crust and fry

interior (Ross and Porter, 1966; 1971). Pre-washed and pre-peeled average-sized tubers were sliced longitudinally into 1.1 and 1.4 cm-thick samples using a Hobart food slicer. Various thicknesses were used to determine whether the thickness of the fry interior would influence the mechanical properties. Two adjacent slices taken from as close as possible to the centre plane were removed from each tuber and marked. The slices were fried for 5, 10, 15 and 20 min at 177 ± 2°C to obtain crusts of various thicknesses (Rose and Southcombe, 1987; Du Pont et al., 1992) and cooled for 15 min prior to measurement of the mechanical properties. In separate experiments, just prior to testing 0.3 cm of crust material was sliced off the top and bottom of the 1.1 and 1.4 cm samples to obtain 0.5 cm- and 0.8 cm-thick slices of crust-free fry interior.

3.2.4.3 Puncture testing

Mechanical properties were measured by means of a puncture test using a 2 mm-diameter flat-end cylindrical probe. The texture instrument was a Chatillon Universal Testing Machine (Model ET 1100, John Chatillon and Sons Inc., NY). The probe was attached to the end of a drill chuck which, in turn, was mounted to a standard load cell (100 N). The probe was forced halfway into the french fry at a crosshead speed of 2 cm min^{-1}. Test parameters were determined in preliminary trials and this crosshead speed was selected because it was slow enough to permit the development of peaks on load-deformation curves. Each french fry was punctured once at the centre. Load-deformation data generated from each test were recorded by a computer software program (Quick Basic Program written at the Department of Biosystems Engineering, University of Manitoba) through a digital output connector in the back of the tester. The parameters obtained from these data, as shown in Figure

2, were peak force (the maximum force (N) exerted), peak deformation (the deformation at peak force (mm) and post-puncture energy consumption per meter of penetration during deformation. Post-puncture energy consumption was calculated from the area under the load-deformation curve from deformation ≥ 3 mm. The reason was it was assured that at deformations ≥ 3 mm, force measurements were those of the fry interior.

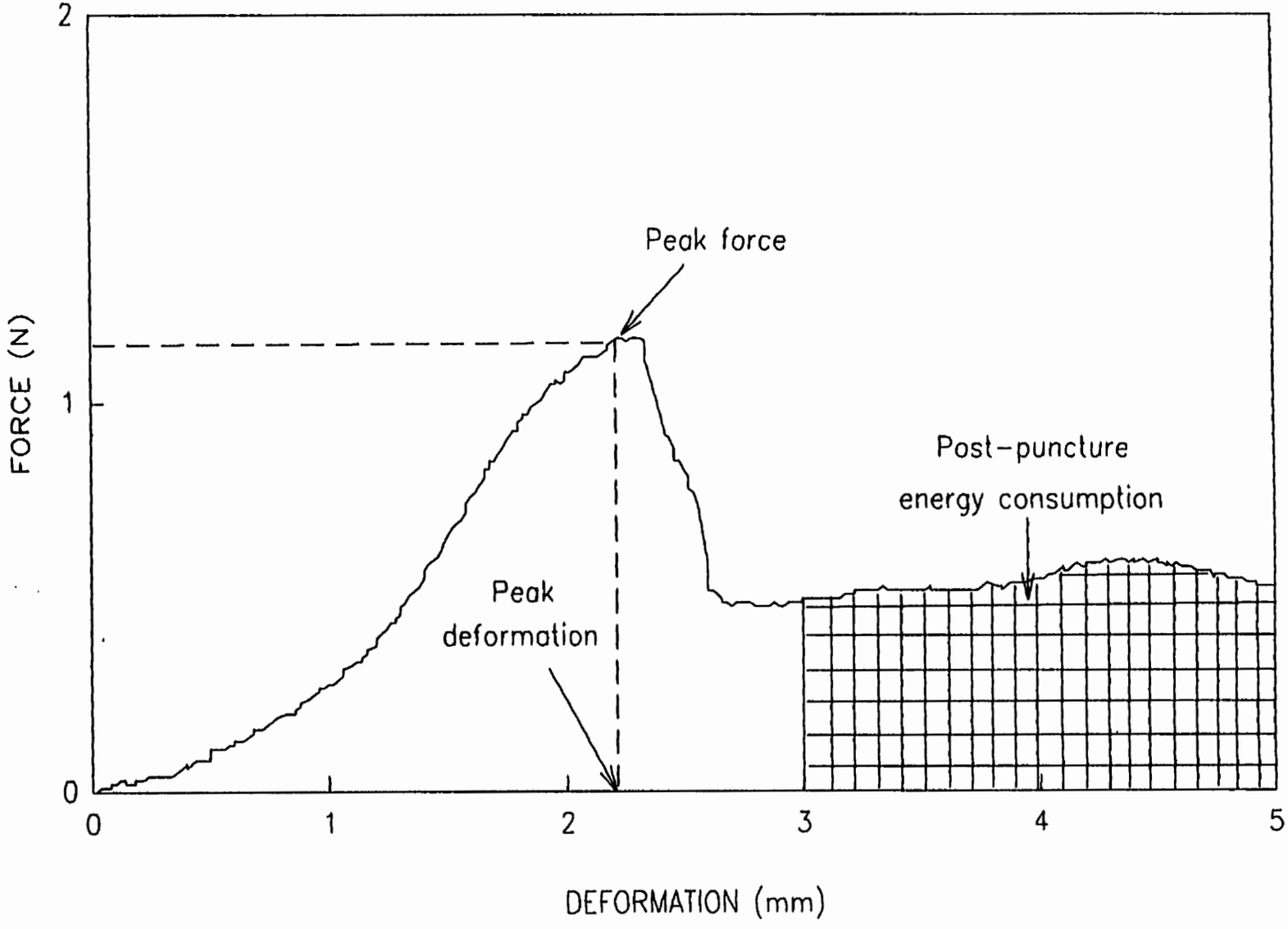
3.2.4.4 Preliminary statistical analysis

A completely randomized design was not feasible because measurements of colour and mechanical properties were taken at predetermined time intervals. Analysis of variance was performed using the General Linear Model (GLM) procedure from the statistical analysis software (SAS), version 6.04 (SAS Institute Inc., Cary, NC). Treatment differences were determined by Duncan's multiple range test ($P \leq 0.05$). Values for post-puncture energy consumption were calculated using the Quattro Pro software, version 4.0 (Borland International, Inc., Scotts Valley, CA).

3.2.4.5 Measurement of mechanical properties using a 0.5 mm-diameter probe

Because preliminary statistical analysis indicated that there was considerable variability associated with the measured mechanical parameters, further experiments were conducted to determine the contribution of the crust and fry interior to the overall mechanical properties. Potato strips, taken from as close as possible to the centre plane, were processed into french fries (as described in section 3.2.2). The frozen fries were finish fried for 1.5 and 2.5 min and cooled to room temperature for 15 min prior to testing. Some strips did not receive any finish fry treatment and were thawed

Figure 2. **Typical load-deformation curve of a french fry showing the parameters obtained.**


2
1
0
FORCE (N)
Peak force
Post-puncture
energy consumption
Peak
deformation
0
1
2
3
4
5
DEFORMATION (mm)

at room temperature prior to testing to attain a temperature of 22°C. Thawing time to achieve 22°C was 2.5 h and was determined by inserting a thermocouple into the centre of the fry.

Initial attempts to perform puncture tests on fully-fried french fries using the 2 mm probe failed because of the inability of the probe to penetrate the crusts. In puncture tests using fried potato slices the probe was forced halfway (i.e. 5 mm) into the sample but the crusts of fully-fried french fries could not be punctured with a deformation of 5 mm. Consequently, the probe size was changed to a 0.5 mm-diameter probe. The reason was that the 0.5 mm probe would create greater stresses and so penetrate the french fry crust. For puncture testing, four indentations were made on each strip: one indent each at the stem and bud ends (approximately 2 cm from the end of the strip) and two indents in the middle, approximately 0.5 cm apart.

3.2.5 Procedures for minimizing the variability associated with the measured mechanical parameters

3.2.5.1 Specific gravity determinations of potato tubers

Samples of potato were taken from 45-kg bags to determine the relative proportions of small-, average- and large-sized tubers. Tuber classification was based on standards for Canadian agricultural products (Agriculture Canada, 1993). Six tubers, four medium and two small, were randomly selected from each bag. The specific gravity of the individual tubers was determined by the weight in air-weight in water method (Dean and Thornton, 1992). All measurements were conducted at room temperature (22 ± 1 °C).

3.2.5.2 Comparing mechanical properties of adjacent strips

The work of Canet et al. (1984) was used to further investigate the source of variation associated with the measured mechanical parameters within a given tuber and between tubers. Because compositional variations occur within a given tuber (Sharma et al., 1959b; Sayre et al., 1975), it was necessary to compare strips taken from as close a position as possible within the tuber to minimize compositional variations. Additionally, because variations occur from the stem to bud end of the tuber (Reeve et al., 1970) it was necessary to identify these ends prior to cutting. By uniformly selecting the appropriate tuber end, the imprints of the french fry cutter on stem end was used as the distinguishing mark.

Two unit operations were studied, namely blanching, and blanching followed by freezing (Figure 3). For a given unit operation, five strips from as close as possible to the centre plane, as shown in Figure 4, were removed from a half-tuber. The strips were marked 1-5 where strips 1 and 5 were outer strips and strip 3, the inner strip. Marked strips from a half-tuber were blanched by HTST conditions (97 ± 1 °C for 2 min) while strips from the other half were blanched by LTLT conditions (see Figure 3). The LTLT blanch was performed in two steps. In the first step strips were blanched at 70 ± 1 °C for 10 min and cooled at 4°C for 2.5 min, and in the second step were blanched at 97 ± 1 °C for 2 min. These blanching conditions were selected because they produced the greatest difference in shear rupture force (Canet et al., 1984). For the blanch and freeze operation, the blanched strips were frozen overnight at -20°C. The rationale for the blanch and freeze operation was to determine whether the effects of blanching were evident in the mechanical properties after freezing. As shown in Figure 3, the above mentioned unit operations were performed using potatoes (cv.

Figure 3. **Layout of experiments for comparing the mechanical properties of adjacent french fry strips. The strips were blanched by two methods, and by blanching followed by freezing. The blanching conditions were: low-temperature long-time (LTLT) and high-temperature short-time (HTST).**

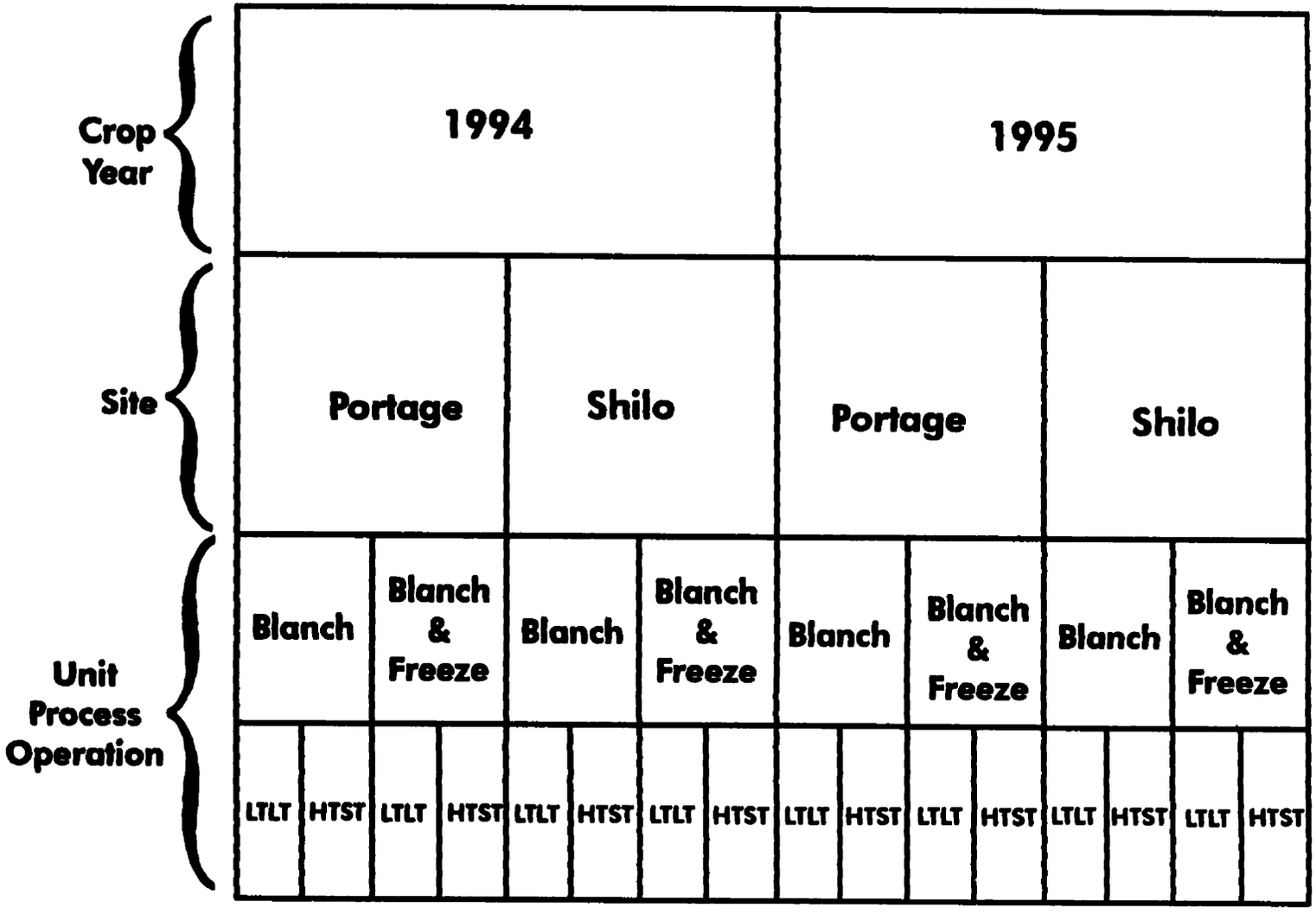

Crop Year
1994
1995
Site
Portage
Shilo
Portage
Shilo
Unit Process Operation
Blanch
Blanch & Freeze
Blanch
Blanch & Freeze
Blanch
Blanch & Freeze
Blanch
Blanch & Freeze
LTLT
HTST
LTLT
HTST
LTLT
HTST
LTLT
HTST
LTLT
HTST
LTLT
HTST
LTLT
HTST
LTLT
HTST

Figure 4. **Selection and marking of strips to compare the mechanical properties of adjacent french fry strips.**

centre
plane
5
4
3
2
1
1
2
3
4
5

Russet Burbank) grown at Shilo and Portage in two consecutive years and the tubers were stored for approximately the same length of time. Just prior to processing, the specific gravity of raw potato strips was determined by the weight in air-weight in water method (Dean and Thornton, 1992).

For puncture testing, the frozen french fry strips were thawed completely at room temperature for 2.5 h (as described in section 3.2.4.5) prior to the test whereas french fry strips blanched with no freezing were cooled to room temperature for 10 min just prior to testing. The time taken to attain room temperature was determined by inserting a thermocouple into the centre of the strip. Because the mechanical properties of cooked potato change during cooling (Bourne, 1982), for blanched french fry strips (with no freezing), while strips from one half-tuber were being tested the raw strips from the other half-tuber were wrapped in moist paper towels and placed in a sealable plastic bag. The reason was to prevent significant moisture loss. These strips remained in the bag at room temperature for a maximum of 45 min prior to blanching.

3.2.6 Procedures to examine differences between french fry strips

3.2.6.1 Measurement of cell agglomerate

The method of Freeman et al. (1992) was used with modification to further investigate differences in the measured mechanical parameters between inner and outer strips. The first modification was that low specific gravity (LSG) (inner) and high specific gravity (HSG) (outer) strips were used instead of LSG and HSG tubers. These strips were cut to 1 x 1 x 8 cm pieces by removing material from both ends. Secondly, the strips were blanched by HTST conditions instead of boiling for 30 min. This was done because the widest differences in the measured mechanical parameters

between inner and outer strips occurred under HTST conditions (see Results Figures 12-14). Thirdly, because the french fry strips were too hard to be pressed between two glass plates they were homogenized in a Sorvall Omni-Mixer (Ivan Sorvall Inc., Norwalk, Conn.) in 50 mL of distilled water for 30 s. The homogenate was passed through a 1 mm sieve and the volume of cell agglomerate passing through the sieve was measured.

3.2.6.2 Microscopy

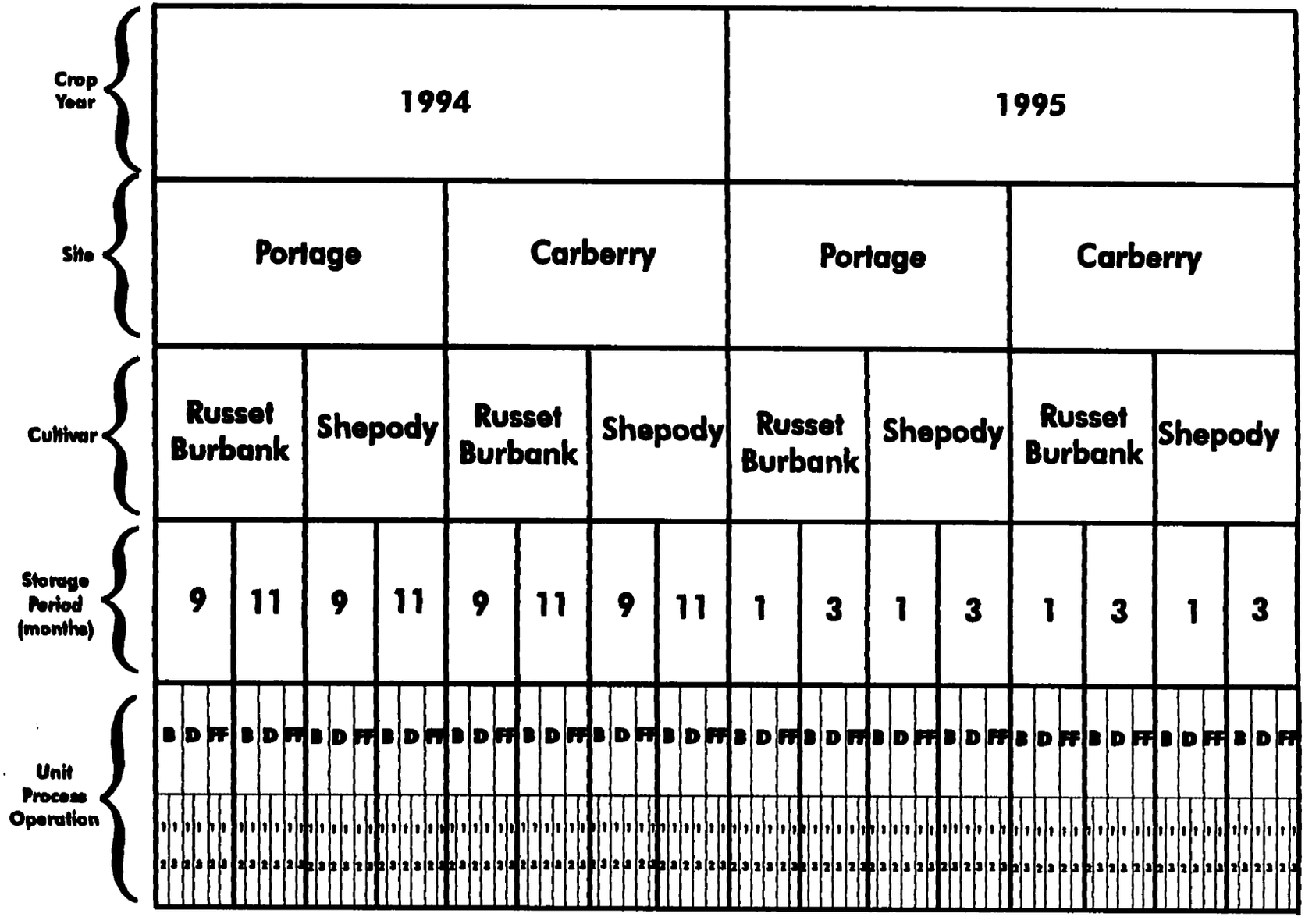
A stereomicroscope (Model SZH, Olympus, Japan) was used to examine structural differences in inner and outer french fry strips. The strips were blanched for 30, 40 and 120 s at 97°C. Short blanch times were used to observe initial structural changes in inner and outer strips. The blanched strips were cooled for 30 min at room temperature, cut into approximately 1 cm-thick sections using a sharp blade and rinsed with distilled water to remove surface-gelatinized starch. The sections were stained with 0.1% (w/v) iodine solution for 15 s. Excess iodine was washed off and the sections were viewed and photographed under the microscope equipped with a camera.

3.2.7 Procedures for determining the effects of unit process operations on the mechanical properties and colour of fully-fried french fries

3.2.7.1 Experimental plan

Three unit operations, blanching, drying and finish frying, were investigated as shown in Figure 5. The rationale was to examine changes in internal tissue structure (Kawabata et al., 1976; Kaymak and Kincal, 1994; Wang and Brennan, 1995) and in

Figure 5. **Layout of experiments to determine effects of unit process operations on the mechanical properties and colour of fully-fried french fries. B - blanch; D - dry; FF - finish fry. 1 - standard conditions; 2 - LTLT conditions; 3 - HTST conditions.**


Crop Year
1994
1995
Site
Portage
Carberry
Portage
Carberry
Cultivar
Russet Burbank
Shepody
Russet Burbank
Shepody
Russet Burbank
Shepody
Russet Burbank
Shepody
Storage Period (months)
9
11
1
3
Unit Process Operation
B
D
FF

the french fry crust (Rose and Southcombe, 1989; Du Pont et al., 1992) during processing. For each unit operation, three processing conditions were studied, namely LTLT, HTST and standard (industry) conditions. The experimental conditions (i.e. LTLT and HTST) were chosen to produce wide differences in mechanical properties and colour (Canet et al., 1984; Du Pont et al., 1992; Kaymak and Kincal, 1994). The standard conditions were used to provide a reference point for determining the effect of a given processing condition. A description of the processing conditions is shown in Table 2. Because strip position was a major source of variation for mechanical properties it was necessary to compare the standard conditions and a given processing condition using strips taken from as close as possible within the same tuber (Figure 5). Additionally, because storage period, cultivar and site are factors influencing french fry quality (Faulks and Griffiths, 1983; Pritchard and Adam, 1992), experiments were performed using Russet Burbank and Shepody potatoes grown at Portage and Carberry which had been stored for either 9 and 11 months or for 1 and 3 months. These storage months were chosen in order to study changes in french fry quality at the beginning and end of the storage period whereas the two cultivars were selected because they account for approximately 70% of potatoes grown in Manitoba for french fry processing (Manitoba Agriculture, 1995). The two sites were chosen because of varying soil types (Manitoba Soil Survey, 1957; 1972).

3.2.7.2 Selection and marking of strips

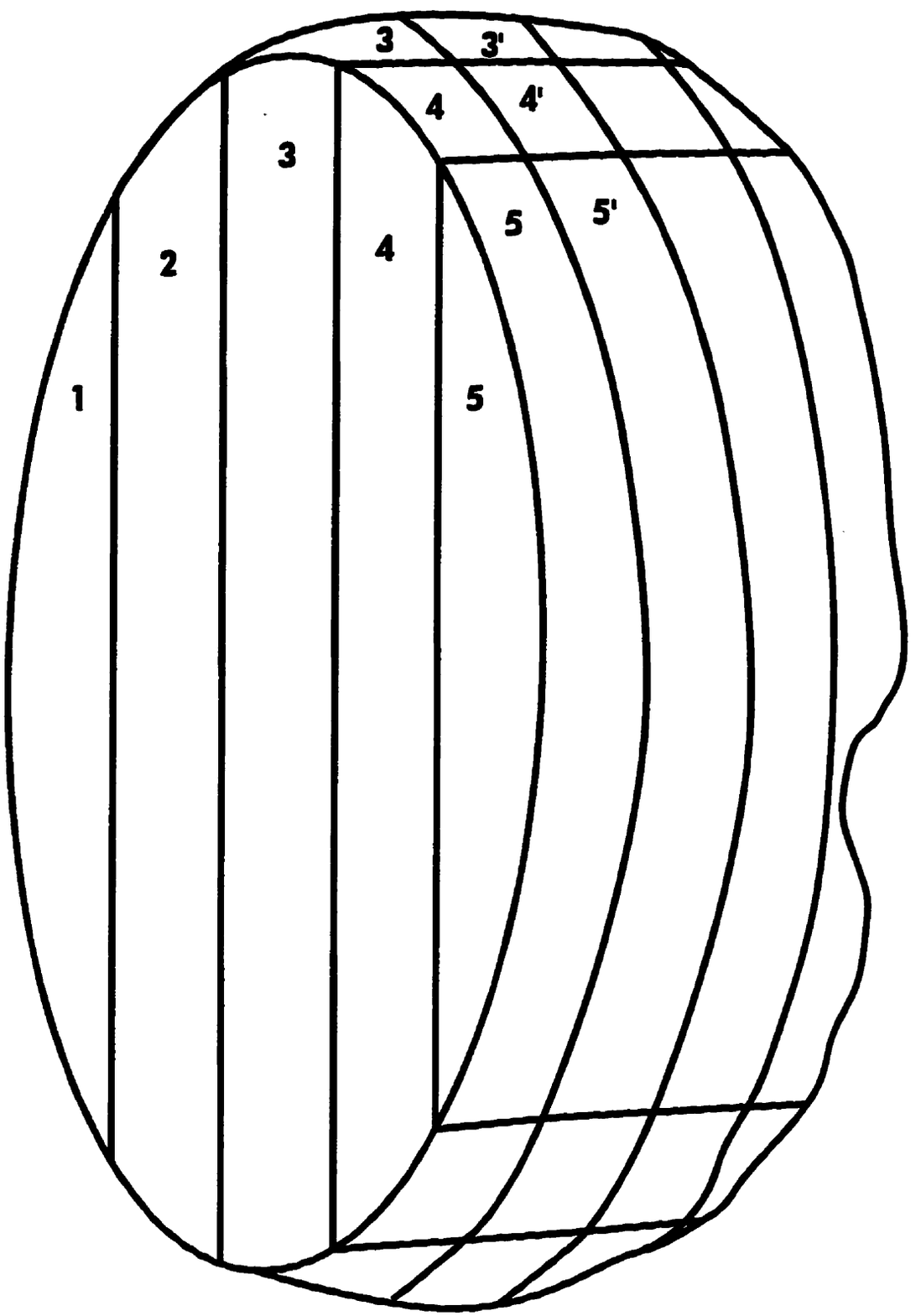
Since the specific gravities of strips 1 and 5, and 2 and 4 were not significantly different from each other ($p \leq 0.05$) (see Results Table 7) strips 1, 2 and 3 from a half-tuber (Figure 6) were designated for measurement of mechanical properties. Strips 4,

Table 2. Time-temperature regimes for the LTLT, HTST, and standard conditions for unit operations used in the study

Unit process operation	Standard		LTLT		HTST	
	Time (min)	Temp (°C)	Time (min)	Temp (°C)	Time (min)	Temp (°C)
Blanch	2	85	10 2	70 97	2	97
Dry[1]	10 11	70 120	10 15	70 100	20	100
Finish fry	2.5	166	3.5	166	1.5	182

[1] For the standard conditions, it took an additional 4 min to raise the temperature from 70 to 120°C and the fries remained in the oven as temperature was raised. For LTLT, it took an additional 1 minute to raise temperature from 70 to 100°C.

Figure 6. **Selection and marking of strips to determine the effects of processing on mechanical properties and colour of fully-fried french fries.**


3
3'
4
4'
3
5
5'
2
4
1
5

4', 5 and 5' from the same half-tuber were used for colour measurements. Strips 3' and 2' (2' not shown in Figure but is behind strip 2) were used for moisture content determinations. Strip 1' was not used. Only those strips used for measurements of mechanical properties were marked prior to processing.

3.2.7.3 Processing

There were six processing experiments for a given storage period, cultivar and site (Figure 5). For each processing experiment four tubers were used. Twenty-eight strips from four-half tubers, 12 for measurement of mechanical properties and 16 for colour measurement, were processed according to the standard conditions for all unit operations (Figure 1). Strips from the other half-tubers were processed by either a LTLT or by a HTST condition for the unit operation under investigation (Table 2) with all other unit operations performed according to the standard conditions. For the drying and finish fry experiments, there were an additional eight strips used for moisture determination. In comparing the standard processing operation versus a given processing condition (LTLT or HTST), all strips were processed at the same time for all unit operations. The rationale was to minimize variability in processing conditions from one unit operation to another.

(i) Blanching experiments

For the blanching experiments, two blanchers were used. In one blancher, strips were blanched according to standard conditions while the other blancher was used for blanching strips designated for LTLT. Because the blanching time for LTLT was considerably longer than the standard blanching conditions (Table 2), strips that

were to be blanched by the standard conditions were wrapped in moist paper towels to prevent significant moisture loss. After the cooling step for LTLT, strips designated for the LTLT blanch and for the standard conditions were blanched at the same time but in separate blanchers. Separate experiments were performed to compare the standard to the HTST conditions. In these experiments, the blanching operation was also performed in separate blanchers.

(ii) Drying experiments

For the drying experiments, blanched strips from four half-tubers were dried by the standard conditions (Table 2) while blanched strips designated for LTLT drying were wrapped in moist paper towels and placed in a plastic bag. To prevent moisture redistribution in the fry (Ross and Porter, 1966), the french fry strips that had been dried by the standard conditions were immediately parfried and frozen according to standard processing conditions. The LTLT drying operation commenced when the desired oven temperature was attained. Drying experiments were randomized from one storage period to another. Separate experiments were conducted to compare the standard to the HTST drying conditions.

(iii) Finish fry experiments

For the finish fry experiments, frozen fries from four half-tubers were finish fried by the LTLT conditions (Table 2). Frozen fries from the other half-tubers were fried separately according to the standard finish fry conditions. Similar experiments were conducted to compare the standard to the HTST finish fry conditions.

3.2.7.4 Measurement of colour and mechanical properties

For colour measurement, 16 fries were selected from frozen storage and finish fried. The fries were cooled to room temperature for 30 min prior to measurement. Colour measurement was performed as described for presentation method #2 (section 3.2.3.2) and the repacking procedure was used (see section 3.2.3.3).

For measurement of mechanical properties, six fries were selected from frozen storage and finish fried. The fries were cooled to room temperature for 15 min. Puncture tests were performed as described in section 3.2.4.3 but with two modifications. Firstly, three indentations were made on each french fry, at the stem end, middle and bud end. Secondly, the 2 mm-diameter probe was forced two-thirds of the way (0.67 cm) into the fry because earlier experiments indicated that the 2 mm probe was unable to penetrate the crusts of french fries when forced half-way (0.5 cm) into the fry.

3.2.7.5 Moisture content determination

Moisture determinations were conducted in accordance with AOAC Methods 32.082-32.084 (AOAC, 1990) but with modification. The samples were not homogenized but were cut into pieces because previous attempts to obtain a homogenate of fully-fried french fries were unsuccessful.

For moisture determination, strips at position 3′ (Figure 6) from four-half tubers were used for moisture determination before processing while strips at position 2′ were used for moisture determination after drying and after finish frying. Moisture determinations were performed at 1 and 3 months storage for both cultivars and sites.

3.2.7.6 Microscopy

Changes in cellular structure during blanching and freezing were examined using light microscopy. These unit operations were selected (i) to examine differences in starch gelatinization during LTLT and HTST blanching and, (ii) to observe cell cleavage during freezing due to extracellular ice crystal formation (Kawabata et al., 1976; Canet et al., 1984). The microstructure of raw potato tissue was used as a reference to examine the effect of processing.

Outer strips from a half-tuber were processed by LTLT and HTST blanch, and HTST blanch followed by freezing. These strips were chosen because the greatest structural changes occur here (Fedec et al., 1977). Immediately after a processing treatment, the strips were immersed into fixative. The fixative was a 2.5% (w/v) glutaraldehyde solution containing 0.1 M sodium phosphate buffer, pH 7.3 (O'Brien and McCully, 1981). Tissue samples, approximately 0.2 cm thick, were cut from the middle of each strip using a sharp blade. After marking the midpoint, the sample was cut into quarters. A notch was made on each quarter representing the midpoint of the 0.2 cm sample. The rationale was to ensure that tissue orientation during sectioning was consistent for each sample. Samples were placed in labelled vials containing fixative and immediately placed under vacuum for approximately 8 h. Samples were then washed three times (15 min each) with 0.1 M sodium phosphate buffer, pH 7.3, twice (15 min each) with distilled water and dehydrated in a graded ethanol series (15 min each in 10, 30, 50, 70, 90 and 100% ethanol). Samples were embedded in LR White resin and 2μm-thick sections were obtained using a microtome. The sections were stained with 0.1% (w/v) cellufluor solution (for cell walls) and 1% (w/v) iodine solution (for gelatinized starch) (Svegmark and Hermansson, 1991) and viewed using

a light microscope (Model 47-16-45, Zeiss, Germany) equipped with a camera.

3.2.7.7 Experimental design and statistical analysis

The experimental design was a paired comparison design. This design was selected in consultation with a statistician (Statistical Advisory Service, University of Manitoba). To compare the mechanical properties of the standard to those of an experimental condition, statistical analysis was performed by the analysis of variance procedure using the General Linear Model (GLM) procedure of SAS (see Appendix 1). Treatment differences were determined by Duncan's multiple range test. For colour measurements, the T-test for paired comparisons was used because for a given processing condition, colour measurements were performed on a composite of 16 fries from four-half tubers. To determine the overall effects of variables, namely processing, storage, cultivar and site, and the interactions of these variables on the mechanical properties and colour of french fries, pairing of strips was eliminated. Therefore, the error terms in the random statement (of proc GLM) presented in Appendix 1 to compare pairs of adjacent strips were eliminated. The random statement was included to calculate errors associated with variability in potatoes.

4. RESULTS

4.1 Selection Of Method For Fry Colour Determination

4.1.1 Method of sample presentation

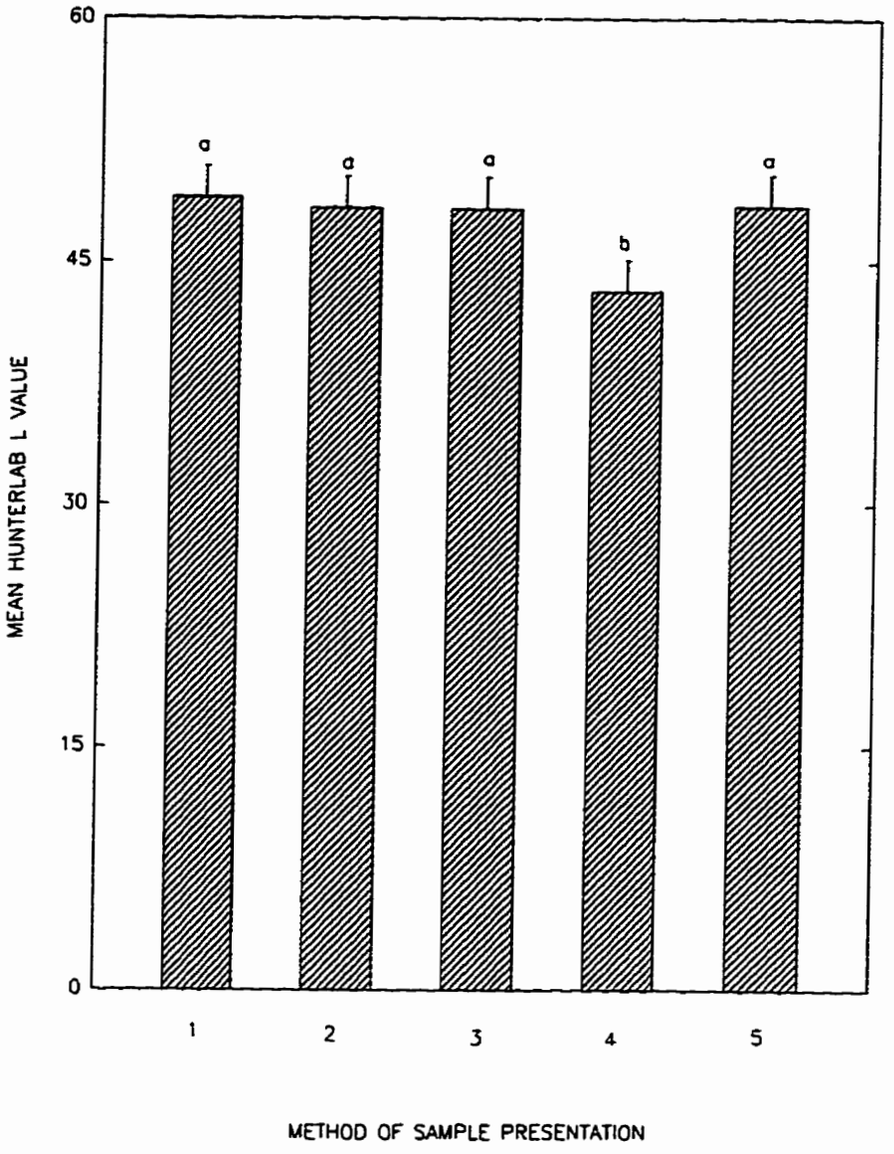
Five methods of sample presentation were studied. In presentations #1, 2, 3, and 5 the french fries were closely packed in one or more layers in the sample cell (see section 3.2.3.2) whereas in presentation #4 the sample cell was loosely filled with fries. The results are shown in Figure 7. There were no significant differences in the measured L value ($p \leq 0.05$) using presentation methods #1, 2, 3 and 5. However, Hunterlab L value was significantly lower for presentation #4 than for the other presentation methods which would be interpreted as darker french fry colour. Therefore this method was not considered suitable for measurement of fry colour.

The time taken to pack fries into the sample cell was also recorded. It took approximately 45 s and 1 min to pack fries into the sample cell using presentations #1 and 2, respectively, whereas for presentations #3 and 5 the respective times were 1.5 and 3 min. It was observed that depending on the degree of curvature of the potato tuber, french fries from outer parts of the tuber were shorter in length than fries from the inner part of the tuber and in some instances did not cover the entire length of the sample cell. Presentation #2 was selected as the most suitable method for measurement of french fry colour because (1) it had a reasonable time to fill and, (2) it ensured that the ends of the fries were fully covered.

4.1.2 Effects of orientation and repacking on Hunterlab L value

Because it is essential to obtain a colour reading that is representative of the

Figure 7. **Effect of method of sample presentation on the mean Hunterlab L value of fully-fried french fries (n = 8). Error bars are ± 95% confidence limits (CL).**

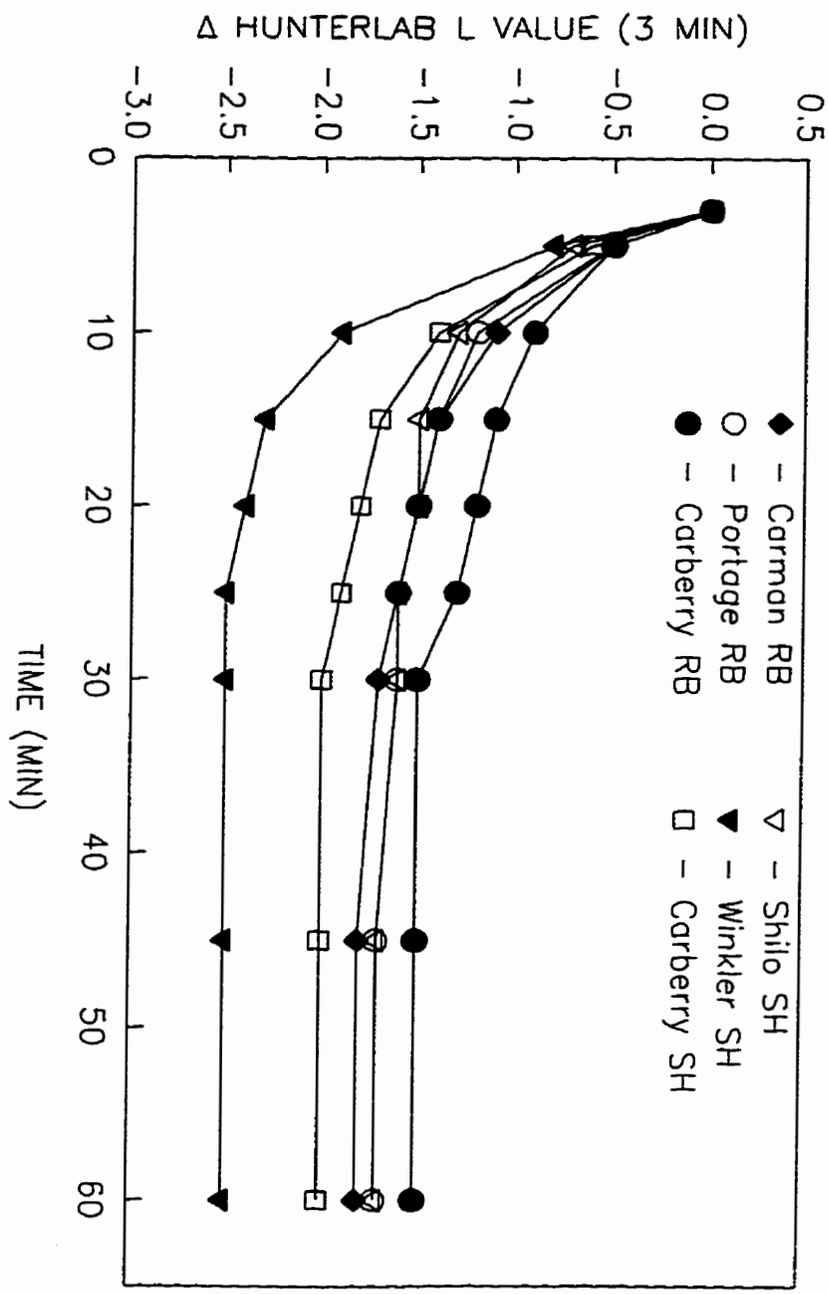

60
45
30
15
0
a
a
a
b
a
1
2
3
4
5
MEAN HUNTERLAB L VALUE
METHOD OF SAMPLE PRESENTATION

sample, preliminary work was carried out to compare an orientation and a repacking procedure. In the orientation procedure the sample cell containing french fries was oriented four times while on the window of the colorimeter and colour readings were recorded after each orientation, whereas in the repacking procedure french fries were emptied onto a tray after the initial colour reading, mixed together and repacked into the sample cell. A comparison of the two methods indicated that there were no significant differences ($p \leq 0.05$) between the orientation and repacking procedures. The mean Hunterlab L value ($n=4$) was 51.2 and 51.1 for the repacking and orientation procedures, respectively. The repacking procedure was selected as the more suitable method. The reason was that for instrumental colour measurements it is necessary to obtain a number of colour readings that are fully representative of the colour of the entire sample.

4.1.3 Effect of cooling on Hunterlab L value

Preliminary work was conducted to determine changes in Hunterlab L value of french fries during cooling. Colour measurements were taken beginning at 3 min after the fries were removed from the fryer, 2 min later and every 5 min up to 1 h. Figure 8 shows the change in Hunterlab L value as a function of time where it appeared that the measured L value remained relatively unchanged after 30 min of cooling. In subsequent experiments colour measurements were performed after fries had cooled for 30 min.

Figure 8. **Normalized curve showing change in the mean Hunterlab L value of fully-fried french fries during cooling relative to reading taken 3 min after removal from the fryer (n = 3). The fries were processed from Russet Burbank (RB) and Shepody (SH) potatoes each grown at three sites.**


Δ HUNTERLAB L VALUE (3 MIN)
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
0
10
20
30
40
50
60
TIME (MIN)
◆ – Carman RB
○ – Portage RB
● – Carberry RB
▽ – Shilo SH
▼ – Winkler SH
□ – Carberry SH

4.2 Measurement Of The Mechanical Properties Of French Fries

4.2.1 Effect of cooling on peak force and post-puncture energy consumption

Preliminary work was conducted to determine whether the mechanical properties were affected by cooling. Potato slices of various thicknesses (see section 3.2.4.1) were fried for various lengths of time prior to measurement of the mechanical properties. The results are presented in Table 3. For both sample thicknesses and frying times, there were no significant differences in peak force and post-puncture energy consumption ($p \leq 0.05$) between 15 and 45 min except in one case where a significant decrease in peak force was observed between 30 and 45 min. In subsequent experiments puncture tests were conducted within a 30-minute duration after the fries had cooled for 15 min to room temperature.

4.2.2 Contribution of the crust and fry interior to the overall mechanical properties

In studies to elucidate the distinct contribution of the crust and fry interior to the overall mechanical properties of french fries, potato slices 1.1 and 1.4 cm in thickness were fried for various lengths of time (see section 3.2.4.2) to produce crusts of varying thicknesses. Puncture tests were performed on these slices with the crusts on and on crust-free fry interior (Table 4). For the 1.1 cm slice, there were no significant differences in peak force as frying time increased although the trend indicated an increase in peak force as frying time increased. For the 1.4 cm slice, peak force was significantly higher at 15 and 20 min compared to 5 min. There were no differences in peak force between the two slice thicknesses. For the fry interior, peak force was significantly higher at 5 min compared to 10, 15 and 20 min for both slice thicknesses. A comparison of the 0.5 and 0.8 cm slice showed inconsistent trends

Table 3. Effect of cooling on mean peak force and post-puncture energy consumption of french fries (n = 2)[1]

Sample thickness (cm)	Frying time (min)	Peak force (N)			Post-puncture energy consumption (Jm^{-1})		
		Cooling period after frying (min)					
		15	30	45	15	30	45
0.8	5	1.24±0.24a	1.05±0.24a	0.93±0.24a	0.61±0.16a	0.47±0.16a	0.43±0.16a
1.1	5	0.69±0.33a	0.80±0.33a	0.98±0.33a	0.49±0.28a	0.46±0.28a	0.66±0.28a
0.8	15	1.61±0.47a	1.69±0.47a	1.43±0.48a	0.48±0.14a	0.41±0.14a	0.37±0.14a
1.1	15	1.35±0.31a	1.60±0.31a	0.89±0.31b	0.50±0.16a	0.48±0.16a	0.37±0.16a

[1]Means within a row for a given parameter followed by different letters are significantly different from each other ($p \leq 0.05$). Values are means±95% CL.

Table 4. Peak force and post-puncture energy consumption of french fries with crusts and with crusts removed (n = 12)*

Sample thickness (cm)	Peak force (N)				Post-puncture energy consumption (Jm^{-1})			
	Frying time (min)							
	5	10	15	20	5	10	15	20
	Crust-free fry interior							
0.5	0.41b[1]	0.32a[2,3]	0.36a[2]	0.27a[3]	0.37b[1]	0.30a[1,2]	0.38a[1]	0.27a[2]
0.8	0.78a[1]	0.38a[2]	0.26b[2]	0.22a[2]	0.66a[1]	0.35a[2]	0.28b[2]	0.27a[2]
	Crusts on							
1.1	0.92a[1]	1.04a[1]	1.19a[1]	1.26a[1]	0.50b[1]	0.45a[1]	0.47a[1]	0.50a[1]
1.4	0.80a[2]	1.06a[1,2]	1.16a[1]	1.12a[1]	1.00a[1]	0.44a[2]	0.41a[2]	0.38a[2]

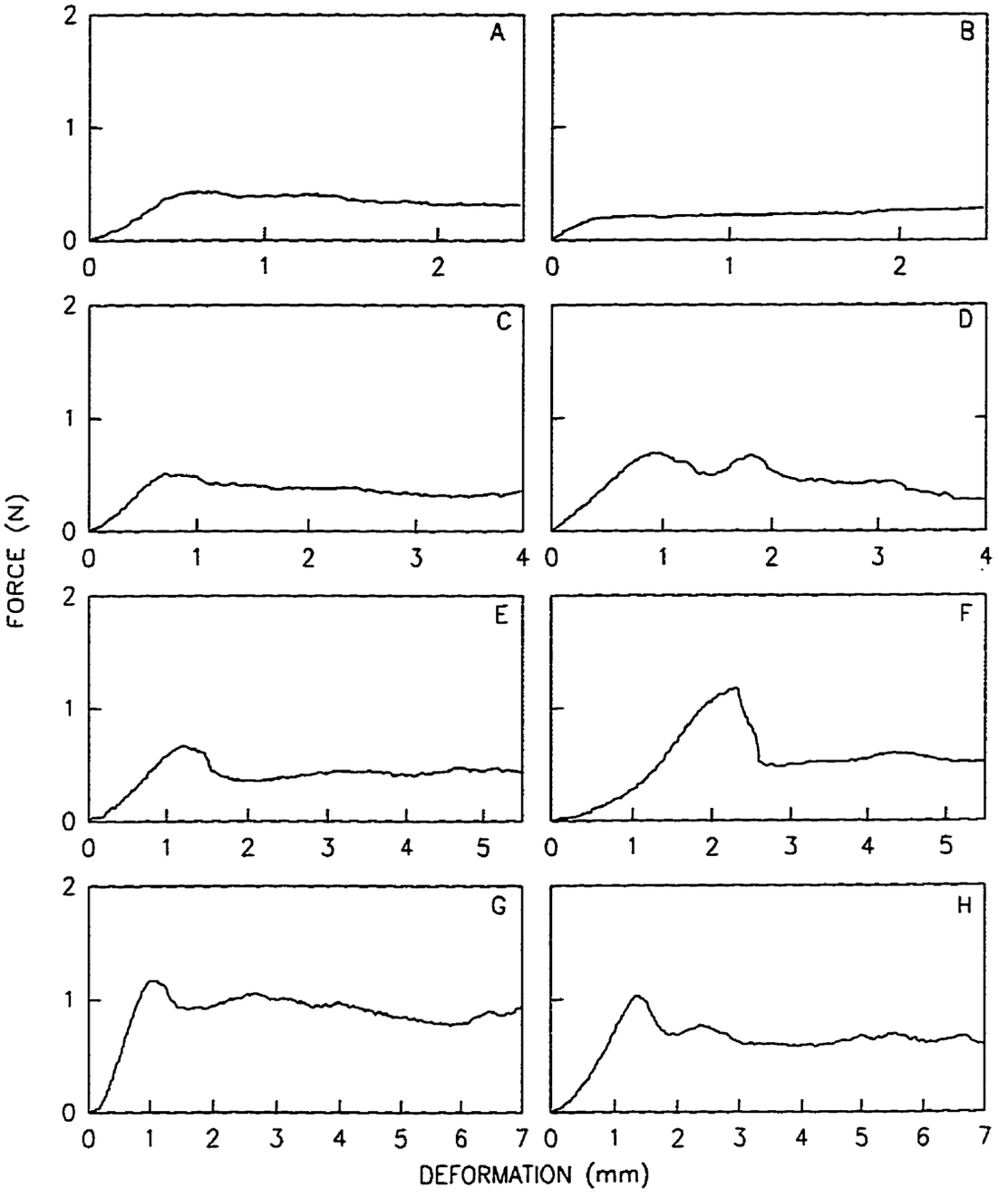
*Means within a column followed by different letters and means within a row for a given parameter followed by different numbers differ significantly from each other ($p \leq 0.05$).

in peak force.

For post-puncture energy consumption, the results for the 1.1 cm slice indicated that there were no differences in energy consumption as frying time increased, whereas for the 1.4 cm sample, post-puncture energy consumption was significantly higher at 5 min compared to the other frying times. There were no significant differences in energy consumption between the 1.1 and 1.4 cm slices except in one case. For the fry interior, there were no differences in post-puncture energy consumption after 5 min of frying for the 0.8 cm slice whereas for the 0.5 cm slice post-puncture energy consumption decreased significantly after 20 min of frying compared to 5 and 15 min. A comparison of the 0.8 and 0.5 cm slice showed that there was no consistent trend in post-puncture energy consumption. Typical load-deformation curves are shown in Figure 9. It was observed from these curves that some of the crust-free interior samples (eg. Figure 9D) had a "hump". Although french fry crusts were sliced off just prior to testing, it is possible that dehydration of the surface tissue of some of the crust-free fry interior samples resulted in the formation of this "hump" which was more typical of samples with crusts on (Figures 9E-H).

In further experiments to measure the contribution of the crust and fry interior to the overall mechanical properties fully-fried french fries were used. These fries were processed according to the conditions in Figure 1. The strips were taken from as close as possible to the centre plane of a tuber. Prior to measurement of mechanical properties the fries were finish fried for various lengths of time to produce crusts of different thicknesses. In one experiment the frozen fries were thawed with no finish fry. Due to unsuccessful attempts to penetrate the crusts of the fully-fried french fries with the 2 mm-diameter probe, the probe was changed to 0.5 mm in diameter. Table

Figure 9. Typical load-deformation curves of french fries showing tuber-to-tuber variations for a given slice thickness. All samples were fried for 5 min at 177°C. Mechanical properties were measured on crust-free fry interior (A to D) and with crusts on (E to H). Puncture tests were performed using a 2 mm-diameter probe. A, B - 0.5 cm-thick; C,D - 0.8 cm-thick; E, F - 1.1 cm-thick; G, H - 1.4 cm-thick.


A
B
C
D
E
F
G
H
FORCE (N)
DEFORMATION (mm)

5 shows peak forces of fully-fried french fries using the 0.5 mm probe. No significant differences in peak force were found ($p \leq 0.05$) between a frying time of 1 and 3.5 min although the trend in the results indicated that peak force decreased. However, as frying time increased to 4.5 min, peak force increased significantly. Typical load-deformation curves are shown in Figure 10. A sudden drop was observed as the probe penetrated the fry and peak force dropped to almost zero. Therefore, measurements of post-puncture energy consumption of the fry interior were not performed.

Bourne (1966) used five probes of varying sizes to establish the relationship between puncture force and probe diameter (see Section 2.6). According to Bourne (1966), equation (1) can be used to calculate the expected puncture force if probe size is changed. Following his reasoning the experimental data for the 2 mm probe could be used to obtain a rough estimate of the expected force for the 0.5 mm probe. However, in order to obtain values for K_c (compression coefficient), K_p (shear coefficient), and C (a constant) two assumptions were made.

(1) According to Bourne (1966), the value of C approximates to zero within the limits of experimental error.

(2) K_p is small for french fries. The basis of this assumption was that:

(i) during puncture testing the probe was observed to compress an appreciable volume of fry interior beneath it indicating that the relative proportion of compression in the overall puncture force was large whereas the shear component was small.

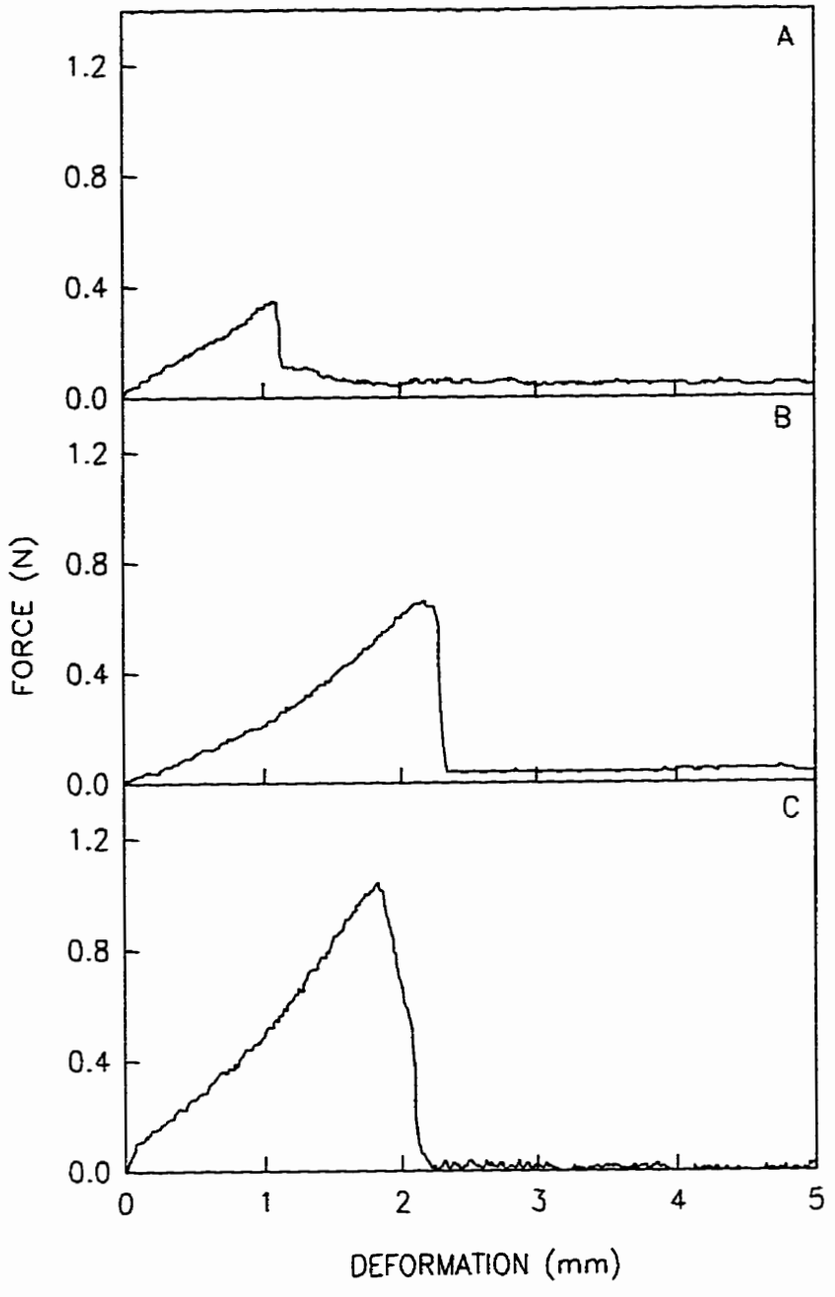
(ii) when probe size is changed from 2 to 0.5 mm in diameter, the area of the probe decreases 16 fold {i.e. area(2 mm probe) ÷ area(0.5 mm probe), where area = (diameter)^2 (Bourne, 1966)} and the perimeter decreases 4 fold {i.e. diameter(2 mm probe) ÷ diameter(0.5 mm probe)} indicating that compression contributed more

Table 5. Peak force of fully-fried french fries measured using a 0.5 mm-diameter probe (n=5)[1]

Frying time (min)[2]	Peak force (N)
1	0.63b
3.5	0.55b
4.5	1.23a

[1]Means within a column followed by different letters are significantly different from each other ($p \leq 0.05$) Values are means of 20 punch locations.
[2] Frying time includes parfry time of 1 min.

Figure 10. **Typical load-deformation curves of fully-fried french fries fried for various lengths of time. Puncture tests were performed using a 0.5 mm-diameter probe. A - 1 min; B - 3.5 min; C - 4.5 min.**


A
B
C
1.2
0.8
0.4
0.0
FORCE (N)
0
1
2
3
4
5
DEFORMATION (mm)

to puncture force than shear.

Using a peak force of 0.92 N (Table 4) for the 1.1 cm sample at 5 min of frying, K_c is calculable using equation (1) (page 27). The reason for selecting a peak force of 0.92 N was this was somewhat comparable to the french fry data since fries were 1 cm^2 in cross-sectional area and had been fried for a total time of 4.5 min. Substituting the values into equation (1):

$$0.92=K_c(2)^2+0(2)+0$$

and $K_c=0.23\ Nmm^{-2}$.

Now, substituting the value of K_c in equation (1), the estimated peak force for the 0.5 mm-diameter probe can be obtained as shown below:

$$F=0.23(0.5)^2+0(0.5)+0$$

A peak force of 0.06 N was obtained which was less than the experimental peak force of 1.23 N (Table 5) suggesting that there were other sources of variation associated with the measured mechanical parameters.

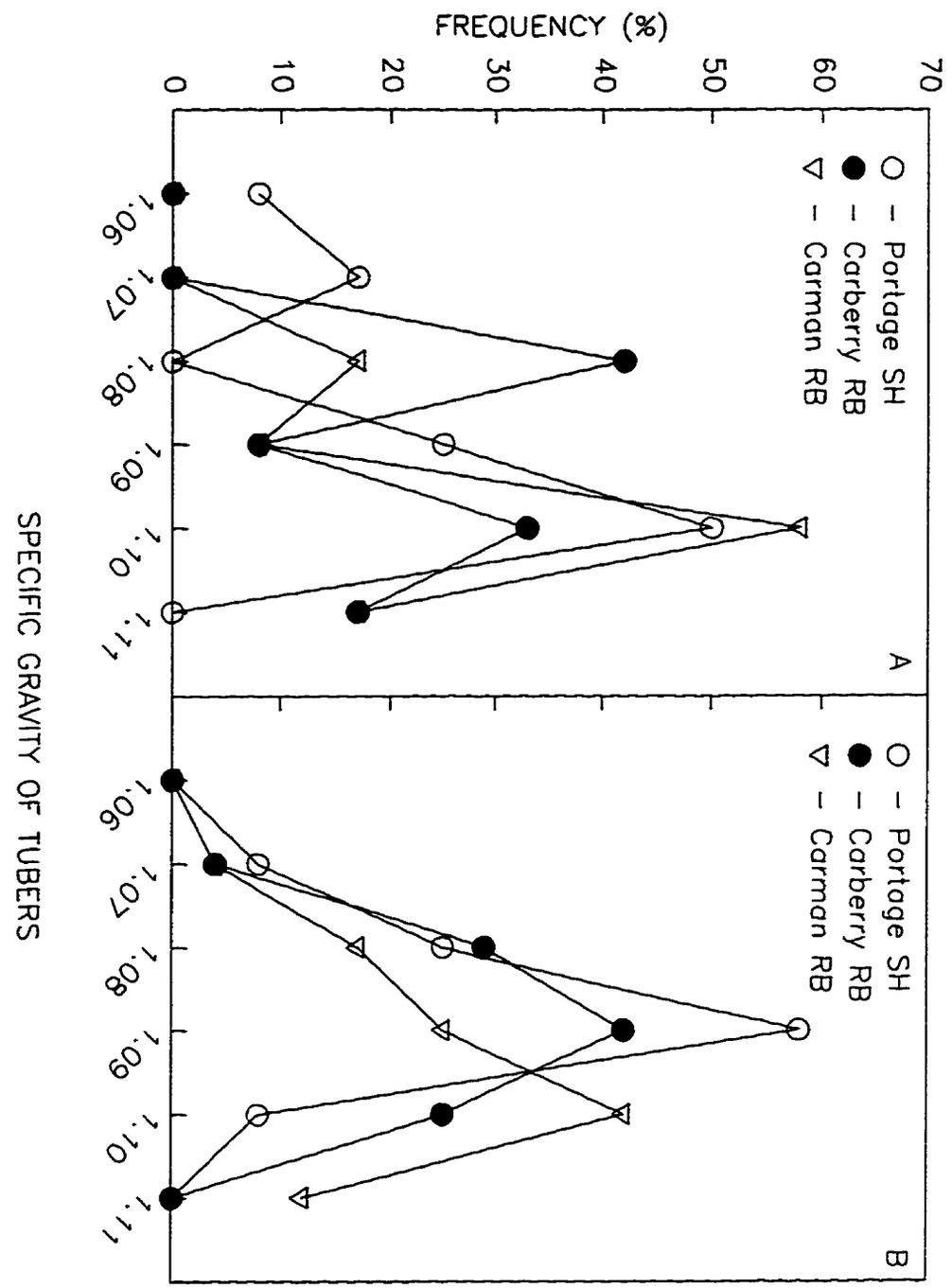
4.3 Methods To Minimize The Variability Associated With The Measured Mechanical Parameters

Because it could not be ascertained whether the variability was inherent in the test method or in the potato, further experiments were conducted.

4.3.1 Measurement of specific gravity

The specific gravity of individual potato tubers was measured. For small- and medium-sized Russet Burbank and Shepody potatoes, the results, shown in Figure 11, revealed that there was a high degree of variability from one tuber to another. This

Figure 11. Mean specific gravity distribution of tubers grown at three sites. A - small-sized tubers (less than 5 cm in diameter) (n = 2); B - medium-sized tubers (5-9 cm in diameter) (n = 6). Tuber classification is based on Agriculture Canada standards (1993). RB - Russet Burbank; SH - Shepody.


FREQUENCY (%)
0
10
20
30
40
50
60
70
1.06
1.07
1.08
1.09
1.10
1.11
SPECIFIC GRAVITY OF TUBERS
O – Portage SH
● – Carberry RB
▽ – Carman RB
A
B

indicated that tuber-to-tuber variability was potentially a source of variation for the mechanical properties.

The specific gravity of french fry strips taken from different regions of the tuber was also measured. A typical V-shaped curve was observed, as shown in Figure 12. Inner potato strips (strip 3) consistently had lower specific gravity than outer strips (strips 1 and 5). These results, which concur with those of Sharma et al. (1959b) and Sayre et al. (1975), revealed that there were large variations within a given tuber. Paired comparisons of the specific gravities of strips 1 and 5, and strips 2 and 4 (Table 6) indicated that strips 1 and 5, and likewise strips 2 and 4 were not significantly different from each other ($p \leq 0.05$). Therefore, in subsequent analyses the results of strips 1 and 5, and 2 and 4 were pooled together.

4.3.2 Comparison of the mechanical properties of adjacent strips

French fry strips taken from as close as possible in the tuber were blanched by LTLT and HTST conditions. The results were analyzed using the statistical model presented in Appendix 2. The general trend, as shown in Figures 13-15, indicated that for both LTLT and HTST blanch, peak force, peak deformation and post-puncture energy consumption were greater for inner french fry strips (strip III) than for outer strips (strips I and II). (No comparison of blanching methods within strips is made in these figures, but is done in Table 7.) Strip I is the pooled result of strips 1 and 5 and strip II is the pooled result of strips 2 and 4. In a number of instances (eg. Figure 13A-C) the differences in peak force between inner and outer strips were statistically significant ($p \leq 0.05$). These differences in the measured mechanical parameters between inner and outer strips were accentuated when the strips were blanched by

Figure 12. Specific gravity of potato strips from different regions of the tuber (n = 10). Error bars are ± 95% CL. A - Shilo (1994) (n = 5); B - Shilo (1995); C - Portage (1994); D - Portage (1995).

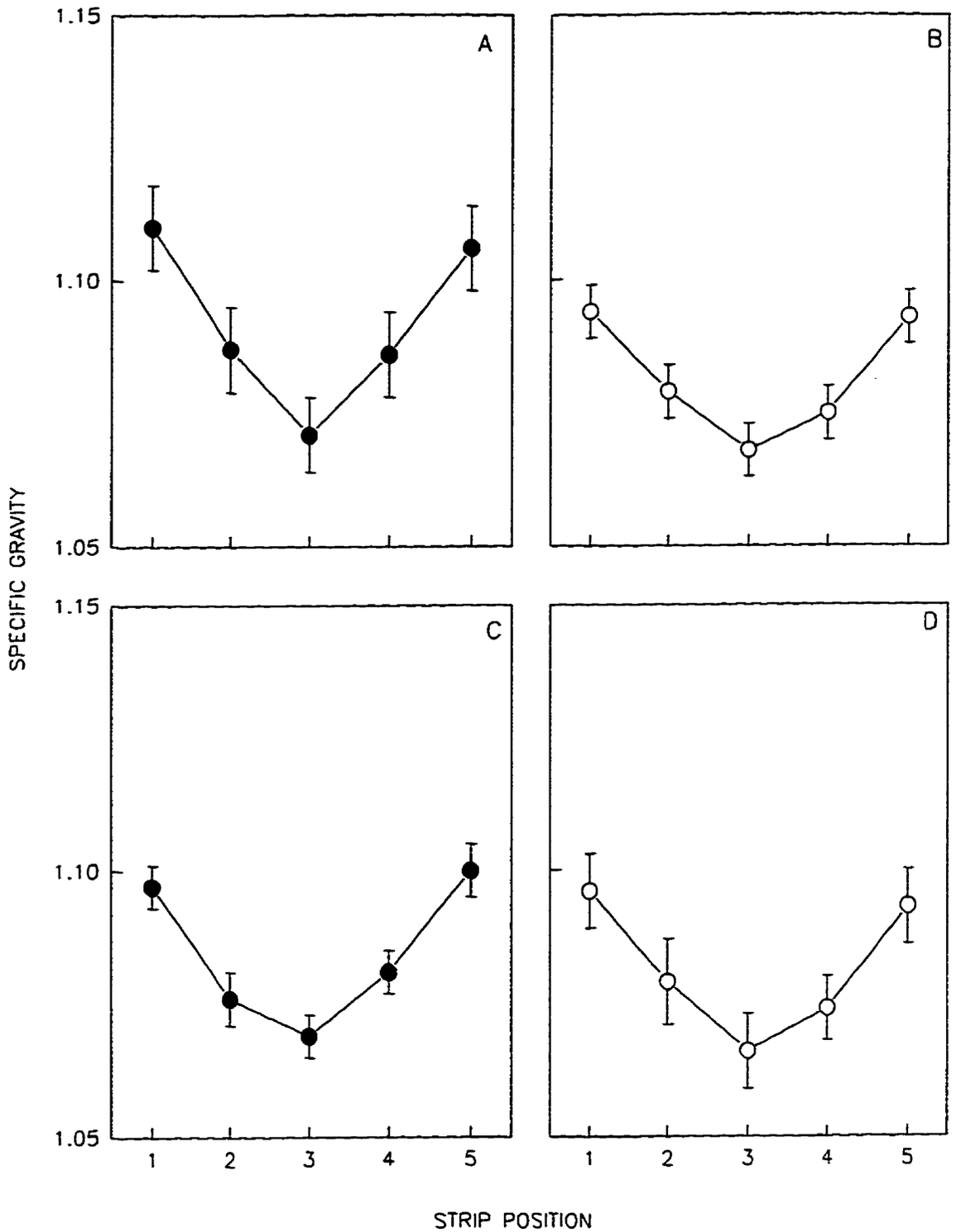

1.15
1.10
1.05
A
B
C
D
SPECIFIC GRAVITY
1
2
3
4
5
STRIP POSITION

Table 6. Results of paired comparisons ($p \leq 0.05$) between strips 1 and 5, and 2 and 4 for Shilo and Portage in 1994 and 1995 ($n = 10$)

Site	Year	Strips 1and 5		Strips 2 and 4	
		T statistic[1]	P>T	T statistic	P>T
Portage	1994	1.01	0.3208	1.36	0.1832
	1995	0.69	0.4945	1.44	0.1575
Shilo	1994[2]	0.70	0.4945	0.27	0.7930
	1995	0.21	0.8320	0.91	0.3689

[1] The T statistic tests the null hypothesis that the means of a pair of strips are equal.
[2] $n = 5$

Figure 13. **Effect of strip position on peak force of french fry strips for two different blanching methods (n=5). Error bars are ±95% CL. A - Shilo (1994); B -Shilo (1995); C - Portage (1994); D - Portage (1995). HTST means followed by different letters (eg. a) are significantly different from each other (p≤0.05). LTLT means followed by a different letter followed by prime symbol (eg. a') differ significantly from each other (p≤0.05).**

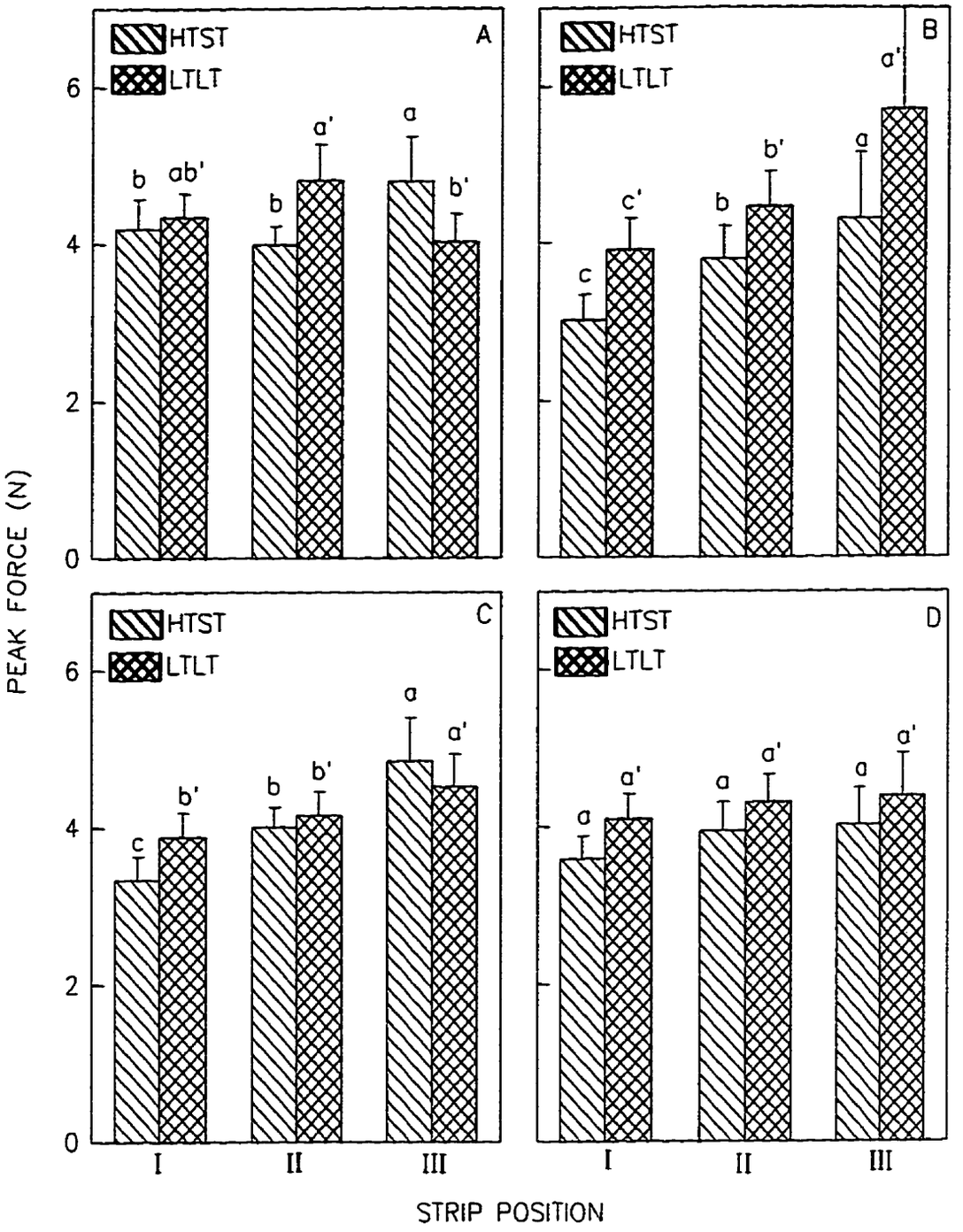

HTST
LTLT
A
B
C
D
PEAK FORCE (N)
0
2
4
6
I
II
III
STRIP POSITION

Figure 14. **Effect of strip position on peak deformation of french fry strips for two different blanching methods (n=5). Error bars are ±95% CL. A - Shilo (1994); B - Shilo (1995); C - Portage (1994); D - Portage (1995). HTST means followed by different letters (eg. a) are significantly different from each other ($p \leq 0.05$). LTLT means followed by a different letter followed by prime symbol (eg. a') differ significantly from each other ($p \leq 0.05$).**

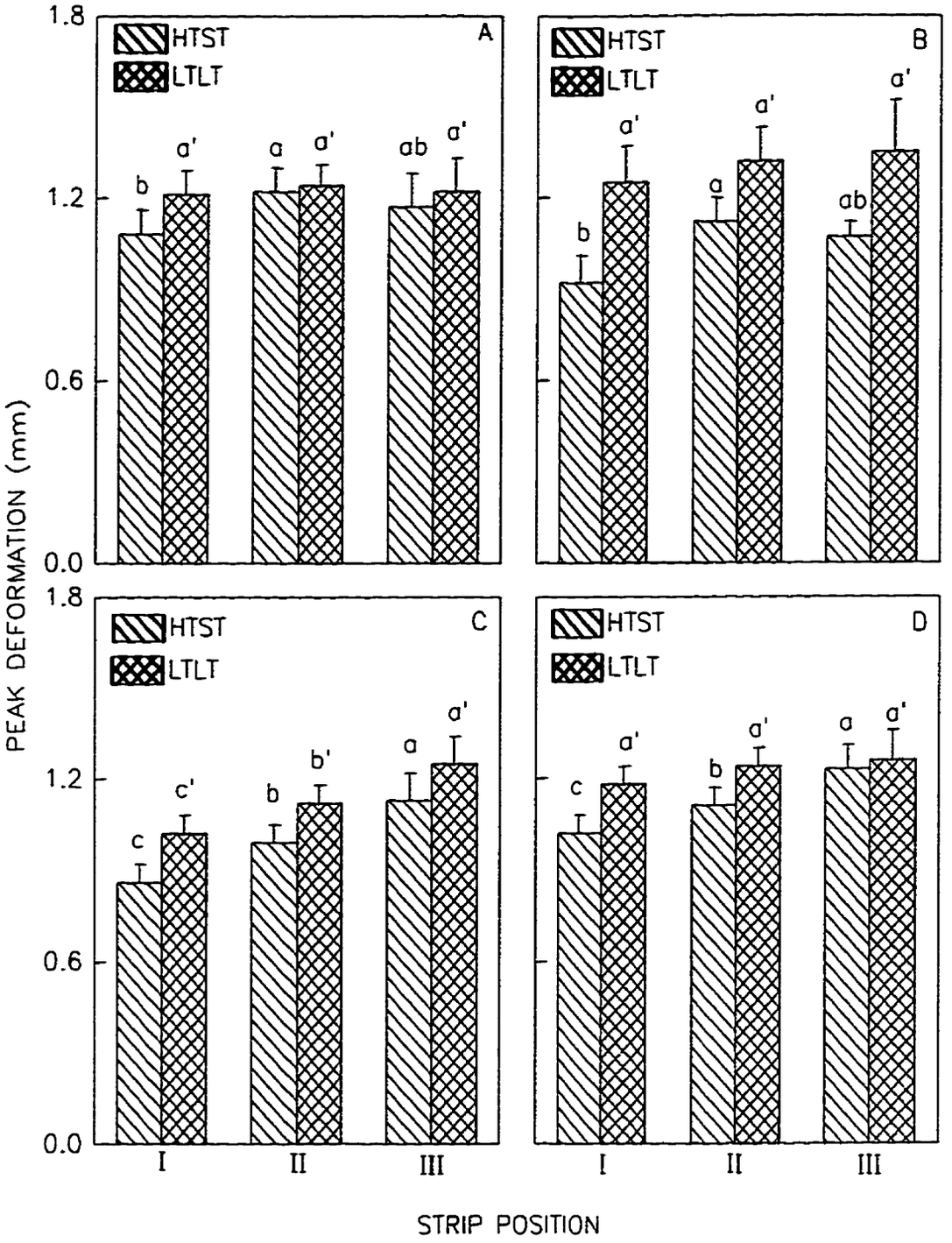
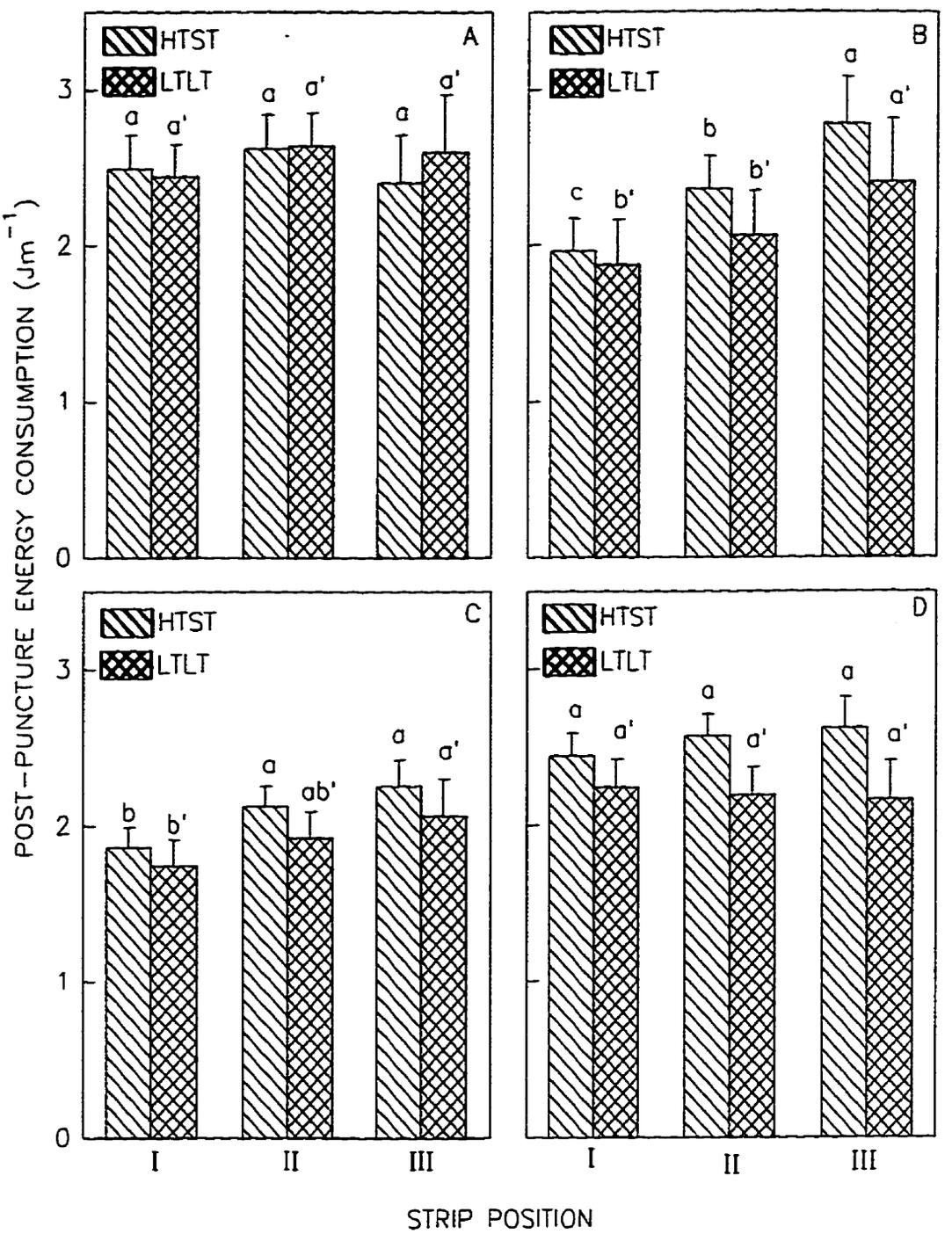

1.8
1.2
0.6
0.0
PEAK DEFORMATION (mm)
HTST
LTLT
A
B
C
D
b
a'
a
a'
ab
a'
b
a'
a
a'
ab
a'
c
c'
b
b'
a
a'
c
a'
b
a'
a
a'
I
II
III
STRIP POSITION

Figure 15. Effect of strip position on post-puncture energy consumption of french fry strips for two different blanching methods (n=5). Error bars are ±95% CL. A - Shilo (1994); B - Shilo (1995); C - Portage (1994); D - Portage (1995). HTST means followed by different letters (eg. a) are significantly different from each other ($p \leq 0.05$). LTLT means followed by a different letter followed by prime symbol (eg. a') differ significantly from each other ($p \leq 0.05$).


HTST
LTLT
A
B
C
D
POST-PUNCTURE ENERGY CONSUMPTION (Jm^{-1})
0
1
2
3
a
a'
b
b'
c
ab'
I
II
III
STRIP POSITION

HTST conditions. Low-temperature long-time conditions appeared to reduce these differences.

Likewise, for blanched and frozen french fry strips, for both LTLT and HTST blanch the measured mechanical parameters were generally higher for inner strips than for outer strips (Figures 16-18). In some instances (eg. Figure 17) peak deformation was significantly higher for inner strips than for outer strips. Low-temperature long-time conditions appeared to decrease the differences in mechanical properties between inner and outer french fry strips but more importantly, the effects of blanching were evident in the mechanical properties, even after freezing.

Results of an interaction between strip position and specific gravity for a given mechanical parameter revealed that for the most part (i.e. in 20 cases) there were no significant interactions ($p \leq 0.05$) except in four instances. These instances were as follows: for the blanching treatment with no freezing significant interactions were found for peak force of fries processed from Shilo (1994) and from Portage (1994) potatoes ($p = 0.001$ and $p = 0.05$, respectively). For the blanching treatment followed by freezing, significant interactions between strip position and specific gravity were found for peak force of fries made from Shilo (1994) potatoes ($p = 0.018$) and, for post-puncture energy consumption of fries processed from Portage (1995) potatoes ($p = 0.0007$). Therefore, these findings were not considered significant.

In comparing the overall effects of blanching (Table 7) and blanching and freezing (Table 8), peak force and peak deformation of french fry strips were generally higher for the LTLT than for the HTST conditions whereas post-puncture energy consumption was generally higher for HTST conditions. Peak force results concur with those of Canet et al. (1984).

Figure 16. Effect of strip position on peak force of french fry strips for two different blanching methods followed by freezing (n=5). Error bars are ±95% CL. A - Shilo (1994); B - Shilo (1995); C - Portage (1994); D - Portage (1995). HTST means followed by a different letter (eg. a) differ significantly from each other ($p \leq 0.05$). LTLT means followed by a different letter followed by prime symbol (eg. a') are significantly different from each other ($p \leq 0.05$).

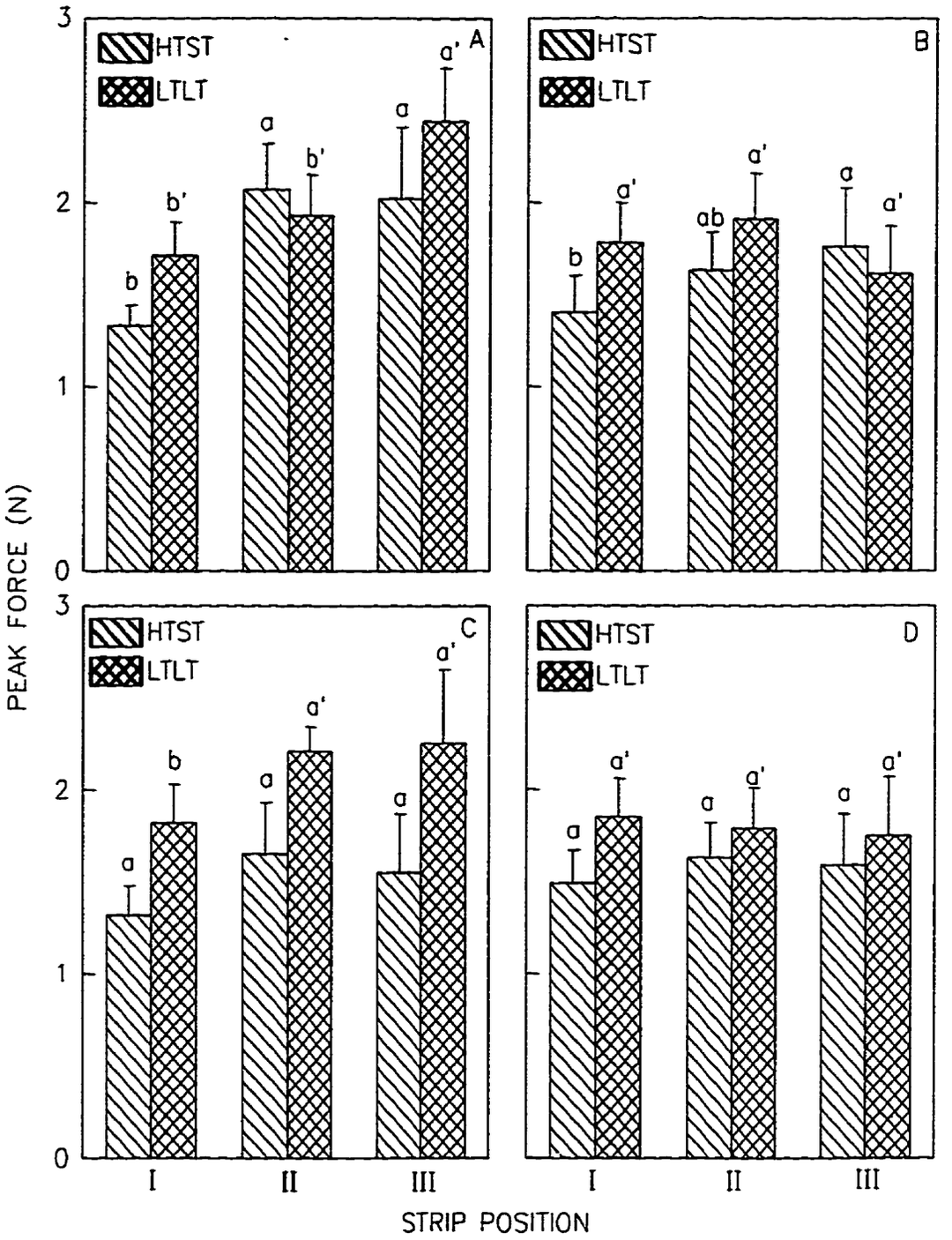

HTST
LTLT
A
B
C
D
PEAK FORCE (N)
STRIP POSITION
I
II
III
0
1
2
3

Figure 17. Effect of strip position on peak deformation of french fry strips for two different blanching methods followed by freezing (n=5). Error bars are ±95% CL. A - Shilo (1994); B - Shilo (1995); C - Portage (1994); D - Portage (1995). HTST means followed by a different letter (eg. a) differ significantly from each other ($p \leq 0.05$). LTLT means followed by a different letter followed by prime symbol (eg. a') are significantly different from each other ($p \leq 0.05$).

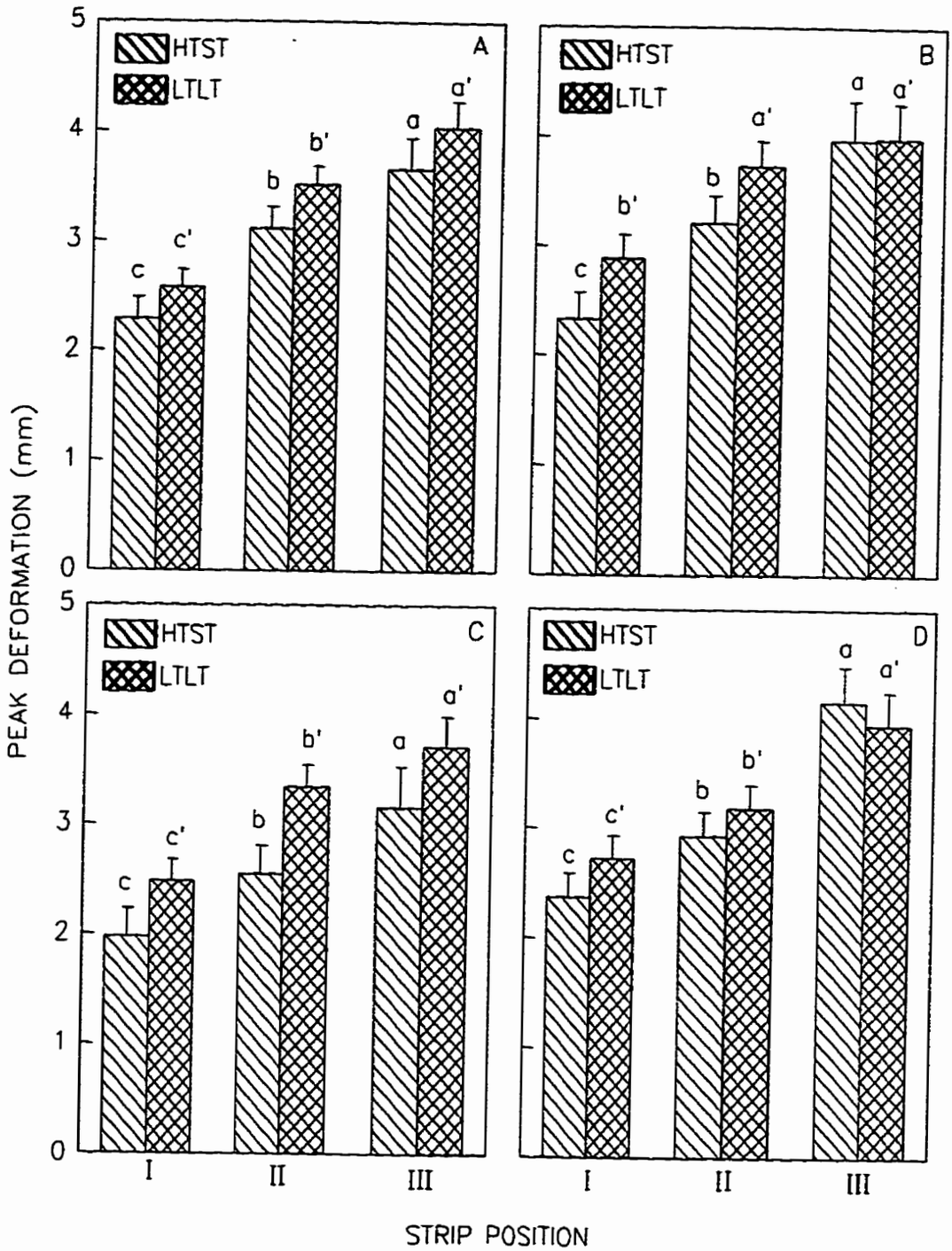

HTST
LTLT
A
B
C
D
PEAK DEFORMATION (mm)
STRIP POSITION
I
II
III
0
1
2
3
4
5
c
c'
b
b'
a
a'

Figure 18. Effect of strip position on post-puncture energy consumption of french fry strips for two different blanching methods followed by freezing (n=5). Error bars are ±95% CL. A - Shilo (1994); B - Shilo (1995); C - Portage (1994); D - Portage (1995). HTST means followed by a different letter (eg. a) differ significantly from each other ($p \leq 0.05$). LTLT means followed by a different letter followed by prime symbol (eg. a') are significantly different from each other ($p \leq 0.05$).

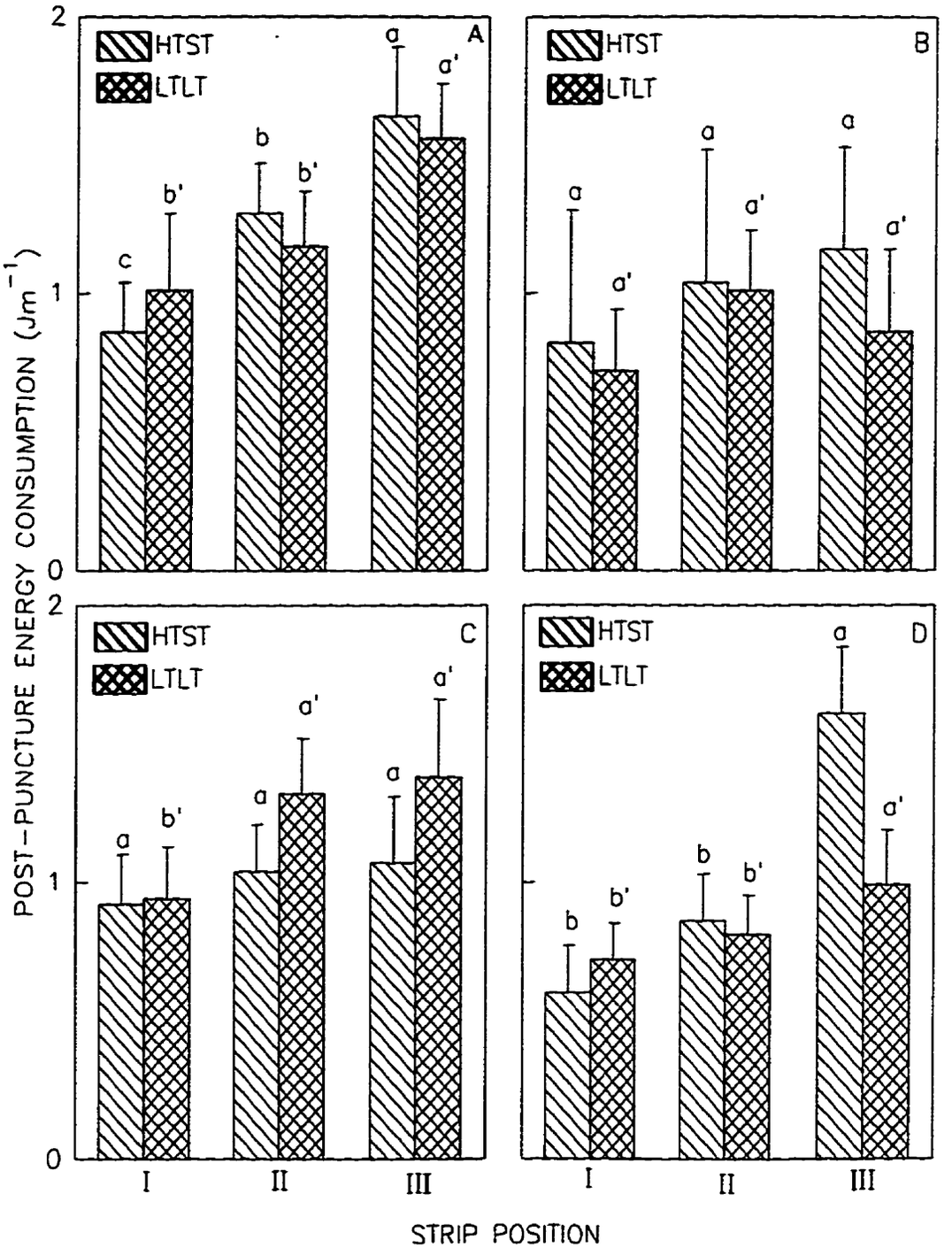

HTST
LTLT
A
B
C
D
POST-PUNCTURE ENERGY CONSUMPTION (Jm⁻¹)
STRIP POSITION
I
II
III
0
1
2

Table 7. Overall effect of blanching conditions on peak force, peak deformation and post-puncture energy consumption of french fry strips (n =5)[1]

Blanching conditions	Peak force (N)			
	Shilo		Portage	
	1994	1995	1994	1995
LTLT	4.46a	4.49a	4.12a	4.24a
HTST	4.23a	3.59b	3.91b	3.82b
	Peak deformation (mm)			
LTLT	1.22a	1.30a	1.10a	1.22a
HTST	1.15b	1.03b	0.97b	1.10b
	Post-puncture energy consumption (Jm^{-1})			
LTLT	2.57a	2.05b	1.88b	2.20b
HTST	2.52a	2.28a	2.04a	2.53a

[1] Numbers in a column for a given mechanical parameter followed by different letters differ significantly from each other ($p \leq 0.05$).

Table 8. Overall effect of blanching conditions followed by freezing on peak force, peak deformation and post-puncture energy consumption of french fry strips (n=5)[1]

Blanching conditions	Peak force (N)			
	Shilo		Portage	
	1994	1995	1994	1995
LTLT	1.94a	1.80a	2.02a	1.81a
HTST	1.76b	1.56b	1.50b	1.56b
	Peak deformation (mm)			
LTLT	3.24a	3.44a	3.07a	3.15a
HTST	2.89b	3.01b	2.44b	2.95b
	Post-puncture energy consumption (Jm^{-1})			
LTLT	1.18a	0.86a	1.18a	0.81b
HTST	1.19a	0.98a	1.00b	0.90a

[1] Numbers in a column for a given mechanical parameter followed by different letters differ significantly from each other ($p \leq 0.05$).

4.3.2.1 Effect of puncture location on peak force of french fry strips

Variations in peak force from stem to bud end were also examined. The results, illustrated in Tables 9 and 10, indicate that for both sites in 1994 and 1995 peak force was significantly higher at the stem than at the bud end except in two cases. For peak deformation, shown in Appendices 3-6, there were no significant differences between stem and bud end. Post-puncture energy consumption, presented in Appendices 3-6, was generally lower at the bud end than at the stem end. Since the mechanical properties of the two middle positions did not differ significantly from each other ($p \leq 0.05$), in subsequent experiments only one puncture was made at the middle of the strip.

4.3.2.2 Overall effect of site on peak force, peak deformation and post-puncture energy consumption of french fry strips

As shown in Table 11, in both 1994 and 1995, there were no significant differences in the peak force of blanched french fry strips processed from Shilo and Portage potatoes ($p \leq 0.05$). Peak deformation and post-puncture energy consumption were inconsistent from year to year. In 1994, these parameters were generally higher for french fry strips processed from Shilo potatoes but in 1995 there were no significant differences ($p \leq 0.05$). No significant interactions were observed (results not shown).

4.4 Differences Between Inner And Outer French Fry Strips

4.4.1 Measurement of cell agglomerate

Differences between inner (low-specific gravity, LSG) and outer (high-specific

Table 9. Effect of puncture location on peak force of blanched french fry strips (n=5)[1]

Year	Site	Blanching Conditions	Peak force (N)			
			Bud end	Middle 1	Middle 2	Stem end
1994	Shilo	LTLT	3.63c	4.41b	4.67ab	5.13a
		HTST	3.54b	4.54a	4.21a	4.61a
	Portage	LTLT	3.67b	4.12ab	4.24a	4.43a
		HTST	3.55b	4.16a	4.13a	3.80ab
1995	Shilo	LTLT	3.23c	4.39b	4.75ab	5.58a
		HTST	2.51c	3.44b	3.53b	4.87a
	Portage	LTLT	3.87b	4.17ab	4.21a	4.72a
		HTST	3.47b	3.78ab	3.80ab	4.21a

[1]Numbers in a row followed by different letters differ significantly from each other ($p \leq 0.05$). Middle 1 and 2 were 0.5 cm apart.

Table 10. Effect of puncture location on peak force of blanched and frozen french fry strips (n=5)[1]

Year	Site	Blanching Conditions	Peak force (N)			
			Bud end	Middle 1	Middle 2	Stem end
1994	Shilo	LTLT	1.41b	1.98a	2.21a	2.17a
		HTST	1.31b	2.04a	1.94a	1.76a
	Portage	LTLT	1.59b	1.98a	2.16a	2.36a
		HTST	1.47a	1.50a	1.53a	1.50a
1995	Shilo	LTLT	1.28c	1.67b	2.00ab	2.24a
		HTST	1.21c	1.50bc	1.61ab	1.93a
	Portage	LTLT	1.56a	1.82a	1.94a	1.91a
		HTST	1.33b	1.48ab	1.70a	1.75a

[1]Numbers in a row followed by different letters differ significantly from each other ($p \leq 0.05$). Middle 1 and 2 were 0.5 cm apart.

Table 11. Overall effect of site on peak force, peak deformation and post-puncture energy consumption of blanched french fry strips (n = 10)[1]

Site	Peak force (N)	Peak deformation (mm)	Post-puncture energy consumption (Jm^{-1})
		1994	
Shilo	3.10a	2.13a	1.87a
Portage	2.89a	1.90b	1.52b
		1995	
Shilo	2.86a	2.19a	1.54a
Portage	2.86a	2.10a	1.61a

[1] Means in a column followed by different letters are significantly different from each other ($p \leq 0.05$). Values are means of four processing treatments.

gravity, HSG) strips were further investigated using a modification of the method of Freeman et al. (1992). Potato strips were blanched by HTST conditions and macerated. The macerated tissue was passed through a sieve with 1 mm openings. The volume of cell agglomerate passing through the sieve was measured. Higher volume of cell agglomerate was indicative of small cell agglomerates passing through the sieve and a more friable structure. For both Portage and Shilo, the measured volume of cell agglomerate was significantly greater for outer french fry strips than for inner strips ($p=0.0011$ and $p=0.0006$, respectively) (Figure 19). These results are consistent with the findings of Freeman et al. (1992) who stated that the volume of cell agglomerate was greater for HSG tubers than for LSG tubers.

4.4.2 Structural changes in inner and outer french fry strips

Figures 20-28 show the structural changes in inner and outer strips examined by stereomicroscopy. After a 30-second HTST blanch it was observed (Figures 20-22) that cells at the periphery of both the inner and outer strips, which had received the most heat treatment, contained gelatinized starch. Further inward the cells contained starch granules undergoing incipient gelatinization (Figures 21A and B). The innermost part of the strip contained mainly ungelatinized starch granules. Differences in cell size between inner and outer strips were apparent. Inner strips contained smaller cells whereas outer strips contained larger cells. The brown discolouration in the outer strip (Figure 20B) is due to enzymatic browning resulting from inadequate inactivation of peroxidase. After 40 s of blanching (Figures 23-25, A and B), gelatinization had occurred throughout the strip but the parenchyma cells in the outer strips appeared engorged with swollen starch granules whereas in the inner strips the extent of

Figure 19. **Volume of cell agglomerate of inner and outer blanched french fry strips (cv. Russet Burbank) (n = 8). Error bars are ± 95% CL. A - Shilo (1995); B - Portage (1995).**

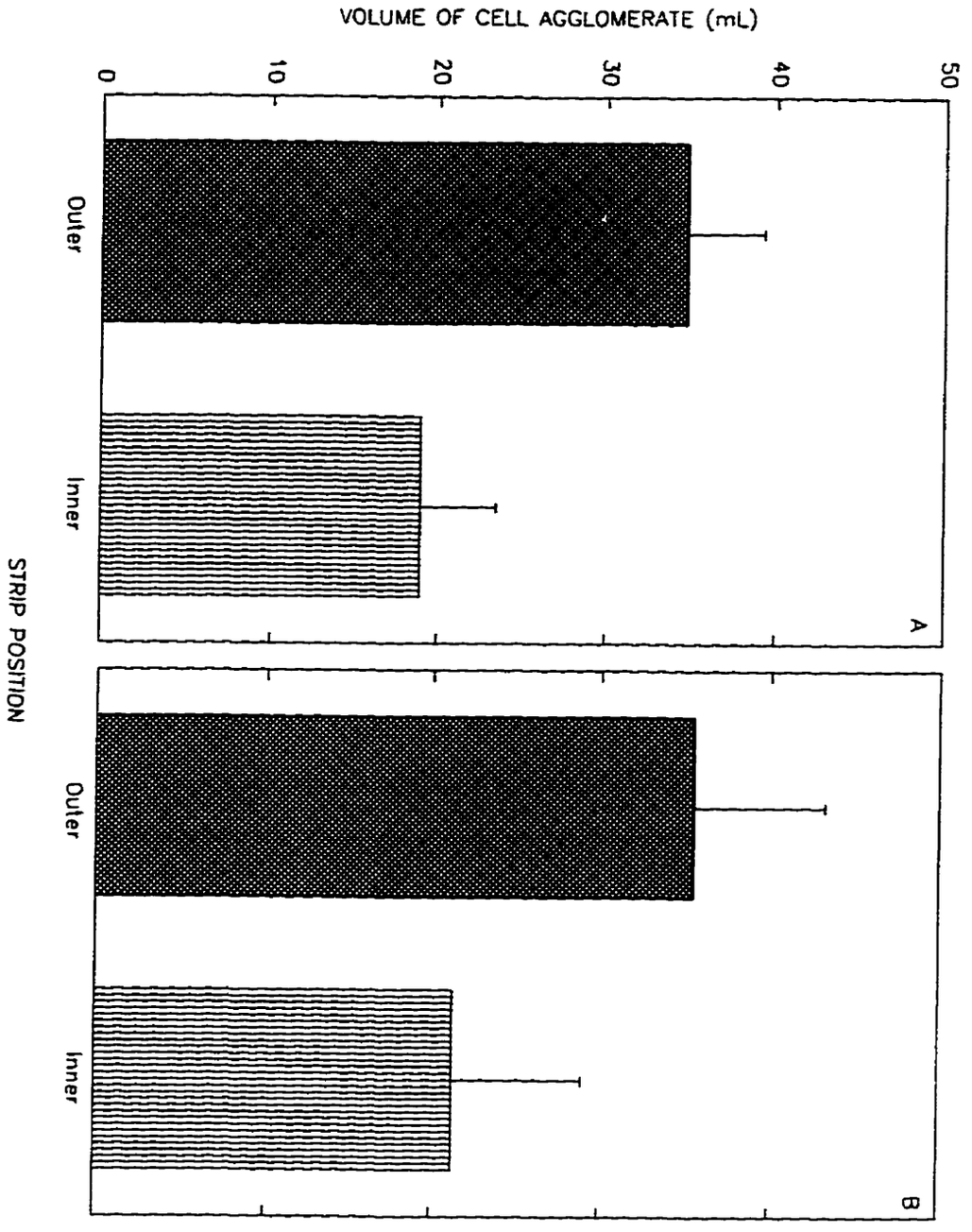
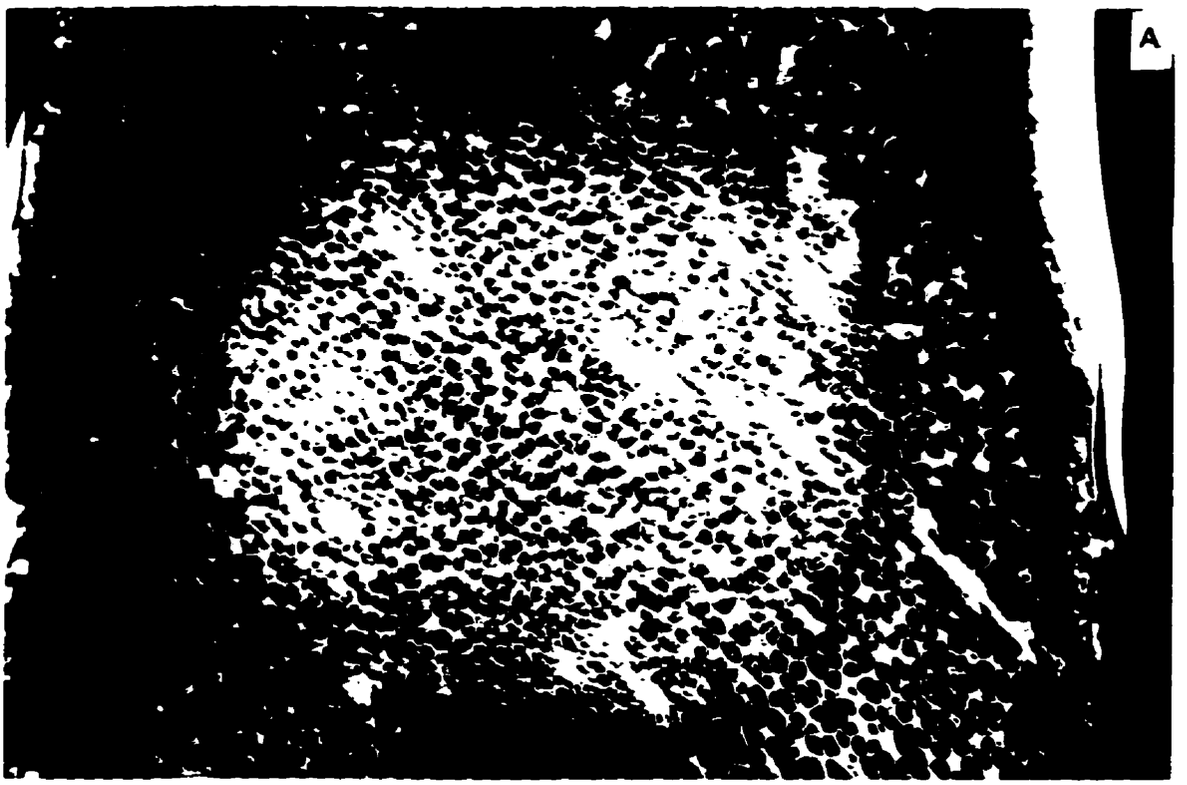
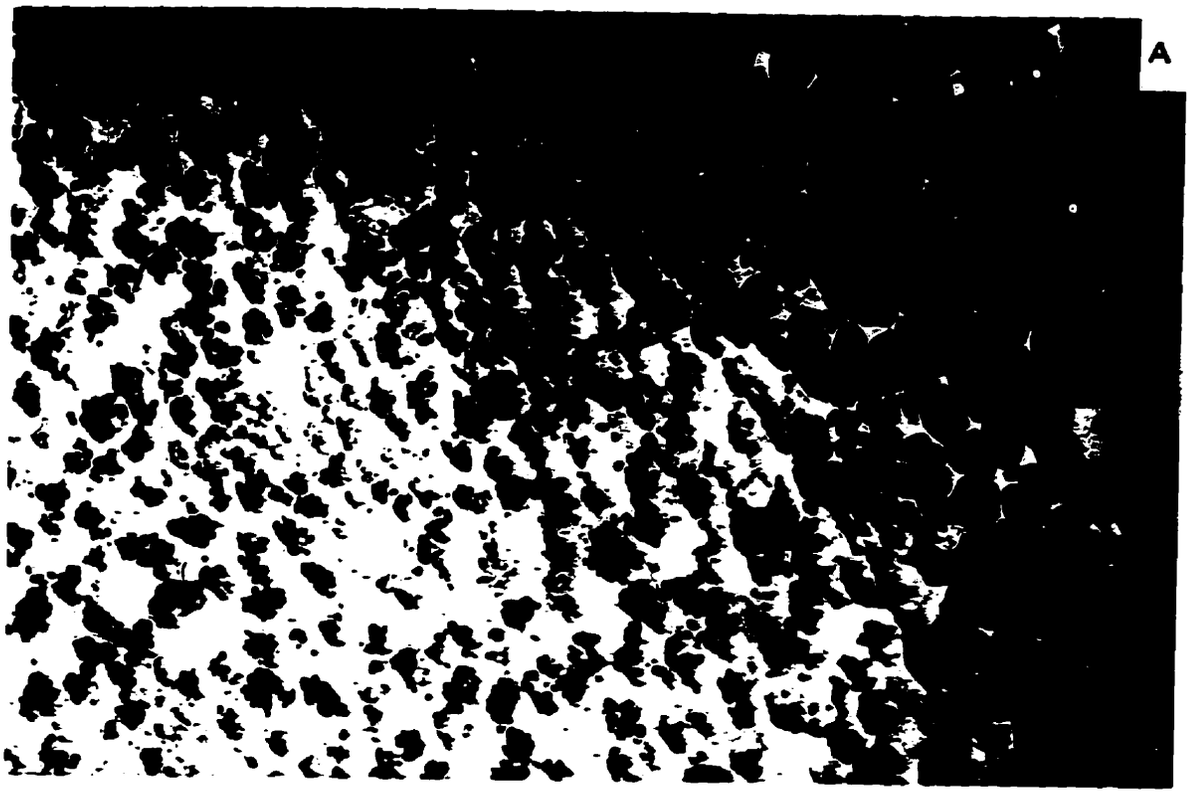

VOLUME OF CELL AGGLOMERATE (mL)
0
10
20
30
40
50
Outer
Inner
A
Outer
Inner
B
STRIP POSITION

Figure 20. **Micrograph of inner and outer blanched french fry strips (cv. Russet Burbank) (Mag x15) after 30 s blanching by HTST conditions. Micrograph shows full view of a 1 cm-thick section. A - inner strip; B - outer strip.**


A


B

Figure 21. **Micrograph of inner and outer blanched french fry strips (cv. Russet Burbank) (Mag x40) after 30 s blanching by HTST conditions. Micrograph shows top right-hand corner of the section. A - inner strip; B - outer strip.**


A

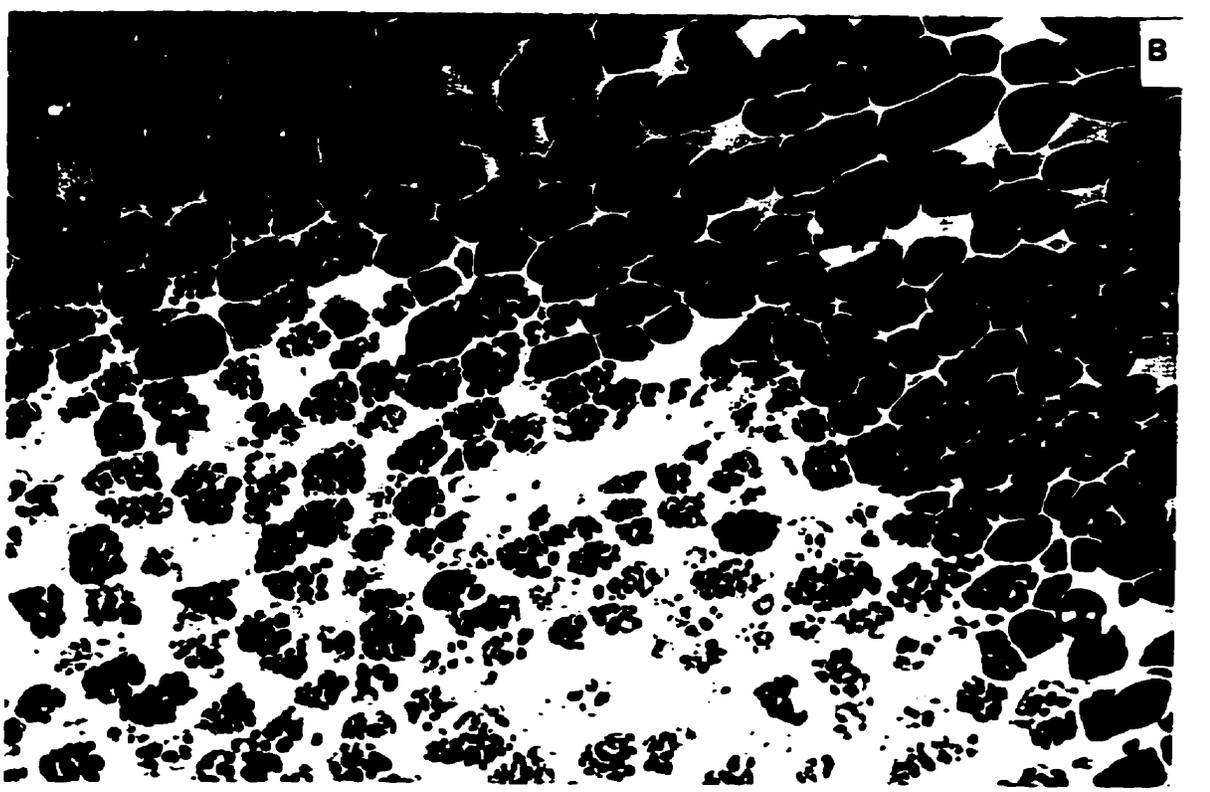
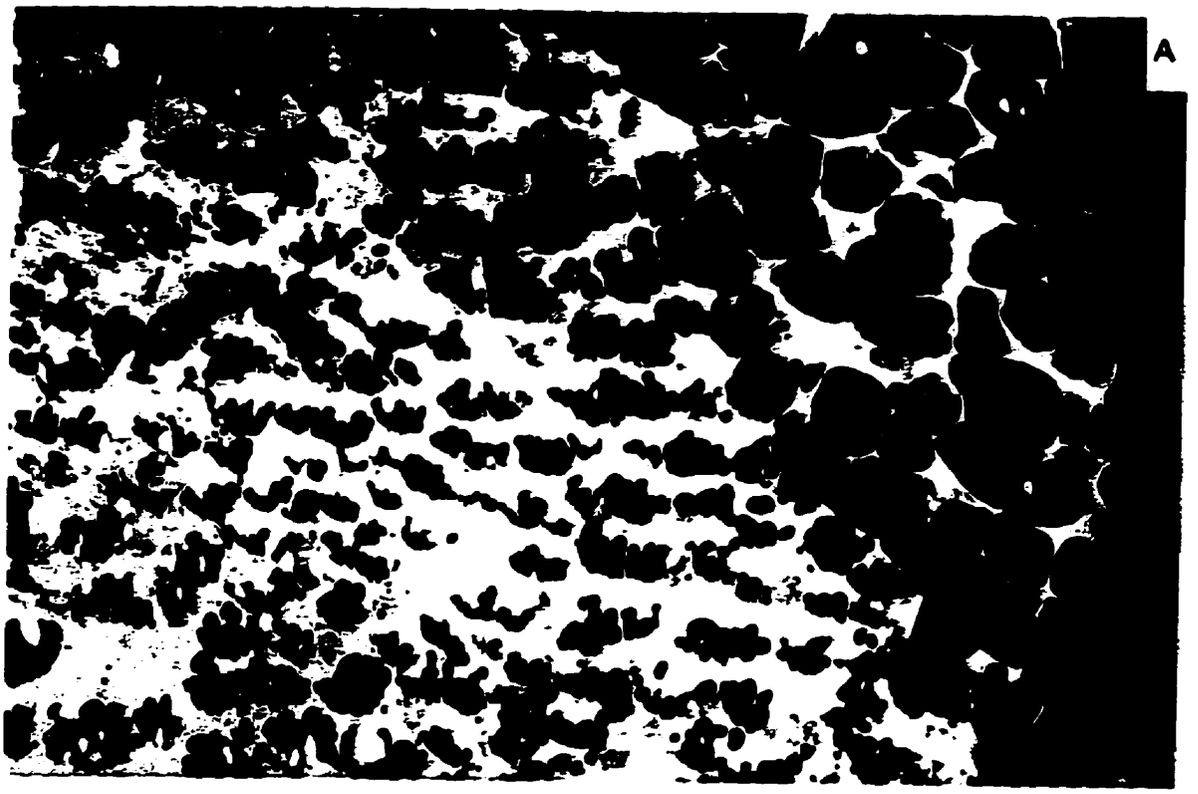

B

Figure 22. **Micrograph of inner and outer blanched french fry strips (cv. Russet Burbank) (Mag x60) after 30 s blanching by HTST conditions. Micrograph shows top right-hand corner of the section. A - inner strip; B - outer strip.**


A

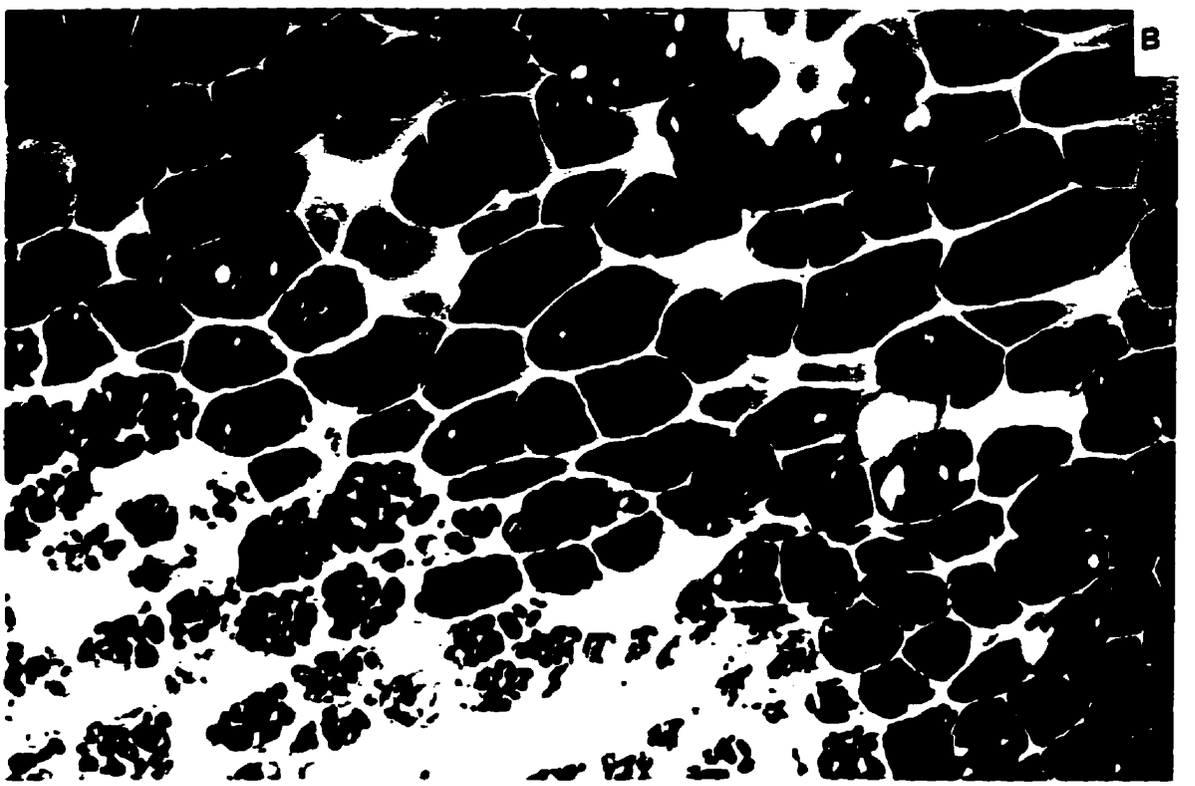
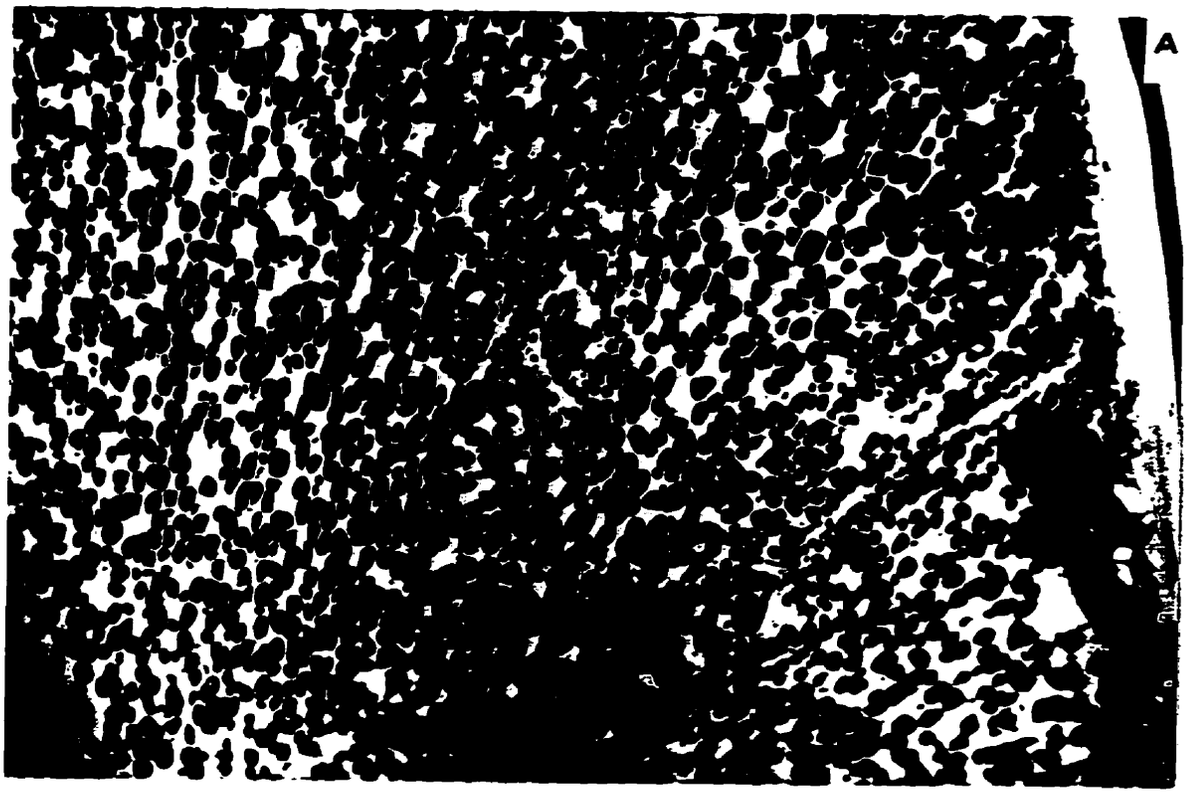

B

Figure 23. **Micrograph of inner and outer blanched french fry strips (cv. Russet Burbank) (Mag x15) after 40 s blanching by HTST conditions. Micrograph shows full view of a 1 cm-thick section. A - inner strip; B - outer strip.**


A

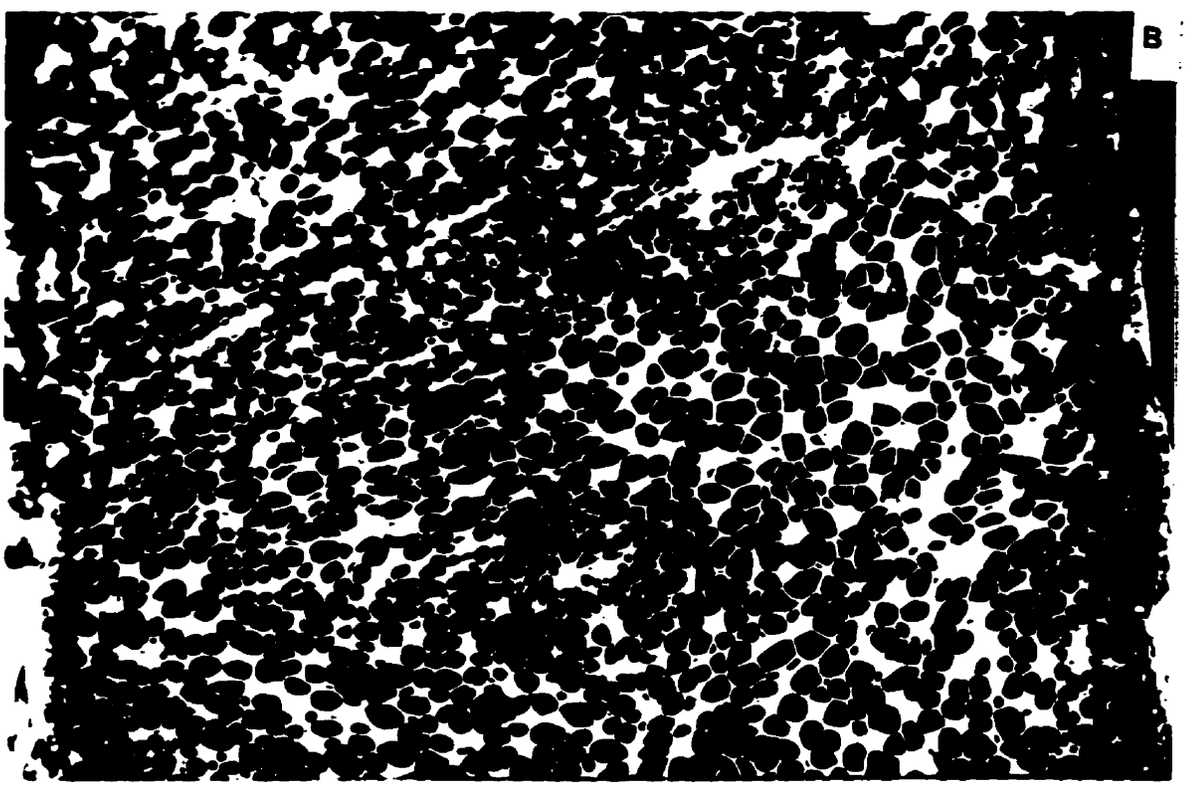
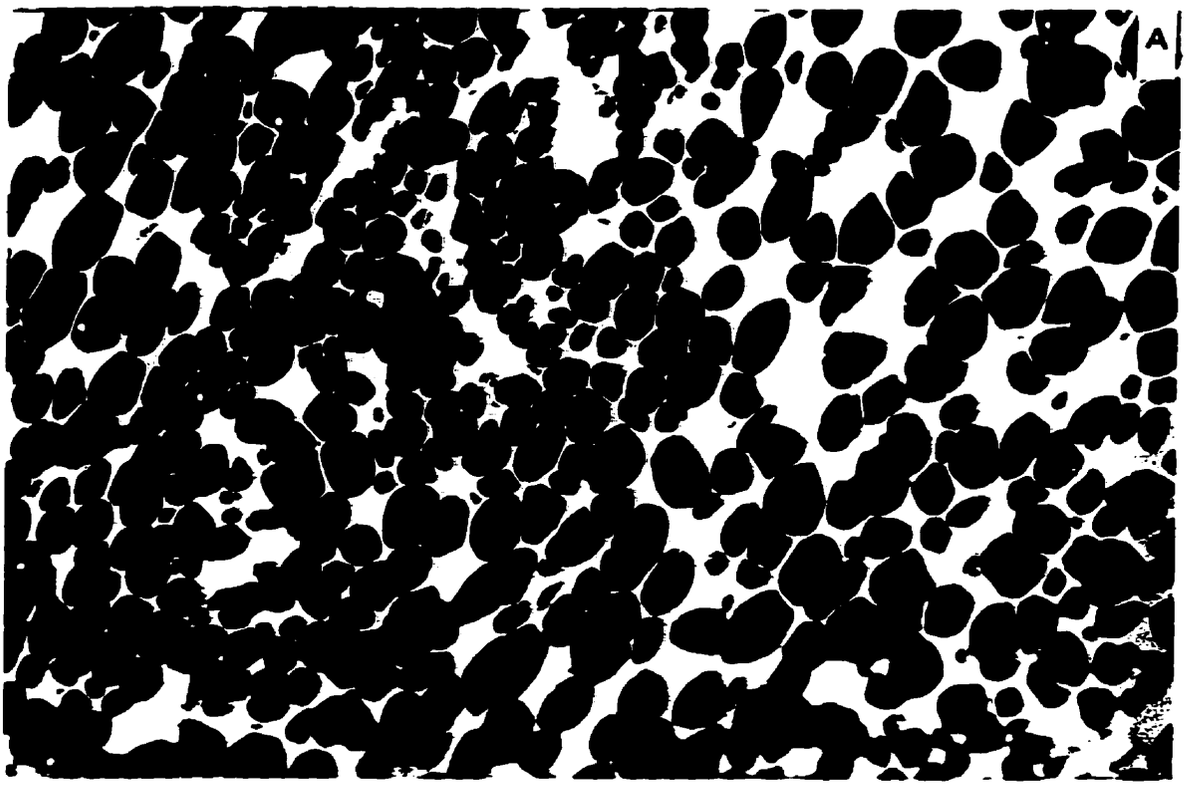

B

Figure 24. Micrograph of inner and outer blanched french fry strips (cv. Russet Burbank) (Mag x40) after 40 s blanching by HTST conditions. Micrograph shows centre of section. A - inner strip; B - outer strip.


A

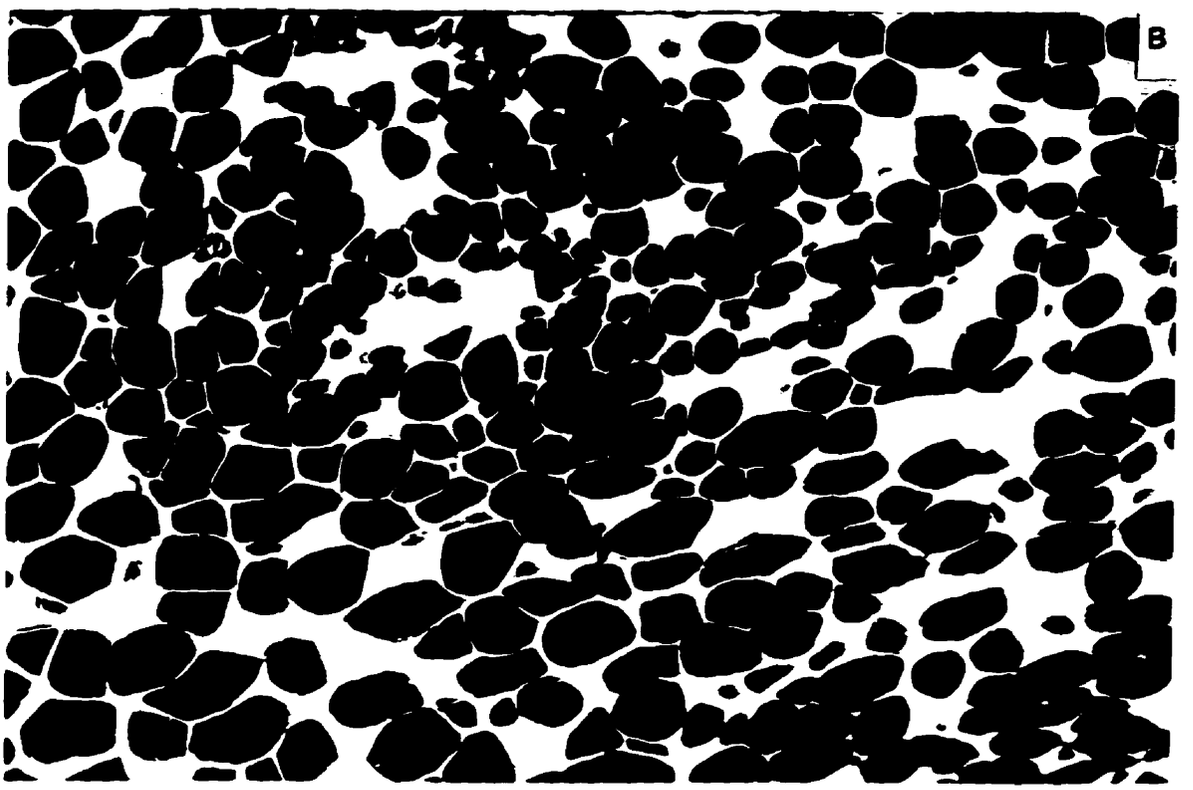

B

Figure 25. Micrograph of inner and outer blanched french fry strips (cv. Russet Burbank) (Mag x60) after 40 s blanching by HTST conditions. Micrograph shows centre of section. A - inner strip; B - outer strip.

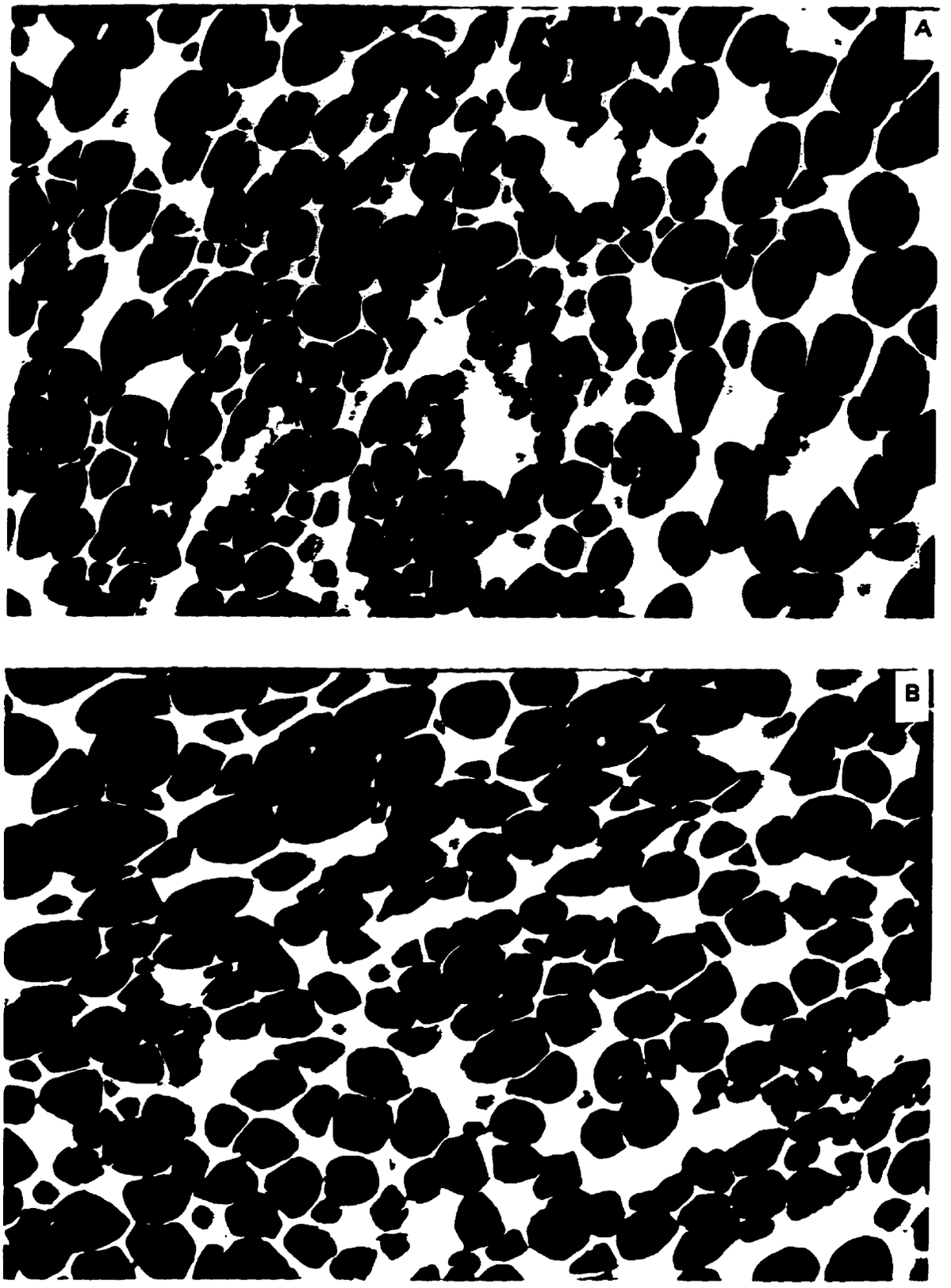
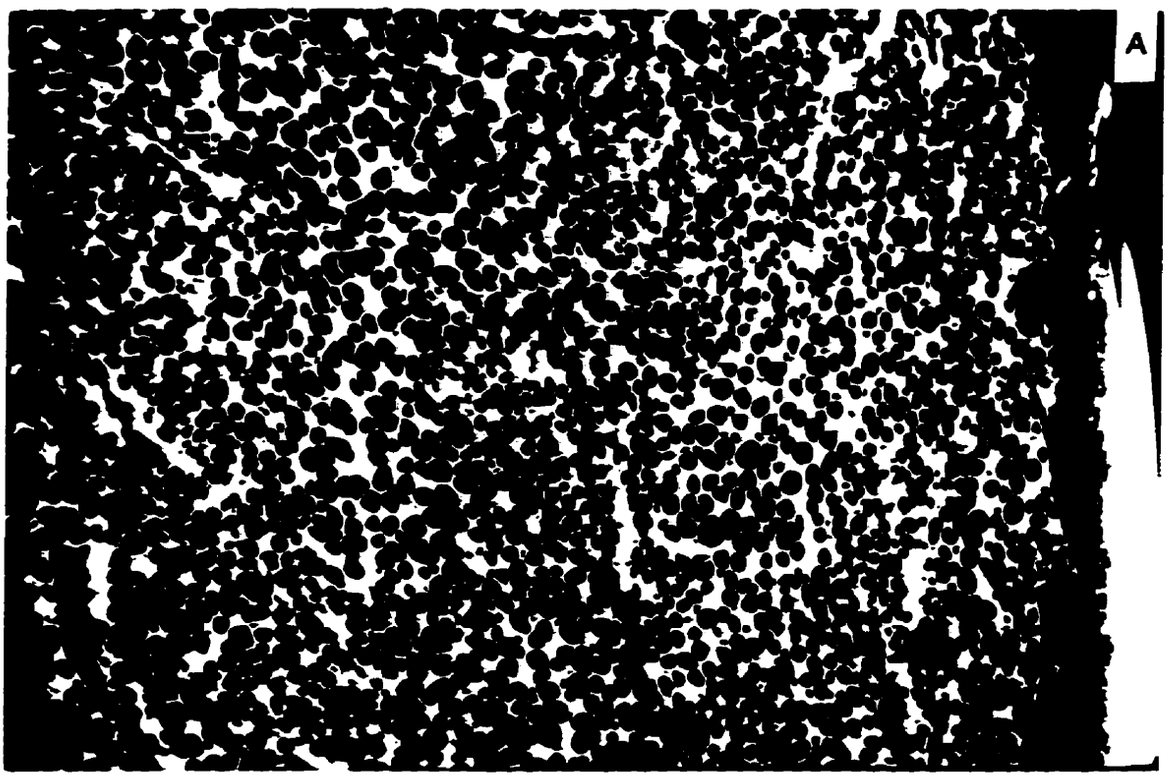

A
B

Figure 26. **Micrograph of inner and outer blanched french fry strips (cv. Russet Burbank) (Mag x15) after 2 min blanching by HTST conditions. Micrograph shows full view of a 1 cm-thick section. A - inner strip; B - outer strip.**


A

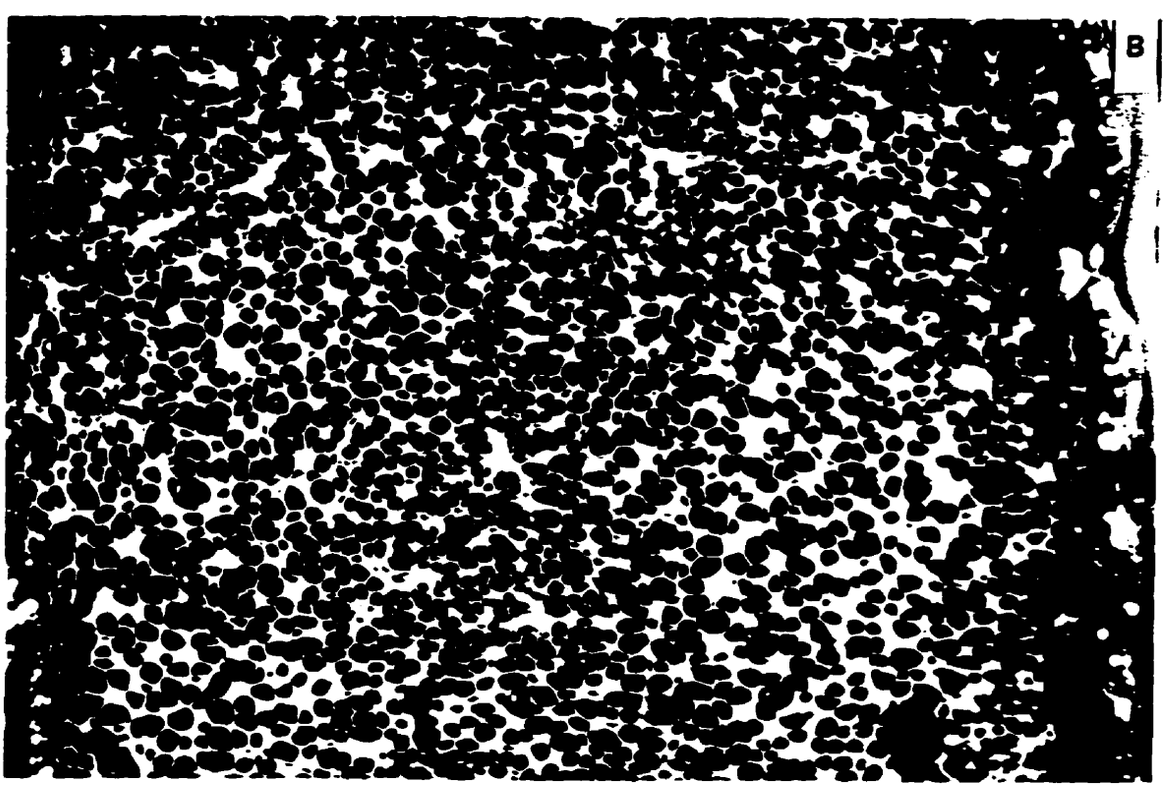
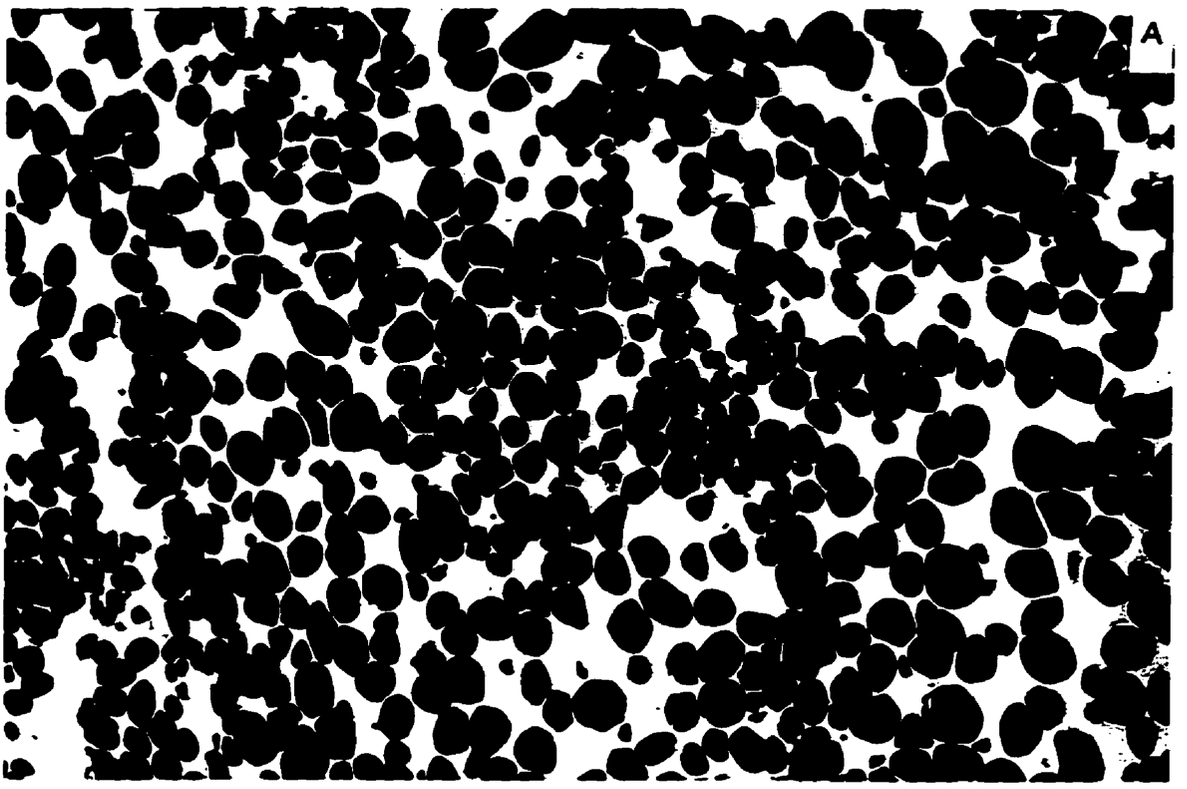

B

Figure 27. **Micrograph of inner and outer blanched french fry strips (cv. Russet Burbank) (Mag x40) after 2 min blanching by HTST conditions. Micrograph shows centre of section. A - inner strip; B - outer strip.**


A

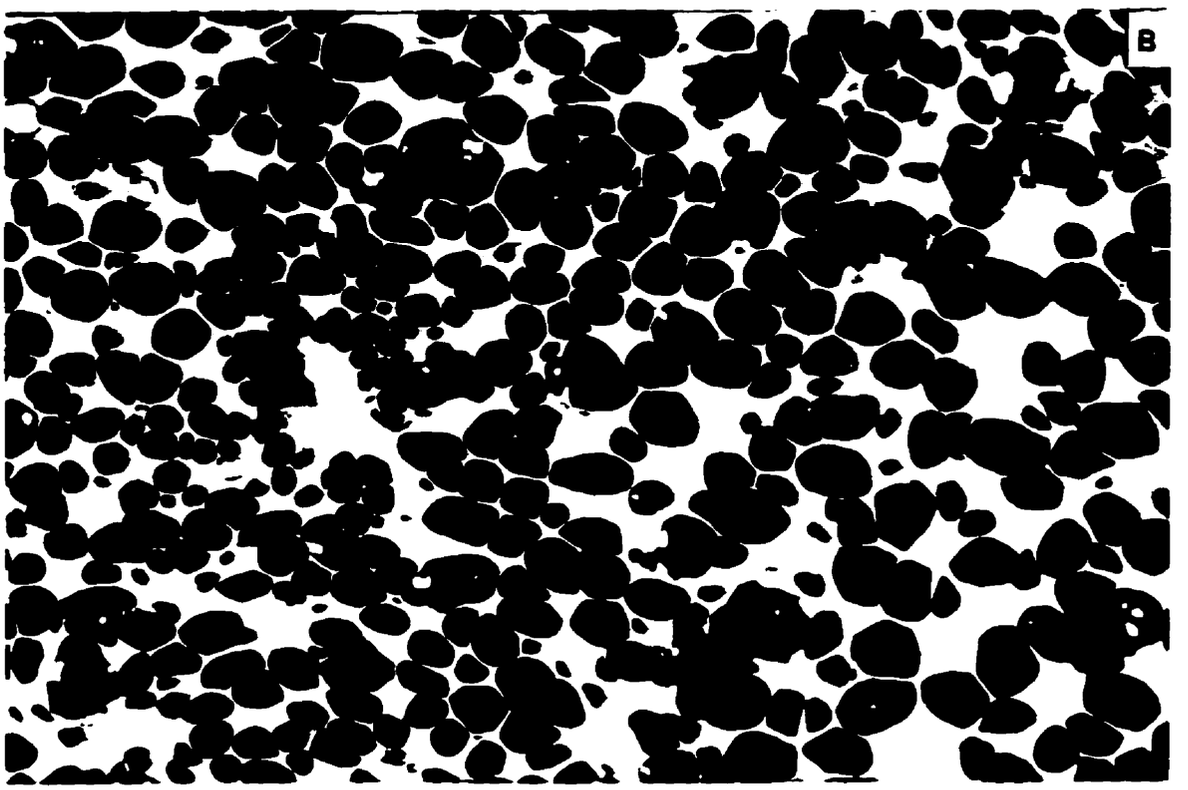
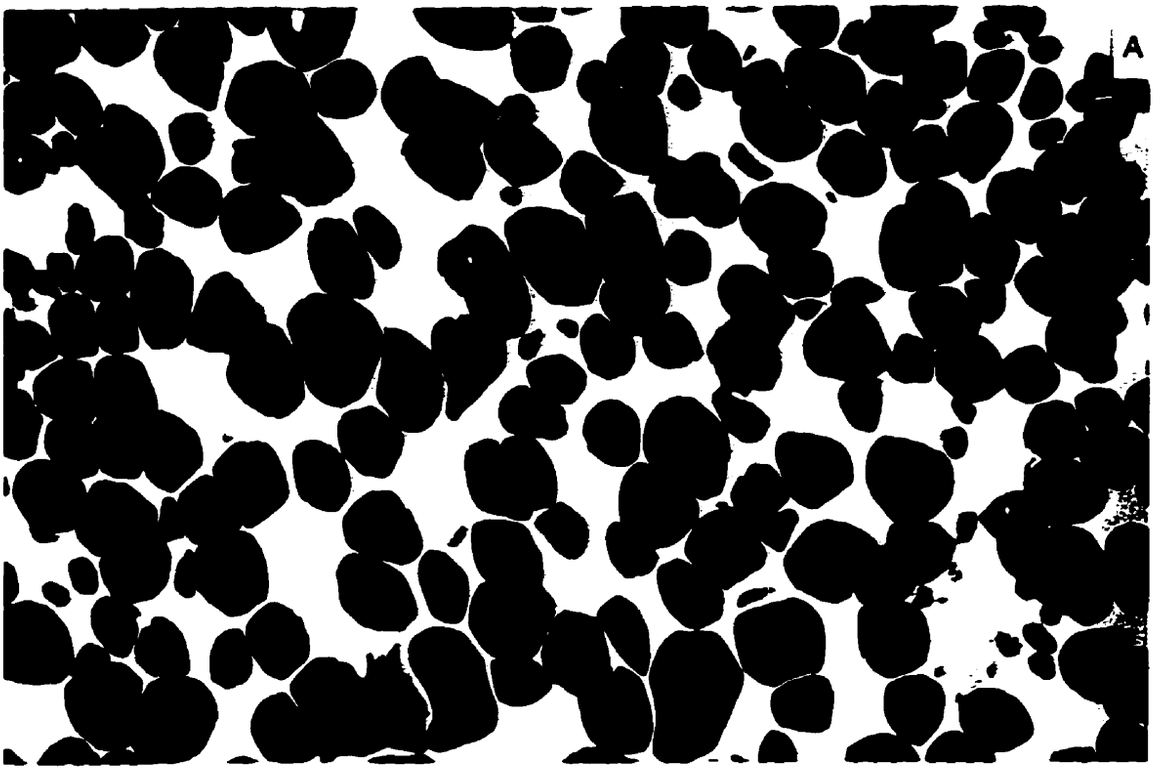
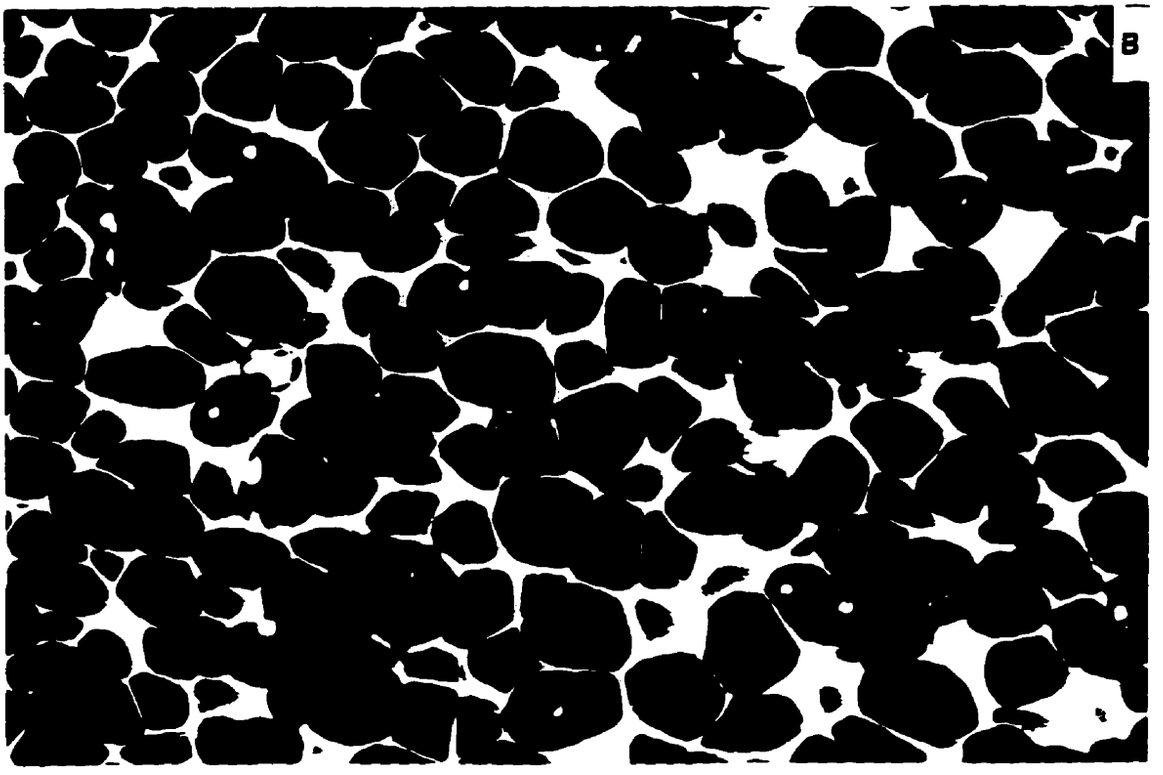

B

Figure 28. **Micrograph of inner and outer blanched french fry strips (cv. Russet Burbank) (Mag x60) after 2 min blanching by HTST conditions. Micrograph shows centre of section. A - inner strip; B - outer strip.**


A


B

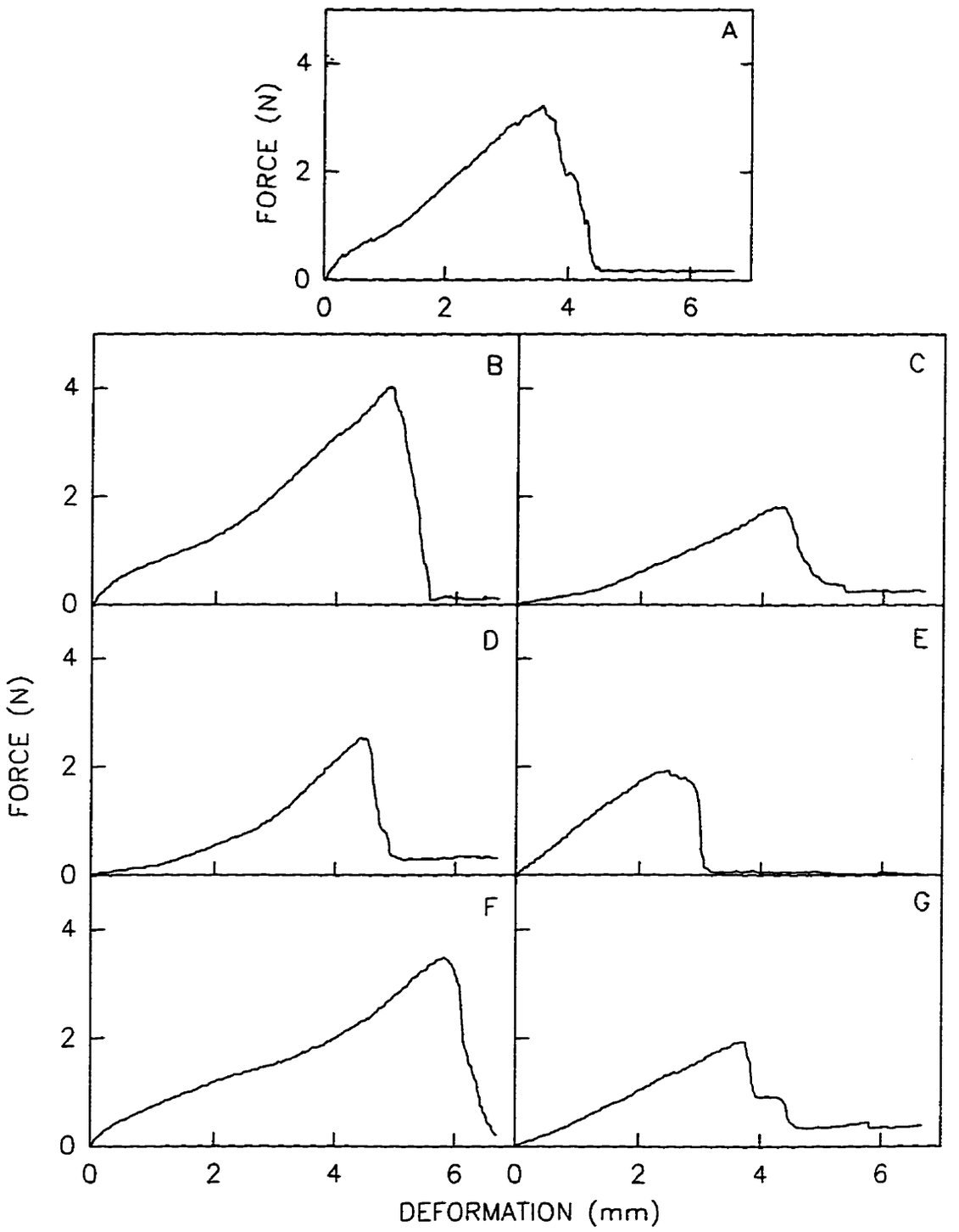
swelling was less. After 2 minutes of blanching (Figures 26-28, A and B), the cells in the outer french fry strips had taken on a "balloon-like" appearance due to excessive swelling of starch accompanied by starch swelling pressure. This "balloon-like" appearance was less evident in inner french fry strips. It was also evident after 2 min that the cell walls in both inner and outer french fry strips were still intact and that no cell separation had occurred. Although the results are not shown, cell wall staining using 0.5% (w/v) ruthenium red solution (Kawabata et al., 1976) also indicated that there was no cell separation. A similar observation was made by Jarvis and Duncan (1992) who noted that cell separation was not apparent in potato tissue that had been boiled for 3 min.

4.5 Effects Of Unit Process Operations On Peak Force, Peak Deformation And Hunterlab L Value Of Fully-Fried French Fries

Previous results (Table 8) indicated that the effects of blanching were evident in the mechanical properties, even after freezing. Experiments were conducted to determine whether the effect of changing the conditions of a given unit operation would be evident in the textural and colour quality of fully-fried french fries. Due to the inherent variations in potato tissue, it was necessary to compare two processing conditions for a given unit operation using strips from the same tuber. Fries processed by the standard conditions were compared to a LTLT or a HTST condition. French fries processed according to standard conditions were used as a reference to compare the effect of processing. Refer to Table 2 for processing conditions used.

Typical load-deformation curves of fries processed by the various processing conditions for all unit operations used are depicted in Figure 29. A sudden drop after

Figure 29. Typical load-deformation curves of fully-fried french fries processed by various processing conditions. Puncture tests were performed using a 2 mm-diameter probe. A - standard conditions; B - LTLT blanch; C - HTST blanch; D - LTLT dry; E - HTST dry; F - LTLT finish fry; G - HTST finish fry.


A
B
C
D
E
F
G
FORCE (N)
DEFORMATION (mm)
0
2
4
6

peak force was observed as the probe penetrated the fry interior and in some instances, (eg. Figure 29E), peak force dropped to almost zero. Because calculations of post-puncture energy consumption was time-consuming, statistical analysis was performed initially on only data obtained for 9 months storage (shown in Appendix 7). The results shown in Appendix 7 indicated that for Portage (Russet Burbank) in four out of six cases significant differences were found between the standard and a given processing condition, whereas for Carberry (Russet Burbank) post-puncture energy consumption was significantly higher for LTLT finish fry compared to standard conditions. For Carberry (Shepody), post-puncture energy consumption was significantly higher for HTST finish fry than for the standard. Because a greater number of significant differences were found between the standard and experimental conditions for finish fry compared with blanching and drying, further analyses of data were performed for only those sites, cultivars and process conditions for which significant differences were found in the frying experiments (Appendix 8). These results indicated that there were no significant differences ($p \leq 0.05$) between the standard and the given finish fry condition. Consequently, only peak force and peak deformation were obtained from all load-deformation curves.

4.5.1 Effects of blanching conditions

Peak force and peak deformation of french fries processed by LTLT conditions for Russet Burbank and Shepody potatoes (Tables 12 and 13, respectively) were not significantly different from the standard conditions although the trend in the data indicated that these mechanical parameters were greater for the LTLT conditions than for the standard conditions. For HTST, in 12 out of 32 cases peak force and peak

Table 12. Mean values of peak force, peak deformation and Hunterlab L value of fully-fried french fries processed by the standard and two experimental blanching conditions (n=4) for Russet Burbank potatoes*

Site	Storage period (months)	Peak force (N)			Peak deformation (mm)			Hunterlab L value		
		Processing conditions								
		Std	LTLT	HTST	Std	LTLT	HTST	Std	LTLT	HTST
					1994					
Portage	9	2.51a[1]	2.55a[2]	2.25a[1]	4.29b[2]	4.77a[1]	3.67c[2]	52.81b[1]	54.20a[2]	56.65a[1]
	11	2.58b[1]	2.99a[1]	2.49b[1]	5.30a[1]	5.08a[1]	5.18a[1]	50.43b[2]	59.40a[1]	52.10b[2]
					1995					
	1	2.50a[2]	2.59a[1]	2.26a[2]	4.94a[1]	4.98a[1]	4.52a[1]	50.13b[1]	55.45a[1]	54.32a[1]
	3	2.85a[1]	3.04a[1]	2.76a[1]	4.49a[2]	4.57a[1]	4.15b[1]	48.24b[2]	52.87a[2]	47.22b[2]
					1994					
Carberry	9	2.56a[1]	2.40a[1]	2.43a[1]	4.09b[2]	3.73b[2]	4.56a[1]	51.90b[2]	55.20a[1]	50.80b[2]
	11	2.51a[1]	2.63a[1]	2.16b[1]	4.87a[1]	4.61a[1]	4.53a[1]	53.92b[1]	55.75b[1]	57.60a[1]
					1995					
	1	2.47a[1]	2.76a[1]	2.51a[1]	5.13a[1]	5.38a[1]	4.74b[1]	52.62b[1]	55.95a[1]	55.55a[1]
	3	2.51a[1]	2.57a[1]	2.45a[1]	4.37a[2]	4.49a[2]	4.39a[1]	50.11b[2]	54.60a[1]	53.12a[2]

* Within a row, mean values of the standard and an experimental processing condition followed by different letters are significantly different from each other ($p \leq 0.05$); n=24 for standard conditions. Within a column, mean values followed by different numbers are significantly different from each other ($p \leq 0.05$). Refer to Table 2 for processing conditions.

Table 13. Mean values of peak force, peak deformation and Hunterlab L value of fully-fried french fries processed by the standard and two experimental blanching conditions (n=4) for Shepody potatoes*

Site	Storage period (months)	Peak force (N)			Peak deformation (mm)			Hunterlab L value		
		Processing conditions								
		Std	LTLT	HTST	Std	LTLT	HTST	Std	LTLT	HTST
					1994					
Portage	9	2.45a[1]	2.31a[2]	2.31a[1]	4.47a[2]	4.31a[2]	4.38a[2]	48.36b[2]	54.77a[2]	51.25a[2]
	11	2.55a[1]	2.78a[1]	2.13b[1]	5.17a[1]	5.53a[1]	5.48a[1]	49.75b[1]	57.07a[1]	52.90a[1]
					1995					
	1	2.68b[1]	3.07a[1]	1.96c[2]	5.16b[1]	5.83a[1]	5.37b[1]	49.18b[1]	46.52c[2]	53.17a[1]
	3	2.63b[1]	3.26a[1]	2.62b[1]	4.44a[2]	3.80b[2]	4.54a[2]	50.39b[1]	53.97a[1]	51.62b[2]
					1994					
Carberry	9	2.42a[1]	2.67a[1]	1.96b[1]	4.23a[2]	4.58a[2]	3.51b[2]	50.67b[1]	56.35a[2]	48.60c[2]
	11	2.48a[1]	2.78a[1]	1.92b[1]	5.06b[1]	5.70a[1]	5.39a[1]	51.72b[1]	57.57a[1]	54.87a[1]
					1995					
	1	2.44b[2]	2.76a[1]	2.07c[1]	5.57a[1]	5.31a[1]	5.46a[1]	50.72b[1]	56.12a[1]	55.95a[1]
	3	2.73a[1]	2.89a[1]	1.97b[1]	4.80a[2]	4.77a[2]	4.28b[2]	50.10b[1]	56.75a[1]	54.77a[1]

* Within a row, mean values of the standard and an experimental processing condition followed by different letters are significantly different from each other ($p \leq 0.05$); n=24 for standard conditions. Within a column, mean values followed by different numbers are significantly different from each other ($p \leq 0.05$). Refer to Table 2 for processing conditions.

deformation were significantly lower compared to the standard. The trend observed indicated that peak force and peak deformation were generally lower for HTST compared to the standard. These results indicated that the effects of blanching were evident in the textural quality of french fries, even after finish frying. Fry colour, on the other hand, was generally lighter for both modified blanching conditions L compared to the standard conditions (Tables 12 and 13) indicating that colour quality appeared to be improved by both LTLT and HTST blanching conditions. These results also suggested that both blanching time and temperature were important factors in determining colour and textural quality of french fries.

4.5.2 Structural changes during processing

Micrographs of the cell wall and starch granules of raw, blanched and, blanched and frozen potato tissue observed by light microscopy are shown in Figures 30-33. In the raw tissue (Figure 30A) the cell walls and starch granules were relatively intact. In HTST-blanched tissue the cell walls appeared relatively unaffected by the blanching treatment (Figures 31A) whereas starch gelatinization had occurred (Figure 31B). For LTLT, the cell walls appeared relatively unaffected by the blanching treatment and starch granules were gelatinized (compare Figure 30 to 32). The extent of starch gelatinization appeared to be greater for LTLT (Figure 32B) than for HTST blanch (Figures 31B). In blanched and frozen tissue (Figure 33A) relative to raw tissue (Figure 30A), cell cleavage along the middle lamella was apparent. In some cells, for example Figure 31B, gelatinized starch had retracted to the centre of the cell or was attached to a section of the wall. A similar observation was made by Davis and Gordon (1984) who noted that this "pulling-away" of gelatinized starch from the cell walls is an

Figure 30. **Micrograph of raw potato tissue (cv. Russet Burbank) (Mag x32). A - cell walls stained with 1% (w/v) cellufluor solution; B - starch granules stained with 1% (w/v) iodine solution.**

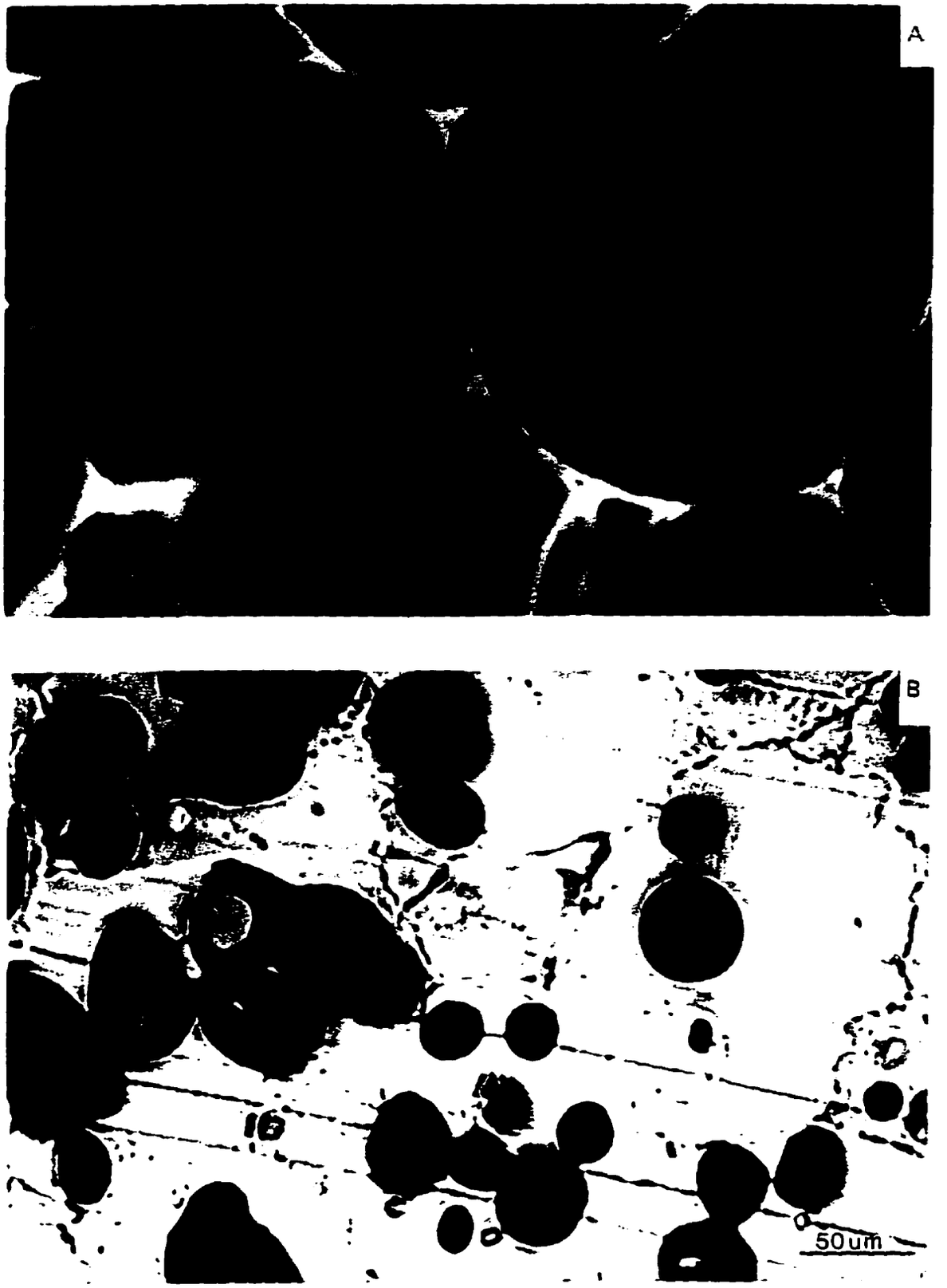

A
B
16
50um

Figure 31. **Micrograph of potato tissue (cv. Russet Burbank) blanched by HTST conditions (Mag x32). A - cell walls stained with 1% (w/v) cellufluor solution; B - starch granules stained with 1% (w/v) iodine solution.**


A


B
50 µm

Figure 32. **Micrograph of potato tissue (cv. Russet Burbank) blanched by LTLT conditions (Mag x32). A - cell walls stained with 1% (w/v) cellufluor solution; B - starch granules stained with 1% (w/v) iodine solution.**


A


B
50um

Figure 33. **Micrograph of potato tissue (cv. Russet Burbank) blanched by HTST conditions followed by freezing (Mag x32). A - cell walls stained with 1% (w/v) cellufluor solution; B - starch granules stained with 1% (w/v) iodine solution.**


A


B
50um

artifact of sample preparation.

4.5.3 Effects of drying conditions

The general trend indicated that peak force and peak deformation were greater for fries processed by the standard conditions than for fries processed by LTLT and HTST conditions (Tables 14 and 15). This was especially true for the HTST conditions for both Russet Burbank and Shepody potatoes. Change in final moisture content of fries during drying is presented in Table 16. With the exception of Russet Burbank potatoes from Carberry dried under LTLT conditions there were no significant differences between the standard and a given processing condition. Relative to the standard, Hunterlab L value of fries was significantly lower for LTLT compared to the standard in six cases although the general trend indicated that fry colour for LTLT was lower. These results suggested that long-time drying conditions were detrimental to french fry colour (Tables 14 and 15). For the HTST samples, nine out of 16 times there were no significant differences in the L value between HTST and the standard. This indicated that the HTST drying conditions did not seem to have a consistent effect on changing colour quality of french fries.

4.5.4 Effects of finish fry conditions

Tables 17 and 18 suggest that there were no significant differences in peak force and peak deformation between the standard and the LTLT conditions although the trend in the data indicated that these mechanical parameters were greater for LTLT than for the standard. For colour, in 11 out of 16 cases no significant differences were found in the L value between LTLT and the standard. These results suggested that a

Table 14. Mean values of peak force, peak deformation and Hunterlab L value of fully-fried french fries processed by the standard and two experimental drying conditions (n=4) for Russet Burbank potatoes[a]

Site	Storage period (months)	Peak force (N)			Peak deformation (mm)			Hunterlab L value		
		Processing conditions								
		Std	LTLT	HTST	Std	LTLT	HTST	Std	LTLT	HTST
					1994					
Portage	9	2.51a[1]	2.38a[1]	2.47a[1]	4.29a[2]	4.19a[2]	3.64b[2]	52.81b[1]	51.27b[1]	54.07a[1]
	11	2.58a[1]	2.41a[1]	2.33a[1]	5.30a[1]	5.18a[1]	4.35b[1]	50.43a[2]	49.55a[1]	52.25a[1]
					1995					
	1	2.50a[2]	2.63a[1]	2.22a[1]	4.94a[1]	4.69a[1]	4.30b[1]	50.13a[1]	45.25b[1]	48.50b[1]
	3	2.85a[1]	2.52a[1]	2.21b[1]	4.49a[2]	3.55b[2]	3.44b[2]	48.24a[2]	46.07b[1]	47.37a[2]
					1994					
Carberry	9	2.56a[1]	2.45a[1]	2.52a[1]	4.09a[2]	3.95a[2]	3.10b[2]	51.90a[2]	52.65a[1]	48.27b[2]
	11	2.51a[1]	2.14b[1]	2.47a[1]	4.87a[1]	4.54a[1]	4.29b[1]	53.92a[1]	46.57b[2]	51.95b[1]
					1995					
	1	2.47a[1]	2.36a[1]	2.27a[1]	5.13a[1]	4.88a[1]	4.60b[1]	52.62a[1]	51.67a[1]	52.75a[1]
	3	2.51a[1]	2.56a[1]	1.90b[2]	4.37a[2]	3.67b[2]	3.50b[2]	50.11b[2]	52.02a[1]	50.32b[2]

[a] Within a row, mean values of the standard and an experimental processing condition followed by different letters are significantly different from each other ($p \leq 0.05$); $n=24$ for standard conditions. Within a column, mean values followed by different numbers are significantly different from each other ($p \leq 0.05$). Refer to Table 2 for processing conditions.

Table 15. Mean values of peak force, peak deformation and Hunterlab L value of fully-fried french fries processed by the standard and two experimental drying conditions (n = 4) for Shepody potatoes*

Site	Storage period (months)	Peak force (N)			Peak deformation (mm)			Hunterlab L value		
		Processing conditions								
		Std	LTLT	HTST	Std	LTLT	HTST	Std	LTLT	HTST
					1994					
Portage	9	2.45a[1]	2.43a[1]	2.44a[1]	4.47a[2]	4.04b[1]	4.35a[1]	48.36a[2]	47.72a[2]	43.42b[2]
	11	2.55a[1]	2.16b[1]	2.57a[1]	5.17a[1]	4.50b[1]	4.00b[1]	49.75a[1]	50.50a[1]	47.50b[1]
					1995					
	1	2.68a[1]	2.33b[1]	2.32b[1]	5.16a[1]	4.57b[1]	5.02a[1]	49.18a[1]	44.97b[2]	50.27a[2]
	3	2.63a[1]	2.49a[1]	2.12b[1]	4.44a[2]	4.09a[2]	3.47b[2]	50.39b[1]	49.22b[1]	51.92a[1]
					1994					
Carberry	9	2.42a[1]	1.88b[2]	1.90b[1]	4.23a[2]	2.99b[2]	2.90b[2]	50.67b[1]	52.65a[1]	50.07b[2]
	11	2.48a[1]	2.38a[1]	2.11b[1]	5.06a[1]	5.12a[1]	4.33b[1]	51.72a[1]	45.97b[2]	53.12a[1]
					1995					
	1	2.44a[2]	2.33a[1]	2.17a[1]	5.57a[1]	4.75b[1]	5.18b[1]	50.72b[1]	52.45a[1]	49.42b[2]
	3	2.73a[1]	2.32b[1]	2.34b[1]	4.80a[2]	4.15b[2]	3.47b[2]	50.10a[1]	46.20b[2]	51.17a[1]

* Within a row, mean values of the standard and an experimental processing condition followed by different letters are significantly different from each other ($p \leq 0.05$); $n = 24$ for standard conditions. Within a column, mean values followed by different numbers are significantly different from each other ($p \leq 0.05$). Refer to Table 2 for processing conditions.

Table 16. Paired comparisons of change in moisture content of fully-fried french fries processed by the standard and an experimental drying condition (n=8)

Cultivar	Site	Processing conditions	Moisture content (%)[1]		Change in moisture[2]
			Initial	Final	(%)
Russet Burbank	Carberry	Standard	76.7±1.1	56.4±2.3	20.3a
		HTST	77.5±1.1	58.7±1.9	18.8a
		LTLT	76.8±1.3	59.5±1.6	17.3b
	Portage	Standard	76.0±2.6	58.1±4.8	17.9a
		HTST	75.6±3.6	57.8±4.4	17.8a
		LTLT	76.8±2.4	58.8±1.6	18.0a
Shepody	Carberry	Standard	80.1±2.2	60.7±3.1	19.4a
		HTST	78.9±1.7	61.4±1.1	17.5a
		LTLT	81.0±1.2	64.1±1.4	16.9a
	Portage	Standard	76.9±2.3	57.8±3.1	19.1a
		HTST	78.0±3.0	59.6±3.2	18.4a
		LTLT	75.7±2.2	58.9±1.7	16.8a

[1] Values are means±standard deviation; n=16 for standard conditions

[2] Means of the standard and an experimental drying condition followed by different letters are significantly different from each other ($p \leq 0.05$).

Table 17. Mean values of peak force, peak deformation and Hunterlab L value of fully-fried french fries processed by the standard and two experimental finish fry conditions (n=4) for Russet Burbank potatoes*

Site	Storage period (months)	Peak force (N)			Peak deformation (mm)			Hunterlab L value		
		Processing conditions								
		Std	LTLT	HTST	Std	LTLT	HTST	Std	LTLT	HTST
					1994					
Portage	9	2.51a[1]	2.45a[2]	2.80a[1]	4.29b[2]	4.93a[1]	3.90a[2]	52.81b[1]	50.42c[1]	54.35a[1]
	11	2.58b[1]	3.04a[1]	2.31b[2]	5.30a[1]	5.25a[1]	5.01a[1]	50.43b[2]	48.65b[1]	52.25a[2]
					1995					
	1	2.50a[2]	2.39a[2]	2.30a[1]	4.94a[1]	4.93a[1]	4.13b[2]	50.13b[1]	52.70a[1]	53.20a[1]
	3	2.85a[1]	3.00a[1]	2.52a[1]	4.49a[2]	4.41a[1]	4.81a[1]	48.24a[2]	49.32a[2]	46.45b[2]
					1994					
Carberry	9	2.56a[1]	2.48a[2]	2.80a[1]	4.09a[2]	4.02a[2]	4.10a[2]	51.90a[2]	51.37a[2]	52.75a[2]
	11	2.51b[1]	2.99a[1]	2.45b[1]	4.87a[1]	5.08a[1]	4.85a[1]	53.92b[1]	55.45b[1]	59.67a[1]
					1995					
	1	2.47a[1]	2.70a[1]	2.36a[1]	5.13b[1]	5.62a[1]	4.45c[1]	52.62b[1]	52.70b[1]	56.07a[1]
	3	2.51a[1]	2.75a[1]	2.47a[1]	4.37a[2]	4.71a[2]	4.04a[1]	50.11b[2]	47.42c[2]	55.17a[2]

* Within a row, mean values of the standard and an experimental processing condition followed by different letters are significantly different from each other ($p \leq 0.05$); n=24 for standard conditions. Within a column, mean values followed by different numbers are significantly different from each other ($p \leq 0.05$). Refer to Table 2 for processing conditions.

Table 18. Mean values of peak force, peak deformation and Hunterlab L value of fully-fried french fries processed by the standard and two experimental finish fry conditions (n=4) for Shepody potatoes*

Site	Storage period (months)	Peak force (N)			Peak deformation (mm)			Hunterlab L value		
		Processing conditions								
		Std	LTLT	HTST	Std	LTLT	HTST	Std	LTLT	HTST
					1994					
Portage	9	2.45a[1]	2.73a[1]	2.58a[1]	4.47a[2]	4.85a[1]	4.42a[1]	48.36a[2]	47.12a[1]	47.97a[2]
	11	2.55a[1]	2.81a[1]	2.37a[1]	5.17a[1]	5.07a[1]	4.67b[1]	49.75b[1]	48.50b[1]	55.20a[1]
					1995					
	1	2.68a[1]	2.88a[1]	2.33b[1]	5.16a[1]	4.79a[1]	4.99a[1]	49.18b[1]	50.70b[1]	53.07a[2]
	3	2.63a[1]	2.82a[1]	2.52a[1]	4.44a[2]	4.71a[1]	4.50a[1]	50.39b[1]	50.30b[1]	55.02a[1]
					1994					
Carberry	9	2.42a[1]	2.68a[1]	2.63a[1]	4.23a[2]	4.53a[1]	4.58a[1]	50.67a[1]	49.62a[2]	48.47b[2]
	11	2.48a[1]	2.71a[1]	2.49a[1]	5.06a[1]	5.05a[1]	4.20b[1]	51.72b[1]	51.95b[1]	56.05a[1]
					1995					
	1	2.44b[2]	2.95a[1]	2.39b[1]	5.57a[1]	5.45a[1]	5.39a[1]	50.72b[1]	53.07a[1]	52.85a[1]
	3	2.73b[1]	3.42a[1]	2.13c[1]	4.80a[2]	4.99a[1]	4.14b[2]	50.10a[1]	47.42b[2]	51.52a[2]

* Within a row, mean values of the standard and an experimental processing condition followed by different letters are significantly different from each other ($p \leq 0.05$); n=24 for standard conditions. Within a column, mean values followed by different numbers are significantly different from each other ($p \leq 0.05$). Refer to Table 2 for processing conditions.

plateau occurred in the L value after 2.5 min of frying (standard conditions), and increase in frying time did not significantly influence colour quality. Increase in frying temperature, on the other hand, caused a change in textural quality. For HTST, there were no significant differences in peak force compared to the standard except in two cases. Peak deformation was generally higher for fries made by the standard conditions compared to HTST. On the whole, Hunterlab L value was higher for HTST relative to the standard and suggested that colour quality is improved by HTST conditions. Change in final moisture content during finish frying, presented in Table 19, was generally greater for fries processed by the LTLT conditions than for the standard conditions suggesting that there was more moisture loss in LTLT samples, particularly for Shepody potatoes. On the other hand, change in final moisture of fries was generally greater for the standard than for the HTST conditions and implied a higher moisture content in HTST samples.

4.6 Overall Effects Of Processing And Storage Conditions, Cultivar And Site On Textural And Colour Quality Of Fully-Fried French Fries

In this section, statistical analyses were performed on overall means using the analysis of variance technique. Pairing of strips was eliminated. Therefore no comparisons are made between the standard conditions and an experimental condition. The reason was to determine the overall effects of various factors namely, processing, storage, cultivar and site on the textural and colour quality of french fries.

4.6.1 Processing

Of the seven processing conditions examined, LTLT blanching consistently

Table 19. Paired comparisons of change in moisture content of fully-fried french fries processed by the standard and an experimental finish fry condition (n = 8)

Cultivar	Site	Processing conditions	Moisture content (%)[1]		Change in moisture[2]
			Initial	Final	(%)
Russet Burbank	Carberry	Standard	77.6 ± 1.1	50.1 ± 2.4	27.5a
		HTST	77.3 ± 1.1	55.3 ± 0.2	22.0b
		LTLT	78.3 ± 0.7	50.5 ± 1.4	27.8a
	Portage	Standard	75.2 ± 3.9	51.8 ± 3.3	23.4a
		HTST	79.8 ± 1.2	58.5 ± 1.1	21.3a
		LTLT	75.1 ± 0.9	49.8 ± 2.5	25.3a
Shepody	Carberry	Standard	81.6 ± 1.1	50.5 ± 3.2	31.1b
		HTST	83.3 ± 1.4	56.7 ± 1.8	26.6c
		LTLT	81.9 ± 0.9	44.1 ± 0.7	37.8a
	Portage	Standard	76.9 ± 1.2	51.9 ± 5.1	25.0b
		HTST	79.5 ± 2.0	57.9 ± 2.3	21.6b
		LTLT	78.4 ± 1.4	44.2 ± 2.3	34.2a

[1] Values are means ± standard deviation; n = 16 for standard conditions

[2] Means of the standard and an experimental finish fry condition followed by different letters are significantly different from each other ($p \leq 0.05$).

increased peak force, peak deformation and Hunterlab L value in the finish fries although the difference was not always statistically significant (Table 20). All other processing conditions either increased peak force and peak deformation of fries but caused darkening of fry colour (eg. LTLT finish fry) or decreased the measured mechanical parameters and increased fry colour (eg. HTST blanch and HTST finish fry). The LTLT and HTST drying conditions, however, decreased both fry colour and mechanical properties. Fries processed by the standard conditions were generally comparable to the LTLT blanch and LTLT finish fry for mechanical properties, but were darker in colour than fries blanched by the LTLT and HTST conditions.

4.6.1.1 Strip position and puncture location

Table 21 shows the overall effect of strip position on peak force and peak deformation of fully-fried french fries. In both 1994 and 1995, the general trend indicated that peak force was higher for fries processed from the outer regions of the tuber than for fries made from the pith region. Peak deformation, on the whole, was higher for fries processed from the pith region compared to those processed from the outer regions of the tuber. These results implied that french fries from the outer regions of the tuber were firmer than fries from the inner region but more importantly, the effect of strip position was evident in the textural quality of french fries, even after finish fry.

For puncture location (Table 22), in both crop years, peak force of fries was generally higher at the stem end than at the bud end of the tuber. The results for peak deformation were not consistent. These results suggested that puncture location influences the textural quality of french fries but also implied that stem-to-bud end

Table 20. Overall effects of processing (n=32) on textural and colour quality of fully-fried french fries[1]

Measured physical property	Processing conditions						
	Standard	LTLT blanch	HTST blanch	LTLT dry	HTST dry	LTLT finish fry	HTST finish fry
	1994						
Peak force (N)	2.51b	2.64ab	2.21c	2.28c	2.35c	2.74a	2.55b
Peak deformation (mm)	4.68ab	4.79a	4.59bc	4.31d	3.87e	4.85a	4.47cd
Hunterlab L value	51.19c	56.29a	53.10b	49.61d	50.08cd	50.40cd	53.34b
	1995						
Peak force (N)	2.60b	2.87a	2.32cd	2.44c	2.20d	2.86a	2.34c
Peak deformation (mm)	4.86a	4.89a	4.68b	4.29c	4.12c	4.95a	4.56b
Hunterlab L value	50.19b	54.03a	53.22a	48.48c	50.22b	48.48c	53.28a

[1]Mean values within a row followed by different letters are significantly different from each other ($p \leq 0.05$); n=192 for standard conditions.

Table 21. Overall effect of strip position (n=48) on textural quality of fully-fried french fries[1]

Site & Cultivar	Strip position	1994		1995	
		Peak force (N)	Peak deformation (mm)	Peak force (N)	Peak deformation (mm)
Carberry RB	1 (outer)	2.62a	3.89b	2.52a	4.51b
	2	2.51ab	4.58a	2.51a	4.78a
	3 (inner)	2.41b	4.46a	2.41a	4.65ab
Portage RB	1 (outer)	2.64a	4.38b	2.75a	4.55a
	2	2.49a	4.83a	2.57b	4.62a
	3 (inner)	2.50a	4.88a	2.50b	4.47a
Carberry SH	1 (outer)	2.51a	4.09b	2.66a	4.90b
	2	2.34b	4.70a	2.59a	4.92b
	3 (inner)	2.34b	4.78a	2.34b	5.13a
Portage SH	1 (outer)	2.59a	4.17b	2.66a	4.41b
	2	2.48ab	4.96a	2.64a	4.89a
	3 (inner)	2.39b	5.05a	2.52a	4.87a

1 Mean values within a column followed by different letters are significantly different from each other ($p \leq 0.05$). Values are means of seven processing treatments.

Table 22. Overall effect of puncture location (n=48) on textural quality of fully-fried french fries[1]

Site & Cultivar	Puncture location	1994 Peak force (N)	1994 Peak deformation (mm)	1995 Peak force (N)	1995 Peak deformation (mm)
Carberry RB	Stem	2.86a	4.21b	2.84a	4.65a
	Mid	2.39b	4.46a	2.39b	4.65a
	Bud	2.29b	4.48a	2.21c	4.64a
Portage RB	Stem	2.84a	4.56b	2.88a	4.50a
	Mid	2.40b	4.82a	2.49b	4.47a
	Bud	2.39b	4.71ab	2.45b	4.66a
Carberry SH	Stem	2.66a	4.19b	2.60a	4.88a
	Mid	2.21b	4.76a	2.53a	5.06a
	Bud	2.31b	4.62a	2.46a	5.00a
Portage SH	Stem	2.67a	4.41b	2.70a	4.60b
	Mid	2.42b	4.89a	2.48b	4.74ab
	Bud	2.36b	4.88a	2.63ab	4.83a

1 Mean values within a column followed by different letters are significantly different from each other ($p \leq 0.05$). Values are means of seven processing treatments.

variations inherent in potato tubers could potentially influence the textural quality of potato chips.

4.6.2 Storage period

Generally, as storage period progressed from 9 to 11 months (Tables 12-15, 17 and 18) there was a concomitant increase in peak force and peak deformation of french fries. In 1995, peak force increased whereas peak deformation decreased implying that french fry firmness increased at the beginning of storage. On the whole, Hunterlab L value of french fries was higher at 11 months than at 9 months whereas at the beginning of the storage period the general trend indicated that the L value was higher at 1 month than at 3 months (Tables 12-15, 17 and 18). This result indicated that colour quality of french fries was improved by prolonged storage conditions.

4.6.3 Cultivar and site

With respect to cultivar, there was no statistical difference in peak force of fries processed from Russet Burbank and Shepody potatoes although peak deformation was generally higher for fries made from Shepody potatoes (Table 23). Hunterlab L value was generally greater for fries processed from Russet Burbank potatoes than for fries from Shepody potatoes (Table 23) suggesting that fries made from Russet Burbank potatoes had better colour quality than fries made from Shepody potatoes. In comparing the initial moisture contents of fries processed from Russet Burbank and Shepody potatoes (Tables 16 and 19), it was observed that Shepody (Carberry) potatoes had significantly higher moisture content (81.0%) ($p \leq 0.05$) than Russet Burbank (Carberry) potatoes (77.4%). For potatoes grown at Portage, the initial

Table 23. Overall effect of cultivar and site on textural and colour quality of fully-fried french fries (n=56)[1]

Cultivar	Peak force (N)		Peak deformation (mm)		Hunterlab L value	
	Portage	Carberry	Portage	Carberry	Portage	Carberry
			1994			
Russet Burbank	2.54a[1]	2.51a[1]	4.69a[1]	4.38b[2]	52.3a[1]	53.0a[1]
Shepody	2.49a[1]	2.39b[2]	4.73a[1]	4.52b[1]	49.7b[2]	51.6a[2]
			1995			
Russet Burbank	2.61a[1]	2.48b[1]	4.54b[2]	4.65a[2]	49.5b[1]	52.2a[1]
Shepody	2.61a[1]	2.53a[1]	4.72a[1]	4.98a[1]	50.3b[1]	51.4a[2]

[1] Means in a row for a given parameter followed by different letters and means in columns followed by different numbers differ significantly from each other ($p \leq 0.05$). Values are means of seven processing treatments.

moisture contents of fries did not differ significantly from each other, 76.1 and 77.3% for fries from Russet Burbank and Shepody potatoes, respectively. Differences in the moisture content of fries made from Carberry potatoes could potentially influence colour and textural quality.

For site, in two out of four cases peak force was significantly higher for fries from Portage potatoes (Table 23). Peak deformation, on the other hand, was inconsistent from year to year, being significantly larger for fries processed from Portage potatoes in 1994 compared to those made from Carberry potatoes. In 1995, fries processed from Carberry potatoes had significantly higher peak deformation than fries from Portage potatoes. Hunterlab L value was generally greater for fries processed from Carberry potatoes than for fries processed from Portage potatoes. These results indicated that Carberry potatoes produced french fries with better colour quality than fries from Portage potatoes.

5. DISCUSSION

5.1 Introductory Comments

The colour and textural quality of french fries are given primary consideration during french fry processing. Although the various biochemical and physiological processes occurring at the molecular and cellular levels in living potato tissue may significantly influence french fry quality, the most feasible option available to the food processor in enhancing french fry quality is the modification of processing conditions.

Because of gross variability in structure and composition that occurs between potato tubers, it is difficult to obtain a uniform finished product. Another major source of variability, namely variability among strips from a given tuber, was detected during initial trials undertaken to determine the distinct contribution of the crust and fry interior to the overall mechanical properties. Therefore, to accurately measure mechanical properties, it was necessary to compare strips taken from as close a position as possible within the same tuber.

In the present investigation, the textural quality of french fries was determined by measuring three mechanical properties of the french fry, namely, peak force, peak deformation and post-puncture energy consumption. Peak force is primarily a property of the crust and a high peak force would be interpreted as an increase in tissue firmness (Bourne, 1965). Peak deformation and post-puncture energy consumption, on the other hand, are indicative of changes in the fry interior. A large peak deformation and a low post-puncture energy consumption would therefore be interpreted as tissue softening (Bourne, 1967). For colour quality, the Hunterlab L (lightness) value was measured. A high L value would be interpreted as a light fry

colour which indicates improved colour quality.

5.2 Compositional And Anatomical Variations In Potato Tubers

Inner potato strips, located in the pith parenchyma, consistently had lower specific gravity than outer strips located in the perimedullary zone and cortex (Figure 12). Also, potato strips from the perimedullary zone had lower specific gravity than strips from the cortex. The differences in specific gravity between inner and outer strips may be due to the density of starch granules in different regions of the tuber. According to Reeve (1967), cortex tissue is packed with starch granules whereas pith tissue is less densely packed. This trend in specific gravity within the tuber was also reported by Sharma et al. (1959b) and Sayre et al. (1975). Sayre et al. (1975) further stated that there is a linear relationship between specific gravity and solids content. Simmonds (1977) also observed a linear relationship between specific gravity and starch content. Therefore, inner potato strips, located in the pith, have a lower solids and starch content than outer strips (Anzaldúa-Morales et al., 1992). The observed differences in specific gravity between the perimedullary zone and cortex could also be due to the high specific gravity tubers that are used for french fry processing in Manitoba; specific gravity differences between the cortex and perimedullary zone were greater in high specific gravity tubers than in low specific gravity tubers (Sharma et al., 1959b).

Peak force, peak deformation and post-puncture energy consumption were greater for inner strips blanched by LTLT and HTST conditions than for outer strips (Figures 13-18). The differences in the measured mechanical properties between inner and outer blanched strips can be attributed to the number and size of starch

granules in the pith and the cortex. During blanching, starch granules swell, generating a swelling pressure, analogous to turgor pressure in the raw tissue, which pushes the cell contents against the cell walls. Because cortex tissue contains numerous large-sized starch granules and pith tissue contains fewer small-sized granules (Reeve, 1967), the magnitude of the swelling pressure appeared to be greater in outer strips than in inner strips (Figures 26-28). Starch swelling pressure induced deformation in cell walls causing cells to appear "balloon-like". Such bulging of potato cell walls has been previously reported by Reeve (1967). Under an external stress the parenchyma cells deform away from the direction of the applied load. In the pre-stressed cells where swelling pressure was greater, less force was required to induce failure.

The measured volume of cell agglomerate was higher in outer strips than in inner strips (Figure 19). This observation can be explained by the fact that during measurement of cell agglomerate, blanched french fry strips were macerated. Because the magnitude of swelling pressure appeared to be greater in outer strips than in inner strips, under an external applied stress induced by maceration, the extent of friability will be greater in outer strips than in inner strips. Consequently, the volume of small-sized cells passing through the 1 mm sieve was greater for outer strips. The results of the present investigation are consistent with those of Freeman et al. (1992) who reported that the volume of cell agglomerate was higher in high-specific gravity tubers than in low-specific gravity tubers.

Differences in puncture force (Sharma et al., 1959a) and puncture energy (Fedec et al., 1977) between the pith and cortex of cooked potato tissue have been reported. Sharma et al. (1959a) attributed these differences to incomplete solubilization of the pectic substances whereas Fedec et al. (1977) indicated that cell

cleavage, induced by starch swelling pressure, was primarily responsible for these differences. The results of the present study support the latter view, but also indicate that potato tissue is a highly variable material differing in specific gravity and in mechanical properties. Therefore, the textural quality of french fry strips is highly dependent upon strip position within the tuber.

The results also indicated that LTLT blanching conditions decreased the differences in peak force, peak deformation and post-puncture energy consumption between the inner and the outer strips (Figures 13-18). A possible explanation is that under prolonged processing conditions, such as LTLT blanching conditions, potato tissue undergoes a number of structural changes. Two of the most important are starch gelatinization and the formation of calcium-pectate complexes (Canet et al., 1984). On cooling, retrogradation of starch chains (McCafferty and Bourne, 1995) and the stabilization of calcium-pectate complexes (Moledina et al., 1981) would be expected to increase tissue strength. Because cortex tissue contains more starch (Reeve et al., 1980) and pectin (Warren and Woodman, 1973) than pith tissue it is surmised that increased tissue strength in outer strips due to formation of calcium complexes and gelling of starch decreased the differences in the measured mechanical parameters between inner and outer strips.

In fully-fried french fries, peak force was greater for fries processed from the outer regions of the tuber than for fries processed from the pith whereas peak deformation was lower for fries processed from the outer regions of the tuber in comparison to fries processed from the inner region (Table 21). This result would be interpreted as increased tissue firmness for fries processed from the outer regions of the tuber and also confirms that the textural quality of french fries is dependent on

strip position within the tuber. This reversal in the textural quality of outer and inner fully-fried french fries compared to outer and inner blanched french fry strips (Figures 13-18) could be attributed to the structural changes occurring in potato tissue after the blanching operation, particularly drying since the drying time is longer in comparison to other unit operations. Because french fries from the outer regions of the tuber contain more starch (Mohr, 1972) and pectin (Warren and Woodman, 1973) compared to fries from the pith region, the extent of starch gelatinization and formation of calcium-pectate complexes was greater for fries processed from outer potato tissue. Retrogradation of cooled starch gels (McCafferty and Bourne, 1995) and stabilization of calcium-pectate complexes during cooling (Moledina et al., 1981) would cause increased tissue firmness. The results reported here agree with those of Mohr (1972) who stated that fully-fried french fries processed from the pith region were more susceptible to sogginess than fries made from the outer regions of the tuber. According to Mohr (1972), the differences in textural quality between french fries from the pith and outer regions of the tuber could be attributed to gelatinized starch which in his work appeared clumped together in fries from pith tissue but which appeared dispersed throughout the cell in french fries that were processed from the outer regions of the tuber.

Peak force was higher at the stem than at the bud end of the tuber (Tables 9 and 10). These results indicated that there were textural differences between the stem and bud end. An explanation for the higher peak force at the stem end is that during tuber development the stem end serves as the point of entry for food nutrients and is therefore higher in dry matter content than the bud end. Cell wall characteristics such as wall thickness, structure and composition vary from stem to

bud end (Reeve et al., 1970). It is therefore plausible that the extent to which cell walls can withstand starch swelling pressure is greater for the stem end than for the bud end. The results of the present investigation concur with those of Sharma et al. (1959a) who noted that potato samples that are hard-to-cook are characterized by a high content of insoluble pectin and hemicellulose, and with Iritani et al. (1977) who reported that tissue from the bud end softened faster during cooking than tissue from the stem end.

In fully-fried french fries, peak force was higher at the stem end than at the bud end whereas peak deformation was lower at the stem end than at the bud end (Table 22). These results implied that the stem end was firmer than the bud end. Differences in the textural quality of french fries between the stem and the bud end could be attributed to the high dry matter content at the stem end (Reeve et al., 1970). During french fry processing, the extent of formation of calcium-pectate complexes and of starch gelatinization would be expected to be greater at the stem end than at the bud end. Therefore, tissue strength is enhanced at the stem end because retrogradation of cooled starch gels (McCafferty and Bourne, 1995) and stabilization of calcium-pectate complexes during cooling (Moledina et al., 1981) increase tissue firmness.

Differences in penetration energy between the stem and bud end have been reported. Böhler et al. (1987) measured the penetration energy of cooked potato tissue using a conical indentor and reported a value of 10 mJ for the stem end and 2 mJ for the bud end. Although Anzaldúa-Morales and Bourne (1992) reported that there were no differences in puncture force between the stem and bud ends of raw potato tissue, their results nevertheless indicated that puncture force was higher at the stem end, and in 3 out of 16 times these differences were significant ($p \leq 0.05$).

5.3 Effects Of Blanching Conditions On The Mechanical Properties And Colour Of Fully-Fried French Fries

Although statistically significant differences were not always apparent, peak force and peak deformation were generally greater for fries blanched by LTLT conditions than for fries blanched by the standard conditions whereas peak force and peak deformation were lower for HTST samples in comparison to those blanched by the standard conditions (Tables 12 and 13). These results suggested that both LTLT and HTST blanching conditions were critical factors influencing the textural quality of french fries.

Changes in peak deformation during blanching can be attributed to tissue softening. Tissue softening is mainly due to a number of factors that include loss of turgor pressure, solubilization of pectin, and hydration and swelling of starch granules (Loh et al., 1982). The extent of softening is greater under LTLT conditions than under HTST conditions. These results are in agreement with Bourne et al. (1993) who reported that during cooking the rate of softening of potato tissue was greater at higher temperatures (100°C) than at lower temperatures (70°C).

Increase in peak force of LTLT samples compared to fries processed by the standard conditions can be explained by an increase in tissue firmness which occurs during blanching. This increase in tissue firmness can be ascribed to two phenomena. Firstly, during LTLT blanching the extent of starch gelatinization increases (Figure 32B), leading to an increase in viscosity of starch gels. On cooling, these gels give rigidity to the tissue structure resulting in increased peak force. Such increase in peak force of cooked potato tissue had been reported by Jankowski (1992). Secondly, at low blanching temperatures the rate of solubilization of pectic substances decreases due

to formation of calcium-pectate complexes (Fuchigami et al., 1995). These complexes increase tissue strength and subsequently, the peak force. Similar observations were made by Canet and co-workers (1984) who reported that the shear rupture force of cooked potato decreased as blanching temperature increased from 70 to 97°C.

Fry colour was generally lighter for the LTLT samples in comparison to the standard (Tables 12 and 13) indicating that both the time and temperature of blanching influence colour quality of french fries. The effect of LTLT blanching conditions on fry colour may be the result of longer blanching time which allows for an increase in the amount of soluble substances (amino acids and reducing sugars) diffusing from potato tissue into the blanch water. These soluble substances are the reactants of the Maillard browning reaction. As a result, the concentration of soluble substances in potato tissue decreases and the extent of browning is reduced during subsequent frying, resulting in a lighter fry colour. These results concur with those of Garrote et al. (1984) who noted that the apparent glucose diffusion coefficient increased as blanching temperature increased from 55 to 85°C. Kozempel et al. (1982) also reported that the concentrations of glutamic and aspartic acids, the predominant amino acids in potato tissue, decreased by 36% and 35%, respectively, after 12 minutes of blanching at 77°C.

Decrease in peak force for fries blanched by HTST conditions could be attributed to two main reasons. Firstly, at high temperatures (97°C) there is rapid swelling and hydration of the pectic polysaccharides resulting in increased pectin solubility. Pectin degradation weakens cell structure and decreases the peak force. These results agree with those of Kawabata et al. (1976) who observed that the middle lamella of potato parenchyma cells were swollen due to pectin degradation after

a high-temperature blanching treatment at 95-100°C for 5 min. Secondly, at high blanching temperatures there is rapid swelling and hydration of starch granules (Figure 28). Starch swelling pressure induced deformation in the cell walls leading to a decrease in peak force (Freeman et al., 1992).

French fries blanched by HTST conditions were generally lighter in colour than fries blanched by the standard conditions (Tables 12 and 13). This observation can be explained by the fact that tissue damage at high temperatures facilitated diffusion of soluble substances into blanch water (Gekas et al., 1993). Consequently, the concentration of soluble substances in the tissue decreased and the extent of browning was reduced, resulting in a lighter fry colour. Such an increase in diffusion of soluble substances was observed by Kaymak and Kincal (1994) who reported losses of up to 34% in soluble substances at high blanching temperatures (97°C).

Peak force, peak deformation and post-puncture energy consumption were lower for blanched and frozen french fry strips (Table 8) than for french fry strips blanched with no freezing (Table 7). During freezing, ice crystals are formed in locations where free water is present (Kawabata et al., 1976). Formation of ice crystals, predominantly in extracellular regions, caused physical disruption of the cells leading to cell cleavage as shown in Figure 33A. As a result of the disruption in tissue structure, the mechanical strength of the tissue decreased and less force was required to induce deformation in frozen tissue. These results agree with those of Canet et al. (1984) that indicate that shear rupture force of blanched and frozen tissue decreased significantly relative to the cooked control. Cell cleavage resulting from the freezing process contributes to mealiness which is a desirable attribute for the textural quality of french fries (Böhler et al., 1986; Du Pont et al., 1992).

5.4 Effects Of Drying Conditions On The Mechanical Properties And Colour Of Fully-Fried French Fries

Although statistical differences between the standard and LTLT for peak force were in most cases not significant, the general trend indicated that this mechanical parameter was lower for fries dried under LTLT conditions than for fries dried under the standard conditions (Tables 14 and 15). This result may be due to the decrease in temperature during the second phase of the drying operation (Table 2). During drying a crust is formed due to dehydration of the surface tissue (Lamberg, 1989). Crust formation increases the mechanical resistance of the fry (Rose and Southcombe, 1987). Because drying rates were lower under LTLT conditions than under the standard conditions, the extent of dehydration of the surface tissue was less and a lower peak force was measured for LTLT samples. Decrease in peak force for fries processed by LTLT drying conditions could also be due to fry moisture content. Although the results presented in Table 16 suggested that the extent to which a change in moisture influences peak force was limited, moisture loss during drying cannot be precluded from playing a role in structural changes. Moisture redistribution leads to softening of the crust (Ross and Porter, 1966) and therefore with a higher final moisture content in the LTLT samples a decrease in peak force would be expected.

Peak deformation of fries processed by LTLT drying conditions was generally lower compared to those processed by the standard conditions (Tables 14 and 15). This decrease in peak deformation could be attributed to less tissue softening at lower drying temperatures, since a large peak deformation was assumed to be associated with increased tissue softening (Bourne, 1967). Tissue softening during drying is mainly due to solubilization of pectic substances in the cell wall and intercellular spaces

(Fornal et al., 1993).

There are a number of possible reasons why peak force was generally lower for fries processed by HTST drying than for those processed by the standard conditions (Tables 14 and 15). Firstly, under HTST drying conditions, starch granules in blanched french fry strips would continue to swell in the dryer generating starch swelling pressure (Lamberg and Olsson, 1989). Therefore, the magnitude of starch swelling pressure would be greater for HTST samples than for the standard. Starch swelling pressure caused weakening in cell structure and, possibly, led to cell separation (Fornal et al., 1993). Secondly, the decrease in peak force for HTST drying could be attributed to the solubilization of pectic substances in the middle lamella which leads to weakening in tissue structure and decreased peak force. Such decrease in peak force is in agreement with Fornal et al. (1993) who noted that the compressive force of fababean seeds decreased from 437 to 124 N as drying temperature increased from 30 to 95°C. Thirdly, because the final moisture content for HTST samples was relatively higher than that of fries processed by the standard conditions (Table 16), it is presumed that moisture redistribution in the tissue could have caused softening of the crust resulting in a reduction in peak force.

On the whole, peak deformation was lower for HTST samples compared to those processed by the standard conditions (Tables 14 and 15). This result implies that fries processed by HTST drying conditions were firmer than fries processed by the standard conditions. During HTST drying, there is rapid swelling, hydration and gelatinization of starch. During cooling, starch gels retrograde (McCafferty and Bourne, 1995) resulting in increased tissue strength and the subsequent reduction in peak deformation.

With respect to colour, although statistical differences were not always apparent, the general trend indicated that french fries processed by the LTLT drying conditions were darker in comparison to fries processed by the standard conditions (Tables 14 and 15). For HTST conditions, however, fry colour was on the whole similar to those processed by the standard conditions (Tables 14 and 15). Because Talley and Eppley (1985) reported that precursors of the Maillard reaction are formed during the initial stages of a dehydration process at temperatures above 103°C, it is presumed that the extent of formation of precursors increased during LTLT drying. As a result, french fries processed by LTLT conditions were more susceptible to darkening during subsequent frying than fries processed by the standard conditions. The drying conditions used in the present investigation suggest that, whereas the textural quality of french fries is determined mainly by drying temperature, colour quality of french fries is influenced mainly by drying time. However, some of the variability in the data could be attributed to uncontrolled relative humidity during the drying operation.

5.5 Effects Of Frying Conditions On The Mechanical Properties And Colour Of Fully-Fried French Fries

Although no significant differences were found, peak force generally increased as frying time increased (Tables 4, 17 and 18). As frying time increases, crust thickness also increases due to dehydration of cells at the tissue surface. Increase in crust thickness would cause an increase in the mechanical resistance of the fry (Rose and Southcombe, 1987) resulting in increased peak force. The results here concur with those of Du Pont et al. (1992) who observed an increase in impact strength and crust thickness as frying time increased. Pinthus et al. (1995) also observed similar

trends in crust yield strength as frying time increased from 0 to 5 min. These authors used fried restructured potato products which were made from gels of varying strengths (37 to 127 kPa). Gel strength, according to Pinthus et al. (1995), was indicative of the extent to which the gels deformed when compressed between two parallel plates. Pinthus and co-workers (1995) reported yield strength values in kPa (1 Pa = 1 Nm^{-2}); yield strength was defined as the maximum force exerted during puncture testing using a 3.2 mm-diameter probe. To accurately compare the results of the present study to those of Pinthus et al. (1995), peak force values were converted to yield strength values as follows:

$$\sigma(Pa) = \frac{F}{A} = \frac{Peakforce(N)}{\Pi r^2 \times 10^{-3}(m^{-2})}$$

where σ = yield strength (stress); F = peak force; A = area of the probe; r = radius (mm).

Therefore, for the 1.1 cm-thick sample (Table 4) with a peak force of 0.92 N, a yield strength value of 2.9×10^5 Nm^{-2} (290 kPa) would be obtained whereas for a peak force of 1.23 N, for fully-fried french fries (Table 5) after 4.5 min of frying, a yield strength value of 3.9×10^5 Nm^{-2} (390 kPa) would be obtained. These values are comparable to a yield strength value of 400 kPa (obtained from curves) for a gel strength of 127 kPa (Pinthus et al., 1995).

Another explanation for the increased peak force of the LTLT samples is that the lower final moisture content of these fries would cause an increase in the mechanical resistance of the fry and a corresponding increase in peak force. According to Du Pont et al. (1992), as frying time increased from 2 to 3 min there was a 14% decrease in fry moisture content.

The analysis presented in Table 24 shows that the contribution of the crust to peak force increased from 55 to 80% as frying time increased. The contribution of the crust to peak force for each frying time was obtained using the following equation:

$$C_c = \frac{P_f(c) - P_f(i)}{P_f(c)} \times 100 \quad (2)$$

where C_c = contribution of crust to overall peak force (%)

$P_f(c)$ = Peak force with crust on (N)

$P_f(i)$ = Peak force of crust-free fry interior (N)

This equation was used because during testing it was observed that as the crust was deforming, interior contents below the crusts were concurrently deforming. It was surmised that peak force of samples measured with crusts on was additive of the crust and fry interior. Therefore, the relative difference between the measured peak force of the crust samples, which is additive of crust and interior, and that of the crust-free fry interior will give the contribution of the crust itself to peak force.

Peak deformation was generally larger for fries processed by LTLT conditions than for those processed by the standard conditions (Tables 17 and 18). Post-puncture energy consumption, on the other hand, decreased as frying time increased (Table 4). This observation may be due to the extent of softening in the french fry interior which is greater when fries are processed under long frying times. Tissue softening during long-time frying is due to solubilization of pectic substances (Rose and Southcombe, 1987). The results of the present study concur with those of Fedec et al. (1977) who noted that during steam-cooking, there was a two-fold decrease in puncture energy as temperature increased from 10 to 80°C.

The analysis presented in Table 24 indicates that there was no consistent trend

Table 24. Contribution of crust and fry interior to overall mechanical properties of french fries

Sample thickness (cm)	Contribution of crust to peak force (%)				Contribution of fry interior to post-puncture energy consumption (%)			
	Frying time (min)							
	5	10	15	20	5	10	15	20
1.1 (0.5)	55	69	70	79	74	67	81	54
1.4 (0.8)	2.5	64	78	80	66	79	68	71

in the contribution of the fry interior to post-puncture energy consumption as frying time increased. This could be due to variations in tuber composition and the extent of breakdown of structural components during frying, which influence the mechanical properties of the fry interior. The contribution of the fry interior to overall post-puncture energy consumption was determined from the following equation:

$$C_i = \frac{U(i)}{U(c)} \times 100 \qquad (3)$$

where C_i = Contribution of fry interior to post-puncture energy consumption (%)

U(i) = Post-puncture energy consumption of the crust-free fry interior (Jm^{-1})

U(c) = Post-puncture energy consumption of fry interior measured with crusts on (Jm^{-1})

The reason for using equation (3) is that the energy consumption during deformation of the fry interior, for crusts on (i.e. U(c)), is due to a number of components. Firstly, the frictional force exerted on the sides of the probe as it penetrates the crust (Thompson et al., 1992), and secondly, compression and shearing of the crust, also associated with penetration by the probe (Bourne, 1975). Thirdly, during testing it was observed that dislodged crust material directly beneath the probe was pushed ahead by the probe in the fry interior. This, in effect, could change the dimensions of the punch since the fry interior was being penetrated by the crust material. Therefore, it was surmised that the dislodged crust material contributed to the force exerted on the fry interior during deformation. Fourthly, the post-puncture energy consumption of the crust-free fry interior would also be expected to contribute to the energy consumption during deformation of the fry interior. Therefore, the ratio between U(i) and U(c) from equation 3 is a measure of the contribution of the fry interior to overall post-puncture

energy consumption.

With respect to fry colour, although statistical differences were not always apparent, french fries processed under LTLT finish fry conditions were generally similar in colour to those processed by the standard conditions (Tables 17 and 18). A plateau occurred in the measured L value within 2.5 min of frying at 166°C, which is the standard conditions for finish fry. Increasing the frying time at this temperature did not cause a change in fry colour. The results here agree with those of Marquez and Anon (1986) who observed a plateau in the Hunterlab L value of potato chips between 5 and 15 min of frying. It would appear that the attainment of this plateau occurred earlier during frying in the present study because a pre-frying treatment, such as blanching, leached out soluble substances which reduced the extent of browning. Scanlon et al. (1994) also reported the occurrence of a plateau in the colour of potato chips. These authors noted that prolonged frying time of 7 min and greater did not significantly affect the lightness value of potato chips ($p=0.81$) measured using an image analysis system.

Peak force of fries processed by HTST finish fry conditions was on the whole similar to fries processed by the standard conditions (Tables 17 and 18). This observation may be due to the frying temperatures that were used (Table 2). The initial stages of deep-fat frying are characterized by a rise in the surface temperature of the frozen french fry to the boiling point of water. No moisture loss occurs at this stage (Singh, 1995). The beginning of the second stage of the frying process, the surface boiling stage, is marked by the formation of bubbles in the oil as moisture is lost from the fry. It was observed that the surface boiling stage began approximately 50 s after immersion of the frozen fries into hot oil. This suggests that the actual frying

times for fries processed by HTST conditions and by the standard were 40 and 130 s, respectively. Since frying time was shorter for HTST, a lower peak force would have been expected due to a decrease in crust thickness of the fries. However, peak force was comparable to the standard. Therefore, it is plausible that case-hardening occurred for fries processed by HTST conditions. Case hardening results from rapid dehydration of the outer tissue layers of the french fry at high frying temperatures (Van Arsdel, 1973) such as those used for HTST. The results presented in Table 19 indicated that the change in moisture content of fries processed by HTST finish fry conditions was lower compared to those processed by the standard conditions and supports the view that case-hardening might have occurred since an impermeable crust layer would reduce moisture loss from the fry.

The general trend indicated that peak deformation was lower for fries processed by HTST finish fry conditions in comparison to fries processed by the standard conditions (Tables 17 and 18). It is possible that the short processing time for HTST samples limited the extent of softening in the fry interior resulting in a decrease in peak deformation. Tissue softening during frying is due to solubilization of pectic substances (Rose and Southcombe, 1987).

Increase in Hunterlab L value of HTST samples compared to the standard (Tables 17 and 18) could also be attributed to the short processing time used for HTST finish fry. The Maillard browning reaction is dependent on frying time (Talley and Eppley, 1985). Under short-time conditions the extent of browning is less than under long-time frying. Consequently, a light fry colour would be expected for fries processed by the HTST conditions. The frying conditions used in the present investigation indicate that while frying time is important for the textural quality of

french fries, frying temperature determines colour quality of french fries.

5.6 Effects Of Storage Period On The Mechanical Properties And Colour Of Fully-Fried French Fries

Peak force and peak deformation of french fries generally increased as the storage time of tubers progressed from 9 to 11 months (Tables 12-15, 17 and 18). Increase in peak deformation of fries processed from tubers in long-term storage can be explained in terms of degradation of tuber components during storage which results in an increase in tissue softening. Tissue softening during long-term storage is due to (1) disintegration of cell membranes (Sowokinos, 1990) and, (2) degradation of starch, pectin and hemicellulose (Sharma et al., 1959a).

Increase in peak force of fries processed from tubers stored for 11 months compared to 9 months can be attributed to an increase in the free calcium content of tubers resulting from starch degradation during prolonged storage. Such increase in the calcium content of tubers during long-term storage has been reported by Turnbull and Cobb (1992). Therefore, it is reasonable to assume that formation of calcium-pectate complexes during processing would result in increased peak force of fries processed from tubers in long-term storage.

For fry colour, fries processed from tubers that had been stored for 11 months were lighter in colour than those processed at 9 months (Tables 12 -15, 17 and 18). This may be due to loss of membrane integrity during prolonged storage (Sowokinos, 1990) facilitating leaching of soluble substances from blanched tissue leading to increased lightness in fry colour at 11 months. This result also indicated that water-blanching was effective in reducing the concentrations of soluble substances in potato

tissue.

Peak force increased and peak deformation decreased for fries processed from potatoes between 1 and 3 months storage in 1995 (Tables 12-15, 17 and 18). This result implied that an increase in french fry firmness occurred at the beginning of the storage period. There are two possible reasons. Firstly, during storage there is an increase in the total number of small-sized starch granules due to enzymatic digestion of large-sized granules (Golachowski, 1985). During processing, these small-sized granules, which are more susceptible to rupture, form viscous gels (Golachowski, 1985). The retrogradation of such cooled starch gels would be expected to increase tissue firmness. Secondly, during starch gelatinization, short-chain amylose molecules, found predominantly in small-sized granules, are susceptible to leaching out of the granule (Jane and Shen, 1993). Formation of amylose-cellulose complexes with their enhanced strength, perhaps, contributed to an increase in tissue firmness (Linehan and Hughes, 1969b) and a resultant increase in peak force and decrease in peak deformation. For colour, darkening in fry colour as storage time of tubers increased from 1 to 3 months (Tables 12-15, 17 and 18) could be attributed to an increase in respiratory activity during the preconditioning process which is used to reduce the concentration of reducing sugars in tubers which accumulate after harvest (Pritchard and Adam, 1992).

5.7 Effects Of Cultivar And Site On The Mechanical Properties And Colour Of Fully-Fried French Fries

French fries processed from Shepody potatoes were darker in colour than fries processed from Russet Burbank potatoes (Table 23). The observed differences in fry

colour between the two cultivars can be attributed to the fact that Shepody potatoes are more susceptible to biochemical degradation during storage than Russet Burbank potatoes (Pritchard and Adam, 1992). Consequently, fries made from Shepody potatoes are darker in colour. It is also possible that the darker colour of fries processed from Shepody (Carberry) potatoes grown in 1995 could be due to their low solids content. The initial moisture content of french fries from Shepody (Carberry) potatoes was significantly higher (81.5%) than those from Russet Burbank (Carberry) potatoes (77.4%). Such darkening in colour of french fries processed from potatoes with low starch content has been reported by Mohr (1972) who demonstrated that french fries from the pith region of the tuber which had significantly lower starch content, were darker in colour than fries processed from other regions of the tuber where the starch content was higher.

Fries processed from Shepody potatoes also yielded larger peak deformation than fries from Russet Burbank potatoes (Table 23). Because Shepody potatoes are more susceptible to biochemical degradation during storage (Pritchard and Adam, 1992), it is reasonable to postulate that cell membrane disintegration, which is indicative of biochemical degradation in potato tubers, causes tuber softening leading to a large peak deformation in the fries made from Shepody tubers.

With respect to area of production (site), peak force was higher for fries processed from potatoes grown at Portage than for those processed from potatoes grown at Carberry (Table 23). This observation can be attributed to variations in soil type from one site to another (Faulks and Griffiths, 1983). Portage soils are generally clay soils and clay loams (Manitoba Soil Survey, 1972) whereas the soils in Carberry and Shilo range from sandy to heavy clay soils (Manitoba Soil Survey, 1957).

However, a distinguishing feature of the Portage soils is that approximately 65% of the soils are saturated with divalent ions, predominantly calcium (Manitoba Soil Survey, 1972). According to Venter and de Villiers (1986) an increase in soil calcium resulted in an increase in the calcium content of tubers. Therefore, it is reasonable to assume that there is increased calcium content in tubers grown at Portage which would potentially increase the peak force of french fries in two ways. Firstly, because tuber resistance to mechanical damage increases as calcium concentration increases (Venter and de Villiers, 1986), a high peak force would be expected in the fries. Secondly, during processing, calcium increases french fry firmness through formation of calcium-pectate linkages (Canet et al., 1984) leading to increased peak force in french fries. The trend for peak deformation and post-puncture energy consumption of fries processed from Portage and Carberry potatoes was inconsistent from year to year (Tables 11 and 23). Mechanical properties are influenced by a variety of factors and some of the inconsistencies could be attributed to uncontrolled factors such as rainfall and temperature (Iritani, 1981; Mohabir and John, 1988).

For colour, french fries processed from Portage potatoes were darker in colour than fries made from Carberry potatoes (Table 23). Increased tissue firmness in fries made from Portage potatoes, resulting from formation of calcium-pectate complexes during processing (Canet et al., 1984), probably restricted leaching of soluble substances from the tissue leading to darkening in fry colour. Further experimentation is required to verify this hypothesis.

5.8 Implications For The Processing Industry

The results of the present study indicate that no single set of processing

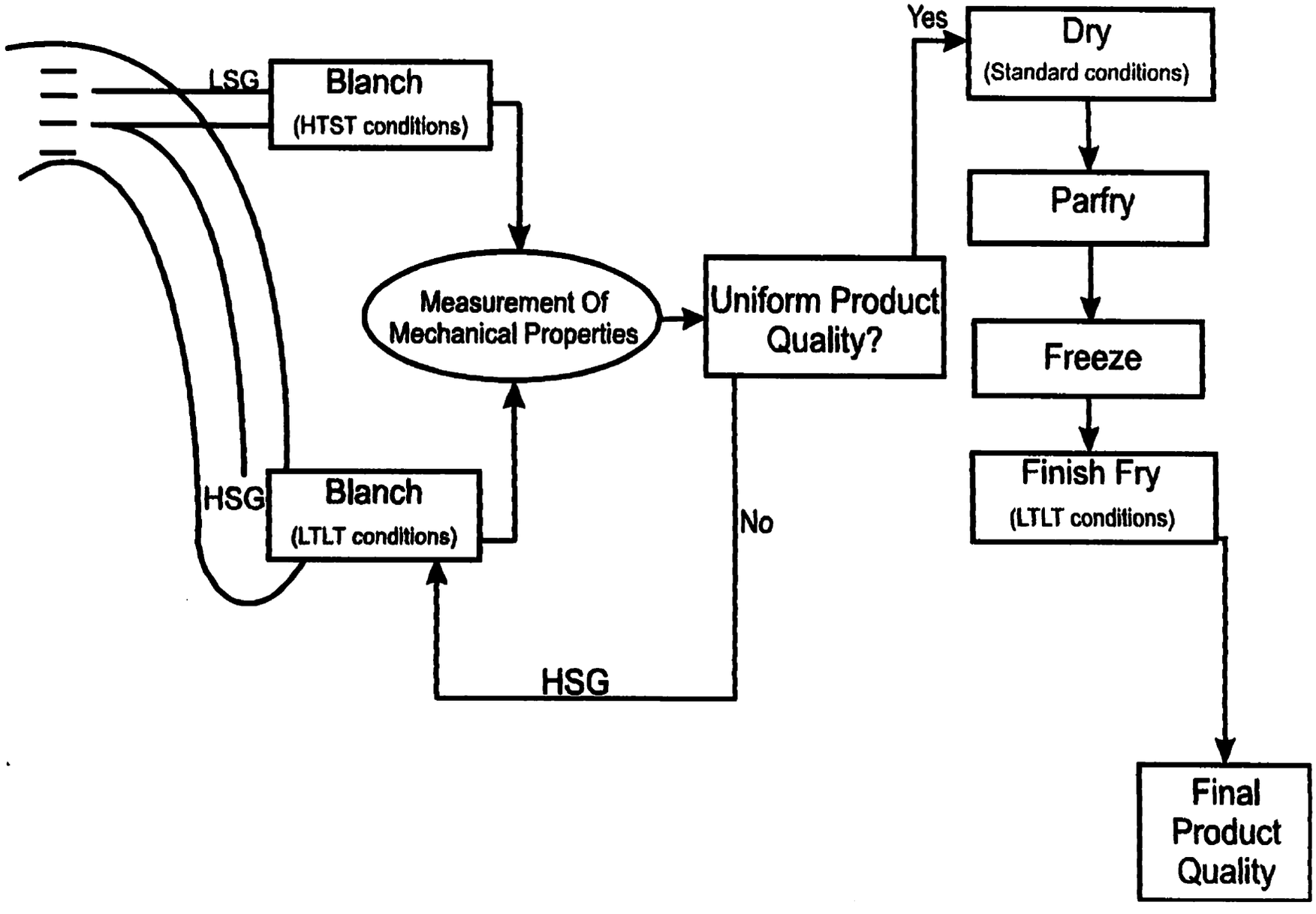
conditions is adequate for obtaining optimum french fry quality (Table 20). If it is assumed that better textural quality is associated with larger peak forces and deformations, then the results also showed that while a set of processing conditions resulted in a light-coloured french fry, the same set of conditions decreased peak force and peak deformation and thereby impaired textural quality. Therefore, a compromise has to be made between colour and mechanical properties (Burton, 1989) with some exceptions. For example, the LTLT blanching conditions increased both colour and mechanical parameters in 1994 and 1995 whereas the LTLT drying conditions consistently decreased the mechanical parameters and colour quality of french fries (Table 20).

During commercial french fry processing, after the size sorting operation, it is routine to process french fries through one processing line while other lines are used for processing other potato products. Therefore, potato strips from the different regions of the tuber are processed altogether using the same set of processing conditions. However, the results of the present study (Figure 13) suggest that if all french fry strips are blanched using the same set of processing conditions, for example a LTLT or a HTST condition, the inherent differences between potato strips from different regions of the tuber are evident in the textural quality of the blanched french fries. More importantly, these differences are evident in the textural quality of french fries, even after finish fry (Table 21). Because the inherent differences between potato strips from different regions of the tuber are a major concern for french fry processors, it would appear that strips from different regions of the tuber have to be processed by different conditions to attain uniformity in product quality.

Based on the results of the present study, the following set of conditions is

proposed for obtaining optimum french fry quality (Figure 34). Immediately after cutting it would be desirable to separate the LSG strips from HSG strips. Since the LSG strips are located in the centre of the tuber, these strips can be directed through one processing line towards a HTST blancher while HSG strips from the outer parts of the tuber are directed through another line to a LTLT blancher. Measurement of the mechanical properties after the blanching operation will provide feedback to the blanching operator to aid in decision making about processing conditions. Obtaining uniformity in product quality after blanching is of critical importance to final product quality. For the drying operation, the standard conditions are proposed. The results of the study indicate that of the conditions tested, the standard conditions produced optimal product quality with respect to colour and mechanical properties. For finish fry, it would be desirable to use the LTLT conditions. Because fully-fried french fries processed by the HTST and LTLT blanching conditions have lighter fry colour than fries blanched by the standard conditions (Tables 12 and 13), it is surmised that colour quality of french fries would be improved when LTLT finish frying is used.

Figure 34. **Proposed processing plant conditions for optimization of french fry quality.**


LSG
Blanch
(HTST conditions)
HSG
Blanch
(LTLT conditions)
Measurement Of
Mechanical Properties
Uniform Product
Quality?
Yes
No
HSG
Dry
(Standard conditions)
Parfry
Freeze
Finish Fry
(LTLT conditions)
Final
Product
Quality

6. CONCLUSIONS

The present study was undertaken to investigate the effects of processing conditions on the mechanical properties and colour of french fries. Because french fry texture is characterized in terms of a crust and fry interior, the initial approach was to elucidate the distinct contribution of each of these components to the mechanical properties of french fries. However, it was apparent that biological variability was a major factor influencing the mechanical properties. Consequently, it became necessary to determine the source of variation associated with the measured mechanical parameters and experimental evidence revealed that compositional variations within potato tubers was a major source of variation. The following conclusions can be drawn from the study:

(1) There are serious processing implications associated with inner french fry strips, located in the pith parenchyma, having lower specific gravity than outer french fry strips located in the perimedullary zone and cortex. Peak force, peak deformation and post-puncture energy consumption of french fry strips blanched by LTLT and HTST conditions were higher for inner strips than for outer strips. The measured volume of cell agglomerate was higher for outer strips than for inner strips indicating greater friability of outer strips. Microstructural analysis of inner and outer french fry strips revealed that during HTST blanching, the magnitude of starch swelling pressure is greater in outer strips. Starch swelling pressure induces deformation in the cell walls and under an external stress less force is required to induce failure in the tissue.

(2) Differences in inner and outer strips affect the textural quality of fully-fried french fries. By using a differential blanching treatment in which outer strips are blanched by LTLT conditions and inner strips by HTST conditions, uniformity in product quality could be achieved.

(3) Puncture location along the french fry strip is another source of variation for mechanical properties. Peak force was higher at the stem than at the bud end of the tuber. Compositional variations from the stem to the bud end could be important for the processing quality of potato chips.

(4) Processing conditions have varying effects on the mechanical properties and colour of fully-fried french fries. Except for the LTLT blanching conditions which increased peak force and peak deformation, and the LTLT drying conditions which decreased the above properties, a compromise has to be made between improved colour quality and improved textural quality.

(5) Traditionally, blanching is used to leach out sugars to improve colour quality. However, the results of this research indicate that blanching is an extremely important unit operation. Both colour and textural quality can be improved in the blancher.

(6) Changes in tuber quality during storage have implications on french fry quality. Fry colour was lighter at the end of the storage period whereas a darker fry colour was observed at the beginning of storage. For mechanical properties, peak force and peak deformation increased towards the end of the storage period. Physiological

deterioration of cell membranes during prolonged storage possibly increased the free calcium content of tubers and facilitated leaching of soluble substances during blanching. Leaching of soluble substances resulted in improved colour quality whereas an increase in free calcium could potentially increase mechanical properties. At the beginning of the storage period an increase in peak force and a decrease in peak deformation were observed. Changes in starch granule size during storage and formation of amylose-cellulose complexes during processing is likely the reason for this increase in tissue firmness.

(7) French fries processed from Shepody potatoes were darker in colour than fries from Russet Burbank potatoes, particularly for tubers grown at Carberry. Low solids content of Shepody (Carberry) potatoes contributed to darkening in fry colour. Process modification, for example LTLT blanching, may improve fry colour for Shepody potatoes. Although there were no differences in peak force, peak deformation was larger for fries made from Shepody potatoes. The extent of physiological and biochemical degradation in Shepody potatoes during storage could have caused tuber softening and a large peak deformation in french fries.

(8) Potatoes grown at Portage produced darker-coloured fries than potatoes from Carberry. For peak force, fries processed from Portage, Shilo and Carberry did not differ from each other.

(9) Microstructural analysis is a powerful tool in understanding structural changes during processing. However, besides the lengthy procedure for sample preparation,

light microscopy introduces artifacts which could be falsely interpreted. Stereomicroscopy, on the other hand, has the advantage of minimal sample preparation and, to a large extent, eliminates artifacts due to sample preparation and is recommended for future work on potato tissue. It is also recommended that internal structural changes during drying and frying be investigated to gain better insight into physicochemical changes which occur in potato strips during processing.

(10) Given the inherent variability in potato tubers, caution and precision in sample preparation is required. To minimize within-tuber variability it is necessary to compare potato strips taken from as close a position as possible within the tuber.

(11) The french fry consists of a crust and a fry interior. Peak force is primarily a property of the crust whereas post-puncture energy consumption is mainly a property of the fry interior. The contribution of the crust to overall peak force was dependent on frying time, increasing from 55 to 80% as frying time increased. The contribution of the crust to overall peak force was additive of the crust and the fry interior. For the fry interior, inconsistent trends were found in its contribution to post-puncture energy consumption as frying time increased. This could possibly be due to compositional variations from one tuber to another which, in turn, influence the extent of structural changes in the fry interior during frying.

(12) Despite the biological variability in potato tissue, this research has demonstrated that it is possible to manipulate unit process operations to attain uniformity in product quality. Additionally, by varying the processing conditions for a given unit operation

optimal french fry quality can be obtained. The ultimate test of quality, however, is a sensory test, and it is recommended that sensory testing of french fries be used to determine consumer acceptability.

(13) Results from this research indicated that peak force, peak deformation and post-puncture energy consumption were higher for inner blanched french fry strips than for outer french fry strips, and for blanched and frozen french fry strips. However, for fully-fried french fries, which had been processed using all five unit operations, peak force and peak deformation were higher for outer french fries than for inner fries. It is recommended that further investigations should be conducted to determine which unit operation after blanching is responsible for this reversal in textural quality.

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APPENDICES

APPENDIX 1. A typical SAS data file for comparing the measured mechanical parameters for the standard conditions to a given processing condition

```
OPTIONS PAGESIZE=60 LINESIZE=78;
TITLE1 'Processing expts #2--Portage RB';
TITLE2 'HTST Blanch Std vs. Mod';
TITLE3 'TRMT 1 = Std cond; TRMT 2 = Mod cond';
TITLE4 'STRIP 1 = outer; 3 = inner';
TITLE5 'PUNCH 1 = bud end; 2 = middle; 3 = stem end';

DATA FRIES;
 INPUT POTATO BLANCH STRIP PUNCH Fmax dmax;
      LABEL POTATO = 'REPLICATE NO.'
           BLANCH = 'BLANCHING TRMT-Std or Mod'
           STRIP = 'FRENCH FRY STRIP NO.'
           PUNCH = 'PUNCH LOCATION.'
           Fmax = 'PEAK FORCE (N)'
           dmax = 'PEAK DEFORMATION (mm)';
CARDS;
1 1 1 1 2.25 5.42
....
4 2 3 3 3.12 5.32
;
proc sort;
  by blanch;
run;

proc glm;
  class potato blanch strip punch;
  model fmax dmax=potato blanch potato*blanch strip potato*strip blanch*strip
    potato*blanch*strip punch potato*punch blanch*punch potato*blanch*punch
    strip*punch potato*strip*punch blanch*strip*punch;
  random potato potato*blanch potato*strip potato*punch potato*blanch*punch
    potato*strip*punch potato*blanch*strip/test;
  means blanch/duncan;
run;

proc glm;
  by blanch;
  class strip punch;
  model fmax dmax=potato strip potato*strip punch potato*punch strip*punch
    potato*strip*punch;
  random potato potato*strip potato*punch potato*strip*punch/test;
  means strip punch/duncan;
run;
```

APPENDIX 2. A typical SAS output for comparing the measured mechanical parameters for the standard conditions to a given processing condition

```
Processing expts #2--Portage RB
    HTST Blanch Std vs. Mod
TRMT 1 = Std cond; TRMT 2 = Mod cond
          STRIP 1 = outer; 3 = inner
PUNCH 1 = bud end; 2 = middle; 3 = stem end

General Linear Models Procedure
    Class Level Information

   Class     Levels    Values

   POTATO         4    1 2 3 4

   BLANCH         2    1 2

   STRIP          3    1 2 3

   PUNCH          3    1 2 3

Number of observations in data set = 252
```

General Linear Models Procedure

Dependent Variable: FMAX PEAK FORCE (N)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	59	77.29011574	1.31000196	1.74	0.0026
Error	192	144.25091601	0.75130685		
Corrected Total	251	221.54103175			

R-Square	C.V.	Root MSE	FMAX Mean
0.348875	33.70393	0.866780	2.571746

Source	DF	Type I SS	Mean Square	F Value	Pr > F
POTATO	3	15.79967619	5.26655873	7.01	0.0002
BLANCH	1	0.26375721	0.26375721	0.35	0.5542
POTATO*BLANCH	3	2.46967057	0.82322352	1.10	0.3521
STRIP	2	1.50933889	0.75466944	1.00	0.3682
POTATO*STRIP	6	16.07368333	2.67894722	3.57	0.0023
BLANCH*STRIP	2	0.44394537	0.22197269	0.30	0.7445
POTATO*BLANCH*STRIP	6	5.64339907	0.94056651	1.25	0.2817
PUNCH	2	9.04603889	4.52301944	6.02	0.0029
POTATO*PUNCH	6	4.51860238	0.75310040	1.00	0.4251
BLANCH*PUNCH	2	2.07594537	1.03797269	1.38	0.2537
POTATO*BLANCH*PUNCH	6	1.98525780	0.33087630	0.44	0.8511
STRIP*PUNCH	4	7.65557540	1.91389385	2.55	0.0408
POTATO*STRIP*PUNCH	12	8.14197381	0.67849782	0.90	0.5449
BLANCH*STRIP*PUNCH	4	1.66325146	0.41581286	0.55	0.6967

Source	DF	Type III SS	Mean Square	F Value	Pr > F
POTATO	3	13.30856739	4.43618913	5.90	0.0007
BLANCH	1	0.26375721	0.26375721	0.35	0.5542
POTATO*BLANCH	3	2.46967057	0.82322352	1.10	0.3521
STRIP	2	1.54908823	0.77454411	1.03	0.3586
POTATO*STRIP	6	15.08849749	2.51474958	3.35	0.0037
BLANCH*STRIP	2	0.44394537	0.22197269	0.30	0.7445
POTATO*BLANCH*STRIP	6	5.64339907	0.94056651	1.25	0.2817
PUNCH	2	9.63769299	4.81884649	6.41	0.0020
POTATO*PUNCH	6	4.53626574	0.75604429	1.01	0.4225
BLANCH*PUNCH	2	2.07594537	1.03797269	1.38	0.2537
POTATO*BLANCH*PUNCH	6	1.98525780	0.33087630	0.44	0.8511
STRIP*PUNCH	4	4.94146098	1.23536524	1.64	0.1648
POTATO*STRIP*PUNCH	12	8.14197381	0.67849782	0.90	0.5449
BLANCH*STRIP*PUNCH	4	1.66325146	0.41581286	0.55	0.6967

General Linear Models Procedure

Dependent Variable: DMAX PEAK DEFORMATION (mm)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	59	81.45629947	1.38061525	1.26	0.1237
Error	192	210.27302751	1.09517202		
Corrected Total	251	291.72932698			

R-Square	C.V.	Root MSE	DMAX Mean
0.279219	19.81242	1.046505	5.282063

Source	DF	Type I SS	Mean Square	F Value	Pr > F
POTATO	3	12.35827937	4.11942646	3.76	0.0118
BLANCH	1	0.41866772	0.41866772	0.38	0.5371
POTATO*BLANCH	3	2.00935767	0.66978589	0.61	0.6083
STRIP	2	14.42339365	7.21169683	6.58	0.0017
POTATO*STRIP	6	8.11793968	1.35298995	1.24	0.2898
BLANCH*STRIP	2	1.70877672	0.85438836	0.78	0.4598
POTATO*BLANCH*STRIP	6	9.44704550	1.57450758	1.44	0.2021
PUNCH	2	2.39368889	1.19684444	1.09	0.3373
POTATO*PUNCH	6	3.35080635	0.55846772	0.51	0.8004
BLANCH*PUNCH	2	4.69180370	2.34590185	2.14	0.1202
POTATO*BLANCH*PUNCH	6	5.53107884	0.92184647	0.84	0.5391
STRIP*PUNCH	4	2.73073016	0.68268254	0.62	0.6464
POTATO*STRIP*PUNCH	12	11.44523175	0.95376931	0.87	0.5776
BLANCH*STRIP*PUNCH	4	2.82949947	0.70737487	0.65	0.6304

Source	DF	Type III SS	Mean Square	F Value	Pr > F
POTATO	3	2.56971323	0.85657108	0.78	0.5052
BLANCH	1	0.41866772	0.41866772	0.38	0.5371
POTATO*BLANCH	3	2.00935767	0.66978589	0.61	0.6083
STRIP	2	8.63244656	4.31622328	3.94	0.0210
POTATO*STRIP	6	10.93891852	1.82315309	1.66	0.1316
BLANCH*STRIP	2	1.70877672	0.85438836	0.78	0.4598
POTATO*BLANCH*STRIP	6	9.44704550	1.57450758	1.44	0.2021
PUNCH	2	3.81094021	1.90547011	1.74	0.1783
POTATO*PUNCH	6	1.14009471	0.19001578	0.17	0.9837
BLANCH*PUNCH	2	4.69180370	2.34590185	2.14	0.1202
POTATO*BLANCH*PUNCH	6	5.53107884	0.92184647	0.84	0.5391
STRIP*PUNCH	4	1.62910582	0.40727646	0.37	0.8285
POTATO*STRIP*PUNCH	12	11.44523175	0.95376931	0.87	0.5776
BLANCH*STRIP*PUNCH	4	2.82949947	0.70737487	0.65	0.6304

General Linear Models Procedure

Source	Type III Expected Mean Square
POTATO	Var(Error) + 3.4286 Var(POTATO*STRIP*PUNCH) + 5.1429 Var(POTATO*BLANCH*PUNCH) + 10.286 Var(POTATO*PUNCH) + 5.1429 Var(POTATO*BLANCH*STRIP) + 10.286 Var(POTATO*STRIP) + 15.429 Var(POTATO*BLANCH) + 30.857 Var(POTATO)
BLANCH	Var(Error) + 5.1429 Var(POTATO*BLANCH*PUNCH) + 5.1429 Var(POTATO*BLANCH*STRIP) + 15.429 Var(POTATO*BLANCH) + Q(BLANCH,BLANCH*STRIP,BLANCH*PUNCH,BLANCH*STRIP*PUNCH)
POTATO*BLANCH	Var(Error) + 5.1429 Var(POTATO*BLANCH*PUNCH) + 5.1429 Var(POTATO*BLANCH*STRIP) + 15.429 Var(POTATO*BLANCH)
STRIP	Var(Error) + 3.4286 Var(POTATO*STRIP*PUNCH) + 5.1429 Var(POTATO*BLANCH*STRIP) + 10.286 Var(POTATO*STRIP) + Q(STRIP,BLANCH*STRIP,STRIP*PUNCH,BLANCH*STRIP*PUNCH)
POTATO*STRIP	Var(Error) + 3.4286 Var(POTATO*STRIP*PUNCH) + 5.1429 Var(POTATO*BLANCH*STRIP) + 10.286 Var(POTATO*STRIP)
BLANCH*STRIP	Var(Error) + 5.1429 Var(POTATO*BLANCH*STRIP) + Q(BLANCH*STRIP,BLANCH*STRIP*PUNCH)
POTATO*BLANCH*STRIP	Var(Error) + 5.1429 Var(POTATO*BLANCH*STRIP)
PUNCH	Var(Error) + 3.4286 Var(POTATO*STRIP*PUNCH) + 5.1429 Var(POTATO*BLANCH*PUNCH) + 10.286 Var(POTATO*PUNCH) + Q(PUNCH,BLANCH*PUNCH,STRIP*PUNCH,BLANCH*STRIP*PUNCH)
POTATO*PUNCH	Var(Error) + 3.4286 Var(POTATO*STRIP*PUNCH) + 5.1429 Var(POTATO*BLANCH*PUNCH) + 10.286 Var(POTATO*PUNCH)
BLANCH*PUNCH	Var(Error) + 5.1429 Var(POTATO*BLANCH*PUNCH) + Q(BLANCH*PUNCH,BLANCH*STRIP*PUNCH)
POTATO*BLANCH*PUNCH	Var(Error) + 5.1429 Var(POTATO*BLANCH*PUNCH)
STRIP*PUNCH	Var(Error) + 3.4286 Var(POTATO*STRIP*PUNCH) + Q(STRIP*PUNCH,BLANCH*STRIP*PUNCH)
POTATO*STRIP*PUNCH	Var(Error) + 7 Var(POTATO*STRIP*PUNCH)
BLANCH*STRIP*PUNCH	Var(Error) + Q(BLANCH*STRIP*PUNCH)

General Linear Models Procedure
Tests of Hypotheses for Mixed Model Analysis of Variance

Dependent Variable: FMAX

Source: POTATO
Error: MS(POTATO*BLANCH) + MS(POTATO*STRIP) - MS(POTATO*BLANCH*STRIP)
+ MS(POTATO*PUNCH) - MS(POTATO*BLANCH*PUNCH)
- 0.4898*MS(POTATO*STRIP*PUNCH) + 0.4898*MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
3	4.4361891314	5.27	2.8582361501	1.5521	0.3063

Source: BLANCH •
Error: MS(POTATO*BLANCH)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
1	0.263757209	3	0.8232235229	0.3204	0.6109

• - This test assumes one or more other fixed effects are zero.

Source: POTATO*BLANCH
Error: MS(POTATO*BLANCH*STRIP) + MS(POTATO*BLANCH*PUNCH) - MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
3	0.8232235229	1.60	0.5201359589	1.5827	0.4415

Source: STRIP •
Error: MS(POTATO*STRIP)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
2	0.7745441138	6	2.5147495811	0.3080	0.7459

• - This test assumes one or more other fixed effects are zero.

Source: POTATO*STRIP
Error: MS(POTATO*BLANCH*STRIP) + 0.4898*MS(POTATO*STRIP*PUNCH)
- 0.4898*MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
6	2.5147495811	5.20	0.9049049433	2.7790	0.1360

Source: BLANCH*STRIP •
Error: MS(POTATO*BLANCH*STRIP)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
2	0.2219726852	6	0.9405665123	0.2360	0.7968

• - This test assumes one or more other fixed effects are zero.

General Linear Models Procedure
Tests of Hypotheses for Mixed Model Analysis of Variance

Dependent Variable: FMAX

Source: POTATO*BLANCH*STRIP
Error: MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
6	0.9405665123	192	0.7513068542	1.2519	0.2817

Source: PUNCH •
Error: MS(POTATO*PUNCH)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
2	4.8188464947	6	0.7560442901	6.3738	0.0328

* - This test assumes one or more other fixed effects are zero.

Source: POTATO*PUNCH
Error: MS(POTATO*BLANCH*PUNCH) + 0.4898*MS(POTATO*STRIP*PUNCH)
- 0.4898*MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
6	0.7560442901	3.10	0.2952147317	2.5610	0.2304

Source: BLANCH*PUNCH •
Error: MS(POTATO*BLANCH*PUNCH)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
2	1.0379726852	6	0.3308763007	3.1370	0.1168

• - This test assumes one or more other fixed effects are zero.

Source: POTATO*BLANCH*PUNCH
Error: MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
6	0.3308763007	192	0.7513068542	0.4404	0.8511

Source: STRIP*PUNCH •
Error: 0.4898*MS(POTATO*STRIP*PUNCH) + 0.5102*MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
4	1.2353652447	51.38	0.7156452852	1.7262	0.1585

* - This test assumes one or more other fixed effects are zero.

General Linear Models Procedure
Tests of Hypotheses for Mixed Model Analysis of Variance

Dependent Variable: FMAX

Source: POTATO*STRIP*PUNCH
Error: MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
12	0.6784978175	192	0.7513068542	0.9031	0.5449

Source: BLANCH*STRIP*PUNCH
Error: MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
4	0.4158128638	192	0.7513068542	0.5535	0.6967

Dependent Variable: DMAX

Source: POTATO
Error: MS(POTATO*BLANCH) + MS(POTATO*STRIP) - MS(POTATO*BLANCH*STRIP)
+ MS(POTATO*PUNCH) - MS(POTATO*BLANCH*PUNCH)
- 0.4898*MS(POTATO*STRIP*PUNCH) + 0.4898*MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
3	0.8565710758	0.05	0.2558591738	3.3478	0.8874

Source: BLANCH •
Error: MS(POTATO*BLANCH)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
1	0.4186677249	3	0.6697858907	0.6251	0.4869

* - This test assumes one or more other fixed effects are zero.

Source: POTATO*BLANCH
Error: MS(POTATO*BLANCH*STRIP) + MS(POTATO*BLANCH*PUNCH) - MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
3	0.6697858907	3.50	1.4011820381	0.4780	0.7171

Source: STRIP •
Error: MS(POTATO*STRIP)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
2	4.3162232804	6	1.8231530864	2.3674	0.1746

* - This test assumes one or more other fixed effects are zero.

General Linear Models Procedure
Tests of Hypotheses for Mixed Model Analysis of Variance

Dependent Variable: DMAX

Source: POTATO*STRIP
Error: MS(POTATO*BLANCH*STRIP) + 0.4898*MS(POTATO*STRIP*PUNCH)
- 0.4898*MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
6	1.8231530864	5.23	1.5052491155	1.2112	0.4221

Source: BLANCH*STRIP •
Error: MS(POTATO*BLANCH*STRIP)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
2	0.8543883598	6	1.5745075838	0.5426	0.6073

* - This test assumes one or more other fixed effects are zero.

Source: POTATO*BLANCH*STRIP
Error: MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
6	1.5745075838	192	1.0951720183	1.4377	0.2021

Source: PUNCH •
Error: MS(POTATO*PUNCH)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
2	1.9054701058	6	0.1900157848	10.0280	0.0122

* - This test assumes one or more other fixed effects are zero.

Source: POTATO*PUNCH
Error: MS(POTATO*BLANCH*PUNCH) + 0.4898*MS(POTATO*STRIP*PUNCH)
- 0.4898*MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
6	0.1900157848	4.51	0.8525880044	0.2229	0.9508

Source: BLANCH*PUNCH *
Error: MS(POTATO*BLANCH*PUNCH)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
2	2.3459018519	6	0.9218464727	2.5448	0.1584

* - This test assumes one or more other fixed effects are zero.

General Linear Models Procedure
Tests of Hypotheses for Mixed Model Analysis of Variance

Dependent Variable: DMAX

Source: POTATO*BLANCH*PUNCH
Error: MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
6	0.9218464727	192	1.0951720183	0.8417	0.5391

Source: STRIP*PUNCH •
Error: 0.4898*MS(POTATO*STRIP*PUNCH) + 0.5102*MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
4	0.407276455	53.12	1.02591355	0.3970	0.8099

• - This test assumes one or more other fixed effects are zero.

Source: POTATO*STRIP*PUNCH
Error: MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
12	0.9537693122	192	1.0951720183	0.8709	0.5776

Source: BLANCH*STRIP*PUNCH
Error: MS(Error)

DF	Type III MS	Denominator DF	Denominator MS	F Value	Pr > F
4	0.7073748677	192	1.0951720183	0.6459	0.6304

Duncan's Multiple Range Test for variable: FMAX

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 192 MSE= 0.751307
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 61.71429

Number of Means 2
Critical Range .3078

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	BLANCH
A	2.5850	216	1
A			
A	2.4925	36	2

Duncan's Multiple Range Test for variable: DMAX

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 192 MSE= 1.095172
WARNING: Cell sizes are not equal.
Harmonic Mean of cell sizes= 61.71429

Number of Means 2
Critical Range .3716

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	BLANCH
A	5.2987	216	1
A			
A	5.1822	36	2

---------- BLANCHING TRMT-Std or Mod=1 ----------

General Linear Models Procedure
Class Level Information

Class	Levels	Values
STRIP	3	1 2 3
PUNCH	3	1 2 3

Number of observations in by group = 216

---------- BLANCHING TRMT-Std or Mod=1 ----------

General Linear Models Procedure

Dependent Variable: FMAX PEAK FORCE (N)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	26.12952454	1.53703086	1.94	0.0166
Error	198	156.78887500	0.79186301		
Corrected Total	215	182.91839954			

R-Square	C.V.	Root MSE	FMAX Mean
0.142848	34.42487	0.889867	2.584954

Source	DF	Type I SS	Mean Square	F Value	Pr > F
POTATO	1	0.23971120	0.23971120	0.30	0.5828
STRIP	2	0.94881759	0.47440880	0.60	0.5503
POTATO*STRIP	2	10.59694463	5.29847231	6.69	0.0015
PUNCH	2	5.14683426	2.57341713	3.25	0.0409
POTATO*PUNCH	2	2.44497352	1.22248676	1.54	0.2161
STRIP*PUNCH	4	6.55929352	1.63982338	2.07	0.0860
POTATO*STRIP*PUNCH	4	0.19294981	0.04823745	0.06	0.9931

Source	DF	Type III SS	Mean Square	F Value	Pr > F
POTATO	1	0.23971120	0.23971120	0.30	0.5828
STRIP	2	7.74417469	3.87208735	4.89	0.0085
POTATO*STRIP	2	10.59694463	5.29847231	6.69	0.0015
PUNCH	2	0.51131543	0.25565772	0.32	0.7245
POTATO*PUNCH	2	2.44497352	1.22248676	1.54	0.2161
STRIP*PUNCH	4	1.32904938	0.33226235	0.42	0.7944
POTATO*STRIP*PUNCH	4	0.19294981	0.04823745	0.06	0.9931

---------- BLANCHING TRMT-Std or Mod=1 ----------

General Linear Models Procedure

Dependent Variable: DMAX PEAK DEFORMATION (mm)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	41.58169037	2.44598179	2.26	0.0040
Error	198	214.07474667	1.08118559		
Corrected Total	215	255.65643704			

R-Square	C.V.	Root MSE	DMAX Mean
0.162647	19.62368	1.039801	5.298704

Source	DF	Type I SS	Mean Square	F Value	Pr > F
POTATO	1	11.62311259	11.62311259	10.75	0.0012
STRIP	2	12.11974815	6.05987407	5.60	0.0043
POTATO*STRIP	2	3.18729185	1.59364593	1.47	0.2315
PUNCH	2	2.55067037	1.27533519	1.18	0.3096
POTATO*PUNCH	2	4.30306741	2.15153370	1.99	0.1394
STRIP*PUNCH	4	3.55125185	0.88781296	0.82	0.5131
POTATO*STRIP*PUNCH	4	4.24654815	1.06163704	0.98	0.4185

Source	DF	Type III SS	Mean Square	F Value	Pr > F
POTATO	1	11.62311259	11.62311259	10.75	0.0012
STRIP	2	7.27494074	3.63747037	3.36	0.0366
POTATO*STRIP	2	3.18729185	1.59364593	1.47	0.2315
PUNCH	2	3.21638519	1.60819259	1.49	0.2285
POTATO*PUNCH	2	4.30306741	2.15153370	1.99	0.1394
STRIP*PUNCH	4	4.86245185	1.21561296	1.12	0.3462
POTATO*STRIP*PUNCH	4	4.24654815	1.06163704	0.98	0.4185

---------- BLANCHING TRMT-Std or Mod=1 ----------

General Linear Models Procedure

Duncan's Multiple Range Test for variable: FMAX

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 198 MSE= 0.791863

Number of Means	2	3
Critical Range	.2925	.3079

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	STRIP
A	2.6783	72	2
A			
A	2.5453	72	1
A			
A	2.5312	72	3

---------- BLANCHING TRMT-Std or Mod=1 ----------

General Linear Models Procedure

Duncan's Multiple Range Test for variable: DMAX

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 198 MSE= 1.081186

Number of Means	2	3
Critical Range	.3418	.3597

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	STRIP
A	5.4756	72	2
A			
A	5.4567	72	3
B	4.9639	72	1

---------- BLANCHING TRMT-Std or Mod=1 ----------

General Linear Models Procedure

Duncan's Multiple Range Test for variable: FMAX

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 198 MSE= 0.791863

Number of Means	2	3
Critical Range	.2925	.3079

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	PUNCH
A	2.7832	72	3
A			
B A	2.5650	72	2
B			
B	2.4067	72	1

---------- BLANCHING TRMT-Std or Mod=1 ----------

General Linear Models Procedure

Duncan's Multiple Range Test for variable: DMAX

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 198 MSE= 1.081186

Number of Means	2	3
Critical Range	.3418	.3597

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	PUNCH
A	5.3956	72	2
A			
A	5.3536	72	1
A			
A	5.1469	72	3

---------- BLANCHING TRMT-Std or Mod=2 ----------

General Linear Models Procedure
Class Level Information

Class	Levels	Values
STRIP	3	1 2 3
PUNCH	3	1 2 3

Number of observations in by group = 36

---------- BLANCHING TRMT-Std or Mod=2 ----------

General Linear Models Procedure

Dependent Variable: FMAX PEAK FORCE (N)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	24.52846500	1.44285088	1.88	0.0974
Error	18	13.83041000	0.76835611		
Corrected Total	35	38.35887500			

R-Square	C.V.	Root MSE	FMAX Mean
0.639447	35.16787	0.876559	2.492500

Source	DF	Type I SS	Mean Square	F Value	Pr > F
POTATO	1	0.07240056	0.07240056	0.09	0.7624
STRIP	2	1.00446667	0.50223333	0.65	0.5321
POTATO*STRIP	2	8.54227111	4.27113556	5.56	0.0132
PUNCH	2	5.97515000	2.98757500	3.89	0.0395
POTATO*PUNCH	2	1.36603444	0.68301722	0.89	0.4284
STRIP*PUNCH	4	2.75953333	0.68988333	0.90	0.4857
POTATO*STRIP*PUNCH	4	4.80860889	1.20215222	1.56	0.2265

Source	DF	Type III SS	Mean Square	F Value	Pr > F
POTATO	1	0.07240056	0.07240056	0.09	0.7624
STRIP	2	6.38082593	3.19041296	4.15	0.0329
POTATO*STRIP	2	8.54227111	4.27113556	5.56	0.0132
PUNCH	2	1.79752593	0.89876296	1.17	0.3330
POTATO*PUNCH	2	1.36603444	0.68301722	0.89	0.4284
STRIP*PUNCH	4	5.30101852	1.32525463	1.72	0.1884
POTATO*STRIP*PUNCH	4	4.80860889	1.20215222	1.56	0.2265

---------- BLANCHING TRMT-Std or Mod=2 ----------

General Linear Models Procedure

Dependent Variable: DMAX PEAK DEFORMATION (mm)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	17	25.68726222	1.51101542	2.73	0.0206
Error	18	9.96696000	0.55372000		
Corrected Total	35	35.65422222			

R-Square	C.V.	Root MSE	DMAX Mean
0.720455	14.35916	0.744124	5.182222

Source	DF	Type I SS	Mean Square	F Value	Pr > F
POTATO	1	0.00150222	0.00150222	0.00	0.9590
STRIP	2	4.01242222	2.00621111	3.62	0.0476
POTATO*STRIP	2	8.43352444	4.21676222	7.62	0.0040
PUNCH	2	4.53482222	2.26741111	4.09	0.0342
POTATO*PUNCH	2	1.92672444	0.96336222	1.74	0.2038
STRIP*PUNCH	4	2.00897778	0.50224444	0.91	0.4807
POTATO*STRIP*PUNCH	4	4.76928889	1.19232222	2.15	0.1159

Source	DF	Type III SS	Mean Square	F Value	Pr > F
POTATO	1	0.00150222	0.00150222	0.00	0.9590
STRIP	2	10.54791111	5.27395556	9.52	0.0015
POTATO*STRIP	2	8.43352444	4.21676222	7.62	0.0040
PUNCH	2	0.18537778	0.09268889	0.17	0.8472
POTATO*PUNCH	2	1.92672444	0.96336222	1.74	0.2038
STRIP*PUNCH	4	5.68417778	1.42104444	2.57	0.0735
POTATO*STRIP*PUNCH	4	4.76928889	1.19232222	2.15	0.1159

---------- BLANCHING TRMT-Std or Mod=2 ----------

General Linear Models Procedure

Duncan's Multiple Range Test for variable: FMAX

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 18 MSE= 0.768356

Number of Means	2	3
Critical Range	.7518	.7888

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	STRIP
A	2.6708	12	2
A			
A	2.5375	12	1
A			
A	2.2692	12	3

---------- BLANCHING TRMT-Std or Mod=2 ----------

General Linear Models Procedure

Duncan's Multiple Range Test for variable: DMAX

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 18 MSE= 0.55372

Number of Means	2	3
Critical Range	.6382	.6696

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	STRIP
A	5.6417	12	2
A			
B A	5.0467	12	3
B			
B	4.8583	12	1

---------- BLANCHING TRMT-Std or Mod=2 ----------

General Linear Models Procedure

Duncan's Multiple Range Test for variable: FMAX

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 18 MSE= 0.768356

Number of Means	2	3
Critical Range	.7518	.7888

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	PUNCH
A	3.0567	12	3
A			
B A	2.3117	12	2
B			
B	2.1092	12	1

---------- BLANCHING TRMT-Std or Mod=2 ----------

General Linear Models Procedure

Duncan's Multiple Range Test for variable: DMAX

NOTE: This test controls the type I comparisonwise error rate, not the experimentwise error rate

Alpha= 0.05 df= 18 MSE= 0.55372

Number of Means	2	3
Critical Range	.6382	.6696

Means with the same letter are not significantly different.

Duncan Grouping	Mean	N	PUNCH
A	5.5067	12	2
A			
A	5.3517	12	3
B	4.6883	12	1

APPENDIX 3. Effect of puncture location (n = 5) on peak deformation and post-puncture energy consumption of blanched french fry strips grown at Shilo.

Blanching conditions	Puncture location	Peak deformation (mm)		Post-puncture energy consumption (Jm^{-1})	
		1994	1995	1994	1995
LTLT	Bud	1.10b	1.27a	2.06c	1.52c
	Middle 1	1.19b	1.35a	2.59ab	1.92bc
	Middle 2	1.22b	1.25a	2.65ab	2.15ab
	Stem	1.39a	1.32a	2.97a	2.61a
HTST	Bud	1.06a	0.94b	2.11c	1.81c
	Middle1	1.20a	1.05ab	2.57b	2.28b
	Middle 2	1.15a	1.01ab	2.40bc	2.36ab
	Stem	1.20a	1.12a	3.01a	2.69a

[1] Means in a column within a blanching condition followed by different letters differ significantly from each other ($p \leq 0.05$).

APPENDIX 4. Effect of puncture location (n = 5) on peak deformation and post-puncture energy consumption of blanched french fry strips grown at Portage.

Blanching conditions	Puncture location	Peak deformation (mm)		Post-puncture energy consumption (Jm^{-1})	
		1994	1995	1994	1995
LTLT	Bud	0.99c	1.21a	1.59b	2.02b
	Middle 1	1.09bc	1.21a	1.85ab	2.25ab
	Middle 2	1.10b	1.24a	1.95a	2.12ab
	Stem	1.24a	1.22a	2.12a	2.43a
HTST	Bud	0.91a	1.07a	1.90b	2.43a
	Middle1	1.00a	1.11a	2.14a	2.52a
	Middle 2	0.95a	1.11a	2.11ab	2.55a
	Stem	1.01a	1.10a	2.04ab	2.60a

[1] Means in a column within a blanching condition followed by different letters differ significantly from each other ($p \leq 0.05$).

APPENDIX 5. Effect of puncture location (n = 5) on peak deformation and post-puncture energy consumption of blanched and frozen french fry strips grown at Shilo[1]

Blanching conditions	Puncture location	Peak deformation (mm)		Post-puncture energy consumption (Jm^{-1})	
		1994	1995	1994	1995
LTLT	Bud	3.18a	3.17b	0.77b	0.58c
	Middle 1	3.40a	3.41ab	1.21a	0.71bc
	Middle 2	3.28a	3.54ab	1.48a	1.05ab
	Stem	3.09a	3.64a	1.27a	1.11a
HTST	Bud	2.84ab	3.01a	0.95b	0.64b
	Middle1	3.11a	2.90a	1.36a	1.05ab
	Middle 2	2.91ab	2.88a	1.28a	0.98ab
	Stem	2.70b	3.25a	1.17ab	1.25a

[1] Means in a column within a blanching condition followed by different letters differ significantly from each other ($p \leq 0.05$).

APPENDIX 6. Effect of puncture location (n = 5) on peak deformation and post-puncture energy consumption of blanched and frozen french fry strips grown at Portage[1]

Blanching conditions	Puncture location	Peak deformation (mm)		Post-puncture energy consumption (Jm^{-1})	
		1994	1995	1994	1995
LTLT	Bud	2.96a	3.10ab	0.87b	0.75a
	Middle 1	3.26a	3.34a	1.21ab	0.89a
	Middle 2	3.13a	3.25ab	1.27a	0.81a
	Stem	2.93a	2.90b	1.38a	0.79a
HTST	Bud	2.40ab	2.86a	0.90a	0.61b
	Middle1	2.66a	3.13a	1.12a	0.95a
	Middle 2	2.71a	2.96a	1.06a	1.10a
	Stem	2.00b	2.85a	0.92a	0.95a

[1] Means in a column within a blanching condition followed by different letters differ significantly from each other ($p \leq 0.05$).

APPENDIX 7. Mean values of post-puncture energy consumption (Jm^{-1}) (n = 4) of fully-fried french fries processed by the standard and a given processing condition (9 months storage)[1]

Site & Cultivar	Unit process operations						
	Standard conditions	Blanch		Dry		Finish fry	
		LTLT	HTST	LTLT	HTST	LTLT	HTST
Portage, RB	0.26b	0.23b	0.18c	0.38a	0.28b	0.38a	0.36a
Carberry, RB	0.25b	0.26b	0.19b	0.25b	0.25b	0.35a	0.22b
Portage, SH	0.24a	0.22a	0.24a	0.27a	0.27a	0.25a	0.31a
Carberry, SH	0.22b	0.19b	0.21b	0.28b	0.18b	0.19b	0.29a

[1] Within a row, means of the standard and an experimental condition followed by different letters differ significantly from each other ($p \leq 0.05$); n = 24 for standard conditions. Refer to Table 2 for processing conditions.

APPENDIX 8. Mean values of post-puncture energy consumption (Jm^{-1}) (n=4) for fully-fried french fries processed by the standard and finish fry conditions (11 months storage).

Site & Cultivar	Standard conditions	LTLT finish fry	HTST finish fry
Portage, RB	0.29a	0.34a	0.31a
Carberry, RB	0.29a	0.31a	
Carberry, SH	0.22a		0.22a

[1] Within a row, means of the standard and an experimental condition followed by different letters differ significantly from each other ($p \leq 0.05$); n=24 for standard conditions. Refer to Table 2 for processing conditions.