# EFFECT OF SPECIFIC PROCESSING METHODS ON THE MICROSTRUCTURAL AND PHYSICAL PROPERTIES OF POTATOES DURING POTATO GRANULE PRODUCTION

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Jose L. Ibave G.

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I wish to dedicate this thesis to my wife and family.

TABLE OF CONTENTS

PAGE

PAGE

PAGE

# LIST OF TABLES

# LIST OF FIGURES

FIGURE PAGE

FIGURE PAGE

# LIST OF ABBREVIATIONS

| | |
|---|---|
| min | minute |
| sec | second |
| D.B. | dry basis |
| ppm | parts per million |
| sp. gr. | specific gravity |
| kg | kilogram |
| J | joules |
| mg | milligram |
| R.H. | relative humidity |
| g | gram |
| kPa | kilopascals |
| W.B. | wet basis |
| mm | millimeters |
| $^{o}C$ | celcius degree |
| h | hour |
| rpm | revolutions per minute |
| nm | nanometers |
| st. dev. | standard deviation |
| F-T | freeze-thaw |
| BVI | blue value index |
| WHC | water holding capacity |
| g | gravity force |

# ABSTRACT

Ibave, G., Jose L. M.Sc., The University of Manitoba, October, 1981. Effect of Specific Processing Methods on the Microstructural and Physical Properties of Potatoes During Potato Granule Production. Major Professor; Dr. M.B. McConnell.

Raw and cooked potatoes, variety Netted Gem (Russet Burbank), grown in Manitoba 1980, specific gravity 1.093-1.098 were examined by scanning electron microscopy, since the objective of this thesis was to investigate and study the effect of specific processing methods on the microstructural, physical and nutritional properties of potatoes during potato granule production. Photomicrographs were provided for Periderm and Cortex, Outer Medulla and Inner Medulla or pith area tissues in the new potato revealing starch grains of various shapes and sizes.

Microwave, boiling water, steam and boiling water plus steam were used for cooking potatoes. Different time-temperature combinations were applied in order to follow the principal changes in the microstructure. Photomicrographs revealed interesting aspects, such as the initial steps in gelatinization, agglomerization and separation of starch granules from the cell wall distinctive for each cooking method. Processing of tubers using added calcium was also studied since organic ions are thought to play an effective role in the formation of strong molecular associations, producing collapsation of the starch granules as observed in the photomicrographs.

Potato granules were produced using freeze-thaw process and continuous process; add-back granules were furnished by a commercial source.

Photomicrographs from those granules showed a striking difference amongst them because the state of the water present in the cells during dehydration played the most important role over the microstructural and production characteristics of the final product. Quality was evaluated on the basis of physico-chemical properties and yield, finding that the freeze-thaw granules were superior to the add-back (swelling power 41-49 ml /10 g dry matter for freeze-thaw and 26 ml/10 g dry matter for add-back) and to the continuous (Blue Value Index of 130-169 for the freeze-thaw and 233-270 for the continuous). Freeze-thaw granules cooked by the microwave system gave the greatest yield (86%). Changes in the nutritional quality of the potato were monitored during each processing operation. In addition, the free starch and pectic substance contents were analyzed as these are thought to play an important role in granule production.

# 1. INTRODUCTION

Most botanists agree that the potato, a dicotyledonous plant, originated in the New World, especially in South America (Smith, 1977; Talburt and Smith, 1975). The name potato is believed to have originated from the Indian name "Batatas". For many centuries the potato tuber served as the primary food source of the Indians of Peru. Apparently, sufficient potatoes were dehydrated to provide for periods when fresh potatoes were not available (Thornton and Sieczka, 1980).

The potato is an important component in the diets of much of the world's population. Considering potato consumption only in the United States, annual per capita consumption for fresh and processed rose from 103 lbs (46.7 kg) in 1956 to 116 lbs (52.7 kg) in 1975 (Table 1). Consumption of fresh product dropped while that of processed product rose during this period. Per capita consumption of frozen potatoes made the greatest gains while the dehydrated product increased its popularity by a factor of five. As life styles continue to change in our society the consumption of the processed product is expected to further erode the consumption of the fresh product.

Potato protein has a very good quality attributed to the presence of essential amino acids but is limiting in methionine and histidine. The tuber is one of the most important natural dietary sources of Vitamin C in many countries (Hadziyev and Steele, 1979); the nutrient composition of the potato is listed in Table 2. In addition to its

TABLE 1. U.S. per capita consumption of potatoes.[1]

| Year | Fresh | Processed | Total |
|---|---|---|---|
| 1956 | 88.0 | 14.7 | 102.7 |
| 1961 | 83.8 | 25.5 | 109.3 |
| 1966 | 72.4 | 44.4 | 116.8 |
| 1971[1] | 56.8 | 61.9 | 118.7 |
| 1976 | 51.2 | 65.2 | 116.4 |

| | Processed[2] | | | |
|---|---|---|---|---|
| | Canned | Frozen | Shoestring, Saratoga and chips | Dehydrated |
| 1956 | 1.3 | 2.9 | 8.9 | 1.6 |
| 1961 | 1.5 | 6.8 | 12.3 | 4.9 |
| 1966 | 1.7 | 17.3 | 16.7 | 8.7 |
| 1971 | 2.2 | 30.3 | 17.3 | 12.1 |
| 1976 | 2.0 | 36.9 | 16.2 | 10.1 |

[1]All the values are in pounds.

[2]Revised to include potatoes used in soups, stews, etc.

Source: Crop Reporting Board, Economics, Statistics and Co-operatives Service, USDA.

TABLE 2. The nutrient composition of potatoes.[1] The values, except for energy, are shown in percentages of the U.S. Recommended Daily Allowances, U.S. RDA.

| | Nutritional values | Percentage U.S. RDA, (150 g approx. one serving) |
|---|---|---|
| Energy | | About 460.3 J |
| Vitamin C | 13.21 - 54.15 mg[2] | 56.6%[3] |
| Iodine | 0.0512 - 0.0423 mg | 15.2% |
| Vitamin $B_6$ | 0.188 - 0.597 mg | 16.4% |
| Niacin | 0.96 - 3.84 mg | 12.1% |
| Copper | 0.130 - 0.491 mg | 16.9% |
| Magnesium | 0.0254 - 0.0381 g | 7.8% |
| Thiamin ($B_1$) | 0.0670 - 0.153 mg | 8.7% |
| Phosphorus | 0.0467 - 0.0980 g | 7.3% |
| Protein | 2.48 - 3.62 g | 4.7% |
| Folic acid | 7.82 - 32.51 mcg | 4.9% |
| Iron | 0.4130 - 2.106 mg | 5.2% |
| Riboflavin | 0.0315 - 0.1326 mg | 3.6% |
| Zinc | 0.492 - 0.801 mg | 3.9% |

[1] Nutritional values selected are those for which averages are expected to show a percentage of U.S. RDA equal to or greater than the percentage of energy provided by one serving of potato. Dates are taken from 1975-76 study sponsored by the Potato Board and conducted by the University of Idaho (Dr. Jorg Augustin), the University of Maine (Dr. John Hogan and Ruth True) and the U.S.D.A. Red River Valley Research Center (Dr. Roy Shaw and Dr. R. Toma).

[2] Ranges are due to variations in values due to storage time (0 - 10 months) and to varietal differences.

[3] Data are averages after weighing the influence of varieties and storage time.

nutritional quality, the potato is an efficient producer of food energy and on a per hectare basis must figure prominently in combating any world food crisis. Recent data indicate that the potato produces 74.5% more food energy per hectare than wheat and 58% more than rice, also, potatoes produce 54% more protein per hectare than wheat and 77.6% more than rice. In fact, no other food can match the potato in its production of food energy and food value per hectare (Thornton and Sieczka, 1980).

Processing of potatoes into dehydrated granules is perhaps the most satisfactory method of creating a product that is not only nutritionally and organoleptically adequate, but remains so over an extended period of time. However, such processing must be carried out in a controlled manner to ensure that most of the potato's original value is retained.

Potato granules are dehydrated mashed potatoes in granular form that can be quickly reconstituted to mashed potatoes by the addition of hot liquid (Harrington, Olson, Weston and Belote, 1959). Various procedures have been advocated to attain potato granules, amongst them, the "Add-back" process which is presently employed on an extensive scale. In this method a portion of the dried product is added to freshly cooked, mashed potatoes, producing a moist granular mixture that is subsequently dried to powder (Olson, Harrington, Neel, Cole and Mullins, 1953, 1954; Olson and Harrington, 1955; Noves, 1969; Talburt and Smith, 1975; Smith, 1977; Hadziyev and Steele, 1979).

A relatively new process recently disclosed by Ooraikul (1978) eliminates or minimizes some of the major problems which have been plaguing the conventional Add-back process and is called Freeze-Thaw

Process. The drying of potatoes using the Freeze-Thaw process, apparently originated 2000 years ago in South America (Treadway, Heisler, Whittenberger, Highlands and Getchell, 1955). This process involves controlled freezing and thawing of the cooked, mashed potatoes before dehydration. Freezing followed by slow thawing, has caused a freezing out of water from the solubilized starch, leaving a firm structure that will maintain its physical proportions throughout subsequent dehydration (Olson, Harrington and McCready, 1951).

The objective of this thesis was to investigate and study the effect of specific processing methods on the microstructural, physical and nutritional properties of potatoes during potato granule production. For this purpose potatoes, variety Netted Gem (Russet Burbank) were used because of their wide acceptability by the potato dehydration industry. The different cooking methods applied are listed in Table 3.

TABLE 3. Cooking methods.

| |
|---|
| 1. Boiling water. |
| 2. Microwave |
| 3. Steam |
| 4. Boiling water in presence of 100 ppm of calcium. |
| 5. Pre-cooking in boiling water and final cooking by steam. |
| 6. Pre-cooking in boiling water in presence of 100 ppm of calcium and final cooking by steam. |

The primary areas of concern were:

1. The effect of specific processes on the cell microstructure and on the properties of the potato granules.

2. The effects of variations in the dehydration process on the

properties of potato granules.

3. The effect of specific processes on the nutrient quality of potato granules.

# 2. LITERATURE REVIEW

## 2.1 Potato Composition

### 2.1.1 Effect of Specific Gravity upon Potato Composition

Specific gravity of raw potato is widely accepted by the potato processing industry as a measure of total solids, starch content and other qualities. However, the specific gravity total solids relationship is not clearly understood since many factors may affect this parameter. These include: variety, area of growth, internal composition of tubers, analytical techniques and perhaps others (Firzpatrick, Porter and Houghland, 1969).

Shippers (1976) found that quantitative relationships between specific gravity and dry matter content were not sufficiently stable to serve as a general measure of prediction under all conditions. For example, tubers grown in fertilizer trials or subjected to different storage treatments may give differences in specific gravity that are not entirely caused by differences in dry matter content. The intercellular spaces in tubers are quite variable and will affect the specific gravity reading (Kushman and Haynes, 1971). The variability may be large enough to overcome real differences in dry matter content and result in no observed differences in specific gravity.

Reeve et al (1971) reported that potatoes may gain in specific gravity and total solids content between early and later harvest dates, however, environmental factors may reverse this trend. On the other

hand, maturity of the tuber was found to have only a minor impact on the relationship between specific gravity and dry matter content (Shippers, 1976). Organoleptic studies showed conclusively that tubers of identical specific gravity from different varieties vary considerably in mealiness and potatoes within one variety with a range of specific gravities differ in mealiness (Unrau and Nylund, 1957; Clark, Lombard and Whiteman, 1940).

Potatoes with low specific gravity tended to be more variable in sugar accumulation between stem and bud portions than high specific gravity potatoes (Figure 1) (Iritani and Weller, 1976).

Low or inadequate fertility caused significantly greater reducing sugar formation in the stem portion at all specific gravity levels than did adequate fertility (Figure 2).

The amino acid and nitrogen contents on the fresh basis tended not to vary with specific gravity. On the other hand, the amino acid content on the dry basis tended to increase as the specific gravity decreased. Thus, the increase in specific gravity is due to an increase in total solids content not to amino acid content and is probably due to starch (Talley and Porter, 1970).

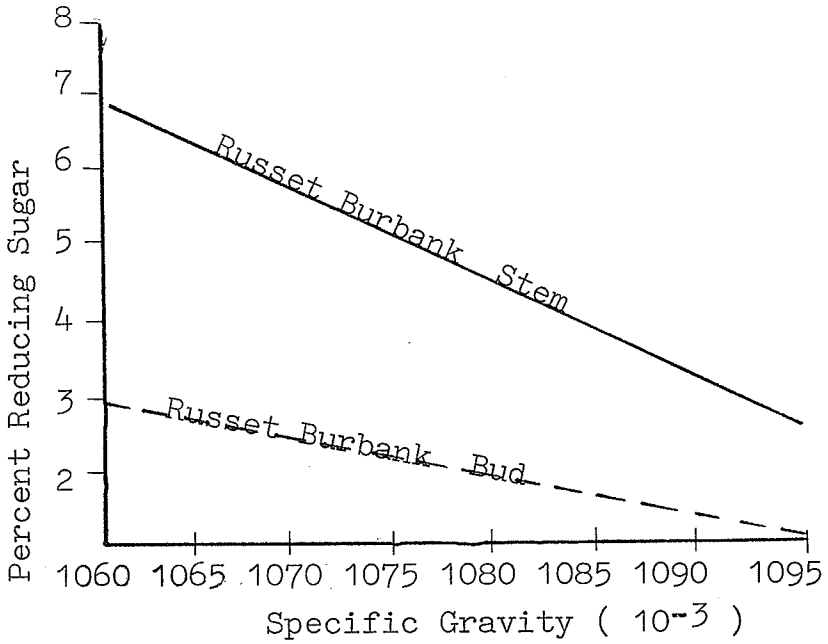
It is highly desirable to have uniform specific gravity among the tubers of a variety particularly for application in the processing industry. This uniformity would reduce some of the problems that occur in the processing of potatoes (Lana et al, 1970).

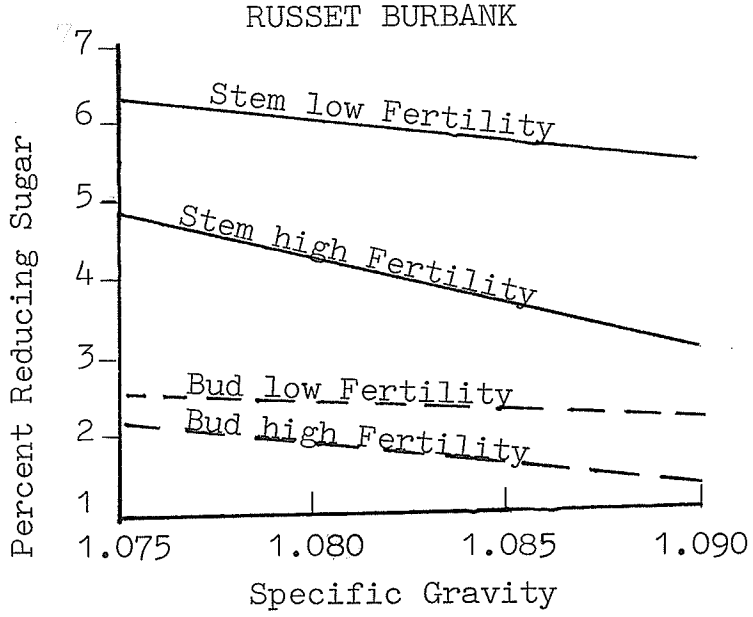
### 2.1.2 Changes in Potato Composition Due to Storage

Solids content of potatoes is of major importance in processing. High solids content has been associated with mealiness, crispness,

Figure 1. Comparison of stem and bud portions of Russet Burbank potatoes on specific gravity and reducing sugar accumulation during storage at 5.6°C (Iritani and Weller, 1976).

Figure 2. The effect of low fertility in comparison to adequate fertility (high fertility) on specific gravity to reducing sugar accumulation in storage of stem and bud portions of Russet Burbank potatoes (Iritani and Weller, 1976).


Percent Reducing Sugar
8
7
6
5
4
3
2
Russet Burbank Stem
Russet Burbank Bud
1060 1065 1070 1075 1080 1085 1090 1095
Specific Gravity ( $10^{-3}$ )


RUSSET BURBANK
Percent Reducing Sugar
7
6
5
4
3
2
1
Stem low Fertility
Stem high Fertility
Bud low Fertility
Bud high Fertility
1.075 1.080 1.085 1.090
Specific Gravity

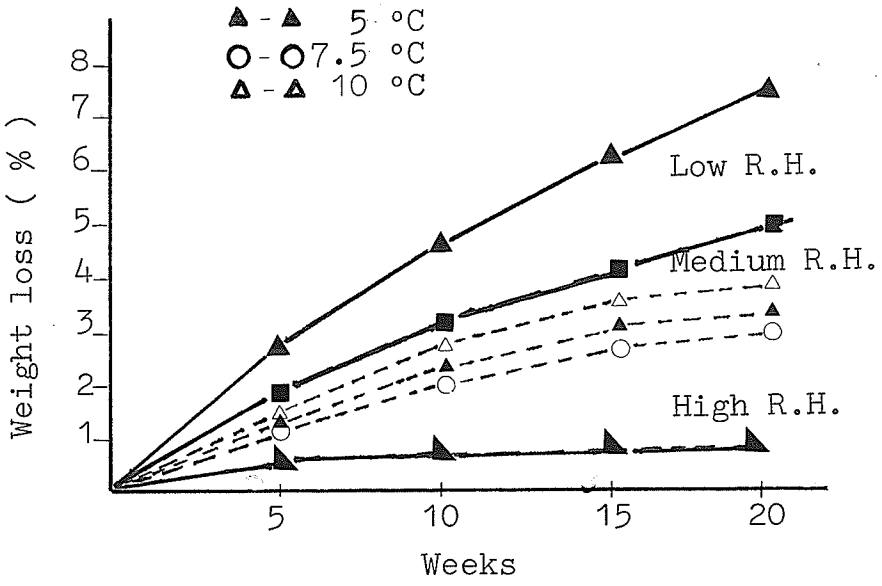
rigidity and reduced oil uptake in french fries, with increasing yield recovery of dehydrated potatoes and chips, and with lower oil content in chips. Low solids potatoes slough less during boiling and are preferred over high-solids potatoes in soups and salads. Since starch comprises 65 to 80% of the potato solids, its composition may also be important in predicting quality of the finished product. The total solids content and the starch composition of potatoes are inherited characteristics and both are influenced by cultural practices and storage conditions. Weaver (1978a) found that the relationships for distribution of solids among different parts of the tubers were not changed by storage treatments in any of the varieties tested. Solids content was changed by storage, but not uniformly in all the varieties.

Changes in weight and, to a lesser degree, in specific gravity of tubers during storage was much more dependent on relative humidity than on temperature (Figure 3). It is evident from the data presented that in the temperature range which is customary in potato storage, the relative humidity is far more important with respect to weight loss than the temperature (Shippers, 1971a, b).

The amount and kind of sugar in a particular variety depends on growing environment, maturity of the tubers at harvest, cultural practices (irrigation, fertilization, etc.) and time and temperature of storage and/or reconditioning (Kushman, 1969). The low temperature used to maintain the tubers for extended periods of time causes an increase in the sugar content of most varieties (Weaver, 1978b; Augustin, 1975).

As the nutritional status of processed products is now being stressed, along with the economic and environmental impacts of new processing technology, the nitrogen content of raw tubers and processed

Figure 3. Interaction between sampling date, temperature and relative humidity with respect to percent weight loss of Russet Burbank potatoes during storage (Schippers, 1971).


5 °C
7.5 °C
10 °C
Low R.H.
Medium R.H.
High R.H.
Weight loss ( % )
8
7
6
5
4
3
2
1
5
10
15
20
Weeks

potato products becomes increasingly important. Weaver (1978c) found that storage treatments significantly changed the total and free amino acid nitrogen contents. However, Talley (1970) found that variations in amino acid content with storage time are not very significant. Alanine, which decreased with time, was the only amino acid showing a definitive trend. Proline showed the opposite trend to alanine in these studies (Talley, 1970; Berkeley and Galliard, 1974b; Sweeney, Hepner and Libecic, 1969).

As far as lipids are concerned, a large decrease in total lipids content occurred during tuber growth (Figure 4), attaining a level at maturity which then remained relatively constant throughout storage. The percentage composition of individual fatty acids remained remarkably consistent throughout the life cycle of the potato tuber with palmitic, linoleic and linolenic acids representing 95% of the total fatty acid. Very little change occurred in either the polar or neutral lipids during storage of the potato tuber (Berkeley and Galliard, 1974a).

## 2.2 Protein in Potato Tuber

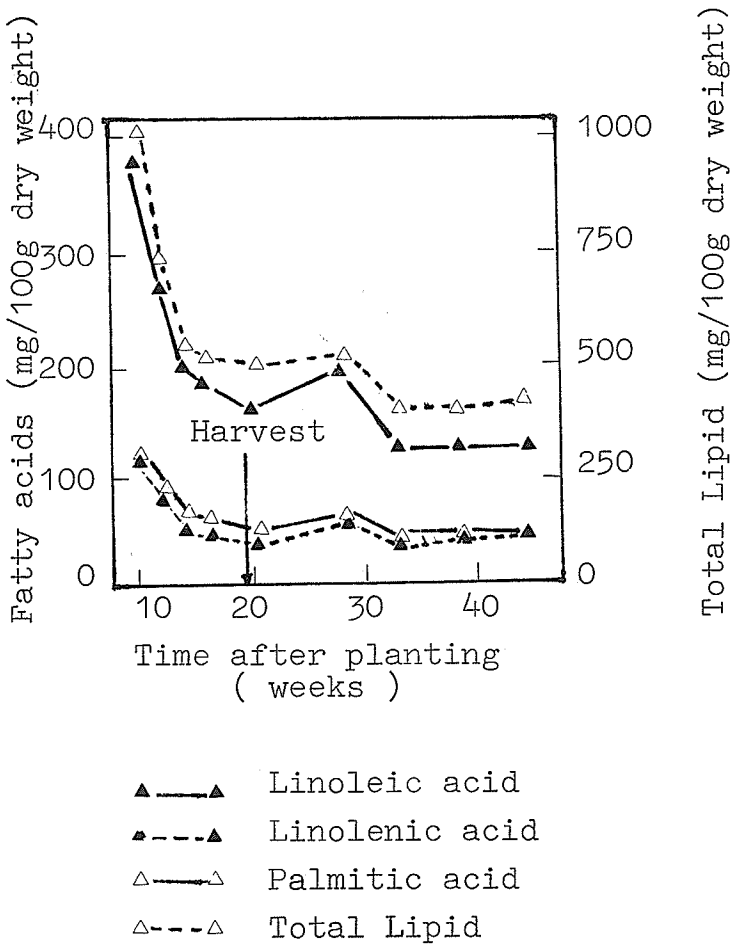
### 2.2.1 Composition

The total Nitrogen content in raw potato varies between 0.24 and 0.36% on a fresh, or 1 to 2% on a dry weight basis. This corresponds to 6 to 12.5% crude protein (N x 6.25). However, since crude protein consists of a heterogeneous mixture of N-containing compounds, the true protein content is one-third to one-half of the calculated theoretical level (Reiter, 1956).

### 2.2.2 Types of Protein

Protein is present in the mature tuber as water-soluble albumin

Figure 4. Changes in total lipid and the major fatty acids throughout growth and storage at 5°C of potatoes. The potato tubers were harvested during the 20th week after planting (Berkeley and Galliard, 1974a).


Fatty acids (mg/100g dry weight)
400
300
200
100
0
1000
750
500
250
0
Total Lipid (mg/100g dry weight)
Harvest
10
20
30
40
Time after planting
( weeks )
Linoleic acid
Linolenic acid
Palmitic acid
Total Lipid

(4% of the total protein), slightly and readily soluble globulins (1.4 and 74.6%, respectively), ethanol-soluble prolamin (1.8%), dilute-alkali-soluble glutelin (5.5%) and non-soluble skeletal protein (11%) (Hadziyev and Steele, 1979).

Racusen and Foote (1980) isolated a major glycoprotein using electrophoretic studies and its composition is given in Table 4.

### 2.2.3 Quality and Type of Amino Acids

Potato protein quality has been attributed to the presence of essential amino acids, which except for histidine, are present in substantially higher amounts than in some cereals (Kaldy and Markakis, 1972). The high lysine content of potato proteins appears to make them potentially valuable as supplements to wheat proteins (Knorr, 1980).

All the bound essential amino acids, particularly lysine, valine and phenylalanine were present in substantial proportions (Jaswal, 1973). The following amino acids were identified by ion exchange and paper chromatography from potato proteins; phenylalanine, methionine, tyrosine, alanine, lysine, glutamic acid, glutamine, aspartic acid and asparagine (Furnholmen, Winefordner, Dennison and Knapp, 1964).

### 2.2.4 Physical Appearance

Hoff et al. (1972) isolated crystalline cubical bodies from potato cytoplasm, mostly in the outer cortex of the tuber and identified them as proteins, predominantly of molecular weight of 77,000. Later, Nuss and Hadziyev (1980) established that only two to three of these cubical proteins are present per cell and those of globular shape comprised close to 75% of the total cell protein.

The cubical proteins were relatively high in lysine and low in cysteine/cystine (Hoff, 1972a).

TABLE 4. Composition of potato proteins.

| Component | g of anhydride amino acid or free sugar per 100 g protein | |
|---|---|---|
| | Glycoprotein | Albumin |
| ala | 5.10 | 4.57 |
| arg | 2.90 | 4.00 |
| asp | 9.50 | 12.05 |
| glu | 10.80 | 9.26 |
| gly | 2.74 | 4.99 |
| his | 2.28 | 1.71 |
| ile | 3.50 | 3.84 |
| leu | 9.20 | 6.61 |
| lys | 6.55 | 6.44 |
| met | 2.36 | 1.77 |
| phe | 5.26 | 4.76 |
| pro | 3.20 | 4.06 |
| ser | 4.90 | 4.94 |
| thr | 6.95 | 3.46 |
| try | not determined | 1.28 |
| tyr | 5.21 | 7.12 |
| val | 4.10 | 3.71 |
| $NH_3$ | not determined | 2.09 |
| Sugars | | |
| Hexosamine | 0.78 | not reported |
| Other sugars | 5.20 | not reported |
| Total | 90.73 | 86.66 |

## 2.3 Lipids of Potato Tuber

### 2.3.1 Composition and Distribution

The lipid content of potato tubers is too low to be nutritionally significant, only 0.5% on dry weight basis (Galliard, 1973). Fat analyses have established that at least 90% of the total acids were a saturated acid, palmitic and two polyunsaturated acids, linoleic and linolenic. Furthermore, it was found that the percentages of individual acids varied only slightly among varieties and that a significant inverse relationship existed between linoleic and linolenic acids (Galliard, 1973; Galliard and Matthew, 1973; Berkeley and Galliard, 1974 a,b).

Reeve, Hautala and Weaver (1969) and Mondy and Mattick (1969) found that the apical bud end had significantly higher total lipid and phospholipid fractions than the basal stem end of the tuber.

### 2.3.2 Composition, Distribution and Importance of Lipids in Potato, Variety Netted Gem

The lipid content of the peel was 2% that of the flesh 0.61% and the whole tuber 0.77% (dry weight basis). Linoleic and linolenic acids were more abundant in the flesh than in the peel, however, peel was rich in acids with a chain length greater than $C_{22}$ (Hadziyev and Steele, 1979).

Pun and Hadziyev (1978) found that phospholipids were 52% of the total lipids of raw tuber, followed by glycolipids (20%) and sterol lipids (16%). The major glycolipids were digalactosyl and monogalactosyl diglycerides, the latter being the most unsaturated tuber lipids. Sterols present were cholesterol, stigmasterol and B-sitosterol, which was close to 80% of the total sterols. Triglycerides and other neutral lipids, including free acids were only 12% of the total lipids.

Accumulated evidence indicates that off-flavors in dehydrated potato products are partly due to fatty acid oxidation, since fatty acids present in potatoes have a high degree of unsaturation (Galliard, 1973).

## 2.4 Starch

Starch is formed by a linear component called amylose and a branched one called amylopectin. Both linear and branched fractions are laid down in a radial fashion. Wherever possible, the linear chains and linear segments of the branched molecules associate laterally to give parallelwise bundles called miscelles (Schoch and Elder, 1955; Banks and Greenwood, 1959). Most of the miscelles are said to be composed of amylopectin, occasionally amylose (Badenhuizen, 1969).

### 2.4.1 Properties of the Starch

Granule size has significant influence on the properties of the starch (Keny, Goering and Watson, 1969), since large granules are seen to gelatinize first, whereas a few small ungelatinize granules often remain when the process is otherwise complete (Banks and Greenwood, 1959).

Granules are resistant to the action of amylases (Fuwa, Sugimoto and Tanaka, 1978).

The amylose films of the starch are highly birefringent, both wet and dry and in convergent polarized light they show a typically uniaxial, optically negative interference pattern (Rundle et al, 1944; Schoch and Maywald, 1956).

Starch has the capacity to complex with many liquid-molecules (Osman-Ismail and Solms, 1972).

2.4.2 Potato Starch Characteristics

Potato starch has relatively large oval granules with pronounced oyster shell-like striations around an eccentrically placed botanical center or hilum (Schoch, 1945). The granule appears to have successive layers or growth rings like an onion and these are particularly well defined in potato starch (Pigman and Horton, 1970). When viewed under polarizing microscope, the granule shows a strong interference cross centering through the hilum (Alsberg, 1938). In addition to this concentric organization, the granule appears to have some sort of radial structure (Sterling and Pangborn, 1960), and/or radial fibrillar clusters structure (Wetzstein and Sterling, 1977; Gallant, Degrois and Sterling, 1972).

In the radial arrangement the microfibrils of the grains are radially organized, often appearing to be individualized as miscelles (Sterling, 1965) against amorphous background (Teller, 1938; Sterling, 1971). Seven individual micelles are closely packed hexagonally in a microfibril and cemented together with amorphous portions of the fibril (Sterling, 1974, 1976). This fibrillar structure implies the presence of pores on the grain surface (Hadziyev and Steele, 1979).

Results have shown that amylose isolated from laboratory-prepared potato starches possesses a number-average degree of polymerization of the order of 4,000 glucose units, having two amylose fractions: (1) easily accessible material of relatively low degree of polymerization and (2) a fraction of higher degree of polymerization requiring disruption of the granule before isolation. Also, granules may contain fractions with properties intermediate between those of amylose and amylopectin (Cowie and Greenwood, 1957). Amylopectins contain up to 26

glucose residues/terminal group (Halsall et al, 1948).

The ratio amylose/amylopectin in potato starch is about 1:3 (Johnston, Urbas and Khanzada, 1968).

### 2.4.3 Properties of the Potato Starch

Potato starch granules display very special properties; they have exceptionally high density, high birefringence and high swelling power (Badehuizen, 1969; Banks and Muir, 1980). The presence of esterified phosphate (present in the form of glucose-6-phosphate concentrated in the amylopectin fraction) in potato starch is reported to be responsible for its high swelling power due to charged particles repelling each other (Otha et al, 1967a, b; Badenhuizen, 1969; Goering, 1978).

## 2.5 Vitamins in Potatoes

Of the six vitamins included in the recommended daily dietary allowances of the Food and Nutrition Board of the National Research Council, potatoes offer substantial amounts of four, Vitamin C (ascorbic acid), thiamin, niacin and riboflavin. Potatoes supply up to 90% of the U.S. recommended daily allowance (USRDA) of vitamin C and are considered a major source of this nutrient (Talburt and Smith, 1975). One hundred fifty grams of raw potatoes can supply as much as 12% of the USRDA for thiamin, up to 8% for riboflavin and folic acid, each as well as up to 20 and 30% for niacin and vitamin $B_6$, respectively (Augustin et al, 1978, 1979a, b; Voirol, 1974). Augustin (1979a, b) established the compositional range of vitamins in raw potato, finding that ascorbic acid varies from 10.7 to 18.3 mg per 100 g of raw potato, thiamine 0.08 to 0.13 mg, riboflavin 0.03 to 0.05 mg, niacin 1.32 to 2.03 mg, vitamin $B_6$ 0.18 to 0.31 mg and folic acid 5.9 to 17.3 mg.

A newly harvested "Netted Gem" potato containing some 30 mg of vitamin C per 100 g fresh weight typically dropped to 22 mg after the first month in storage, 15 mg after the second, 11 mg after the third and about 8 mg after the fifth month of storage, while additional storage had only a slight influence (Sweeney, Hepner and Libeck, 1969; Hadziyev and Steele, 1979; Augustin, 1975).

Ascorbic acid is low in the epidermis and absent in the cork tissue of potatoes (Smith, 1977). Since potatoes are low in fat, they contain very little of the fat-soluble vitamins (Talburt and Smith, 1975).

## 2.6 Mineral Constituents in Potato Tuber

The potato is known to be one of the richest food sources of minerals and probably the least expensive source of most of the other nutritional essentials of our diet. Although the raw potato contains about 1% mineral matter (Pike and Johnson, 1940), it is low in calcium content (Haydar et al, 1980).

True et al (1979), working with three major U.S. varieties found that the mineral content did not change appreciably during cooking. The approximate composition of minerals for raw potato are presented in Table 5.

### 2.6.1 Distribution of Mineral Constituents in the Tuber

The main differences in the distribution of several constituents in the potato tuber were as follows: the periderm, vascular material and outer cells of the cortex shown higher levels of calcium, parenchyma cells shown low concentration. Magnesium was present in higher levels in the vascular material and periderm. The concentration of potassium and phosphorous increased from stem to bud end; the pith area, as com-

TABLE 5. Mineral composition of raw potato tuber.

| Mineral | Composition per 150 g FWB[1] | USRDA[2] | % of USRDA supplied per 150 g |
|---|---|---|---|
| Calcium, g | 0.003 - 0.009 | 1.0 | 0.27 - 0.93 |
| Copper, mg | 0.150 - 0.320 | 2.0 | 7.50 - 15.98 |
| Iodine, mg | 0.014 - 0.025 | 0.15 | 9.22 - 16.40 |
| Iron, mg | 0.250 - 0.808 | 18.00 | 1.39 - 4.49 |
| Magnesium, g | 0.026 - 0.029 | 0.40 | 6.50 - 7.25 |
| Phosphorus, g | 0.047 - 0.069 | 1.0 | 4.70 - 6.90 |
| Zinc, mg | 0.256 - 0.500 | 15.0 | 1.71 - 3.33 |
| Aluminum, mg | 0.182 - 0.525 | | |
| Boron, mg | 0.106 - 0.167 | | |
| Manganese, mg | 0.141 - 0.244 | | |
| Molybdenum, mg | 0.018 - 0.039 | | |
| Potassium, g | 0.378 - 0.483 | | |
| Selenium, mg | 0.012 - 0.012 | | |
| Sodium, g | 0.005 - 0.012 | | |

[1]Fresh weight basis.

[2]United States Recommended Dietary Allowance.

pared with the remainder of the tuber had a lower content of manganese, zinc, copper and a higher content of chlorine (Johnston et al, 1968; Warren and Woodman, 1973).

Bretzloff (1971), working with "Netted Gem" found that the cortex tissue, which is more prone to sloughing than the pith had a higher calcium concentration. This would appear paradoxical if intrinsic calcium is really a major factor in cell adhesion. He also found that dividing the pith area into inner and outer regions revealed that calcium levels were nearly the same throughout the pith.

## 2.7 Pectins

Pectins are esterified galacturans or more commonly rhamnogalacturans in which the 1-4 linked D-galacturonan chains are interrupted at intervals by the insertions of -L rhamnopyranose residues. Other constituent sugars are attached in side-chains and include D-galactose, L-arabinose, D-xylose and occasionally trace amounts of other sugars (Stumpf and Conn, 1980; Rendleman, 1978b; Pigman and Wolfrom, 1945, 1946).

### 2.7.1 Distribution of Pectin in Plants

In the case of plant cells, carbohydrates of the cellular matrix are largely concentrated in the cell wall, a distinctive structure lying external to the plasmalemma. In general, the wall is composed predominantly of carbohydrate (mostly polysaccharides), though proteins, lipids and polyphenols are other important components (Wolfe, 1972; Gunning and Steer, 1975). The cell walls are formed by a highly ordered fibrillar component, consisting largely of cellulose, arranged in a less ordered or amorphous matrix of hemicelluloses, pectins, proteins and other substances (Cook and Stoddart, 1973).

### 2.7.2 Structure of Pectins

A "pectic triad" was proposed in order to explain the pectins structure; this is as follows: a protopectin (insoluble, native pectin), pectic acid (an ideal galacturan) and pectinic acid (its ideal methyl esther (Eskin et al, 1971; Cook and Stoddart, 1973).

### 2.7.3 Importance

The pectin substances play an important part in the cohesion and rigidity of cells. The so-called middle-lamella, i.e. the contacting surface of parenchymatous cells which binds together the cell wall, consists mainly of calcium and some magnesium salts of protopectin, as do the primary and secondary cell walls (Jaswall, 1969).

### 2.7.4 Pectins in Potato Tubers

Pectin substances in raw tuber exist in the form of protopectin, the water-insoluble parent substance, and pectin which is composed of water-soluble pectinic acid. Protopectin can be subdivided into two fractions. The first can be rendered water-soluble by treatments with sequestering agents, while the second is strongly bound by enmeshing with other filamentous macromolecules in the cell wall and is not soluble in the presence of sequestering agents (Bettelheim and Sterling, 1955b; Peters et al, 1954; Ooraikul et al, 1974; Hadziyev and Steele, 1979).

### 2.7.5 Distribution of Pectins in the Tuber

It has been shown that pectin substances are present in the primary cell wall. They are also found as a cementing material in the middle lamella between adjoining cells, where they are assumed to be made up principally of calcium salts of pectic and pectinic acids (Parsonius

and Sharp, 1939a, b; Gee, Reeve and McCready, 1959; Bettelheim and Sterling, 1955a, b; Haydar et al, 1980).

The water-soluble pectin is characterized by a relatively high methoxyl content, low calcium content and a high viscosity, contributing little to any cementing effect (Bartolome and Hoff, 1972a, b).

Pectic acid generally had a low degree of esterification (about 40%) and was present in higher concentrations in the cortex and periderm than in the interior tissues. The degree of cross-linking due to calcium and magnesium ions is lowest in the outer layers of the potato tuber and may be the reason that sloughing occurs in this area (Warren and Woodman, 1973; Reeve et al, 1969b).

### 2.7.6 Pectin Composition in Potato Tubers

Potato tubers contained an average of 1.2% (wet basis) of cell wall middle lamella material. This material was composed of 55% pectin substance, 7% hemicellulose, 28% cellulose and 10% protein. The isolated pectin substance contained 51% anhydrogalacturonic acid and 49% polysaccharide, while the hemicellulose contained 7% anhydrogalacturonic acid and 93% polysaccharide. The pectin polysaccharide were composed of 6% rhamnose, 0.6% fucose, 5.6% arabinose, 1.8% xylose, 5.8% mannose, 12% galactose and 56.7% glucose (Hoff and Castro, 1969).

### 2.7.7 Role of Pectins in Potato Tuber

The pectin substances have usually been assumed to fulfil a structural role in plant tissues, good adhesiveness causing coherent tissues, low pectin strength (poor adhesiveness) leading to weak tissues which readily disintegrate (Warren and Woodman, 1973; Freeman and Ritchie, 1940; Bettelheim and Sterling, 1955a, b).

## 2.8 Minor Constituents of Potatoes

### 2.8.1 Phenolic Compounds and Their Importance

It has been known that the darkening of potatoes involved an enzymatic oxidation reaction which produced the characteristic blue-gray-black color and this is especially prominent at the stem-end portion of a tuber (Cheng and Hanning, 1955). It has been suggested that the colorless precursor was produced by tyrosinase (Phenolase) action (Sweenwy, 1969; Muneta, 1981). Tyrosine, other free alpha amino acids and chlorogenic acid amongst others have been listed as substrates (Reeve, Hautala and Weaver, 1969b).

Chlorogenic acid was found to be the only tannin-like substance present in detectable amounts in extracts obtained from all three of the types of potato tissues, the skins, the discolored areas and the center flesh. In addition, L-tyrosine was found to be present in detectable amounts in the discolored areas and the center flesh of the tubers; Caffeic acid was present in the skins (Reeve et al, 1969b; Henderson, 1968; Cheng and Hanning, 1955). The normal tuber contained 62 mg of total phenols and 4.9 mg of O-dihydrophenols per 100 g (Johnson and Shaal, 1957).

### 2.8.2 Reducing Sugars

Glucose, fructose and sucrose are the major sugars in potatoes (Wilson et al, 1981) and a highly significant relationship exists between these sugars and the extent of non-enzymatic browning of processed potato products (Shwimmer et al, 1957). Potatoes stored at low temperatures accumulate sugars due to relatively low respiratory activity (Eskin et al, 1971; Laties, 1964) and this accumulation is accomplished

at the expense of starch (Paez and Hulton, 1970).

### 2.8.3 Acids in the Tuber

Acids in potatoes were found to be citric, malic and oxalic acids. Citric and malic acids were found in a proportion of about 20 to 1 (Curl and Nelson, 1940).

### 2.8.4 Others Constituents

It is pertinent here to review other minor constituents of potatoes, to provide a more complete record of tuber constituents. Amongst them Soladine and Solanin have been demonstrated to be present mainly in buds end of mature tubers. These compounds are present in "Netted Gem", increasing the problems of bitter flavor and toxicity (Reeve et al, 1969b; Maga, 1980).

Other compounds such as calcium oxalate crystals are also found in cortex and pith area of the tubers as well as crystals of basic calcium phosphate found in the cortex tissue of potatoes (Reeve et al, 1969b).

## 2.9 Histology of the Tuber

Reeve et al (1969a) developed the sequential origins of tuber tissues as shown in Figure 5 and may be compared with the scheme presented in Figure 6. Figure 5 shows three routes of limited contribution (broken lines) for development of (i) periderm, (ii) primary phloem and primary xylem and (iii) storage perenchyma of the perimedullary zone.

The different tuber zones, tissues and synonymous terms used in describing mature tuber anatomy are compared with some common misapplications (Table 6) that appear in scientific literature.

Figure 5. Diagram of tissue organs and the tissues comprising zones of potato tuber. Broken lines indicate limited pathways of differentiation.

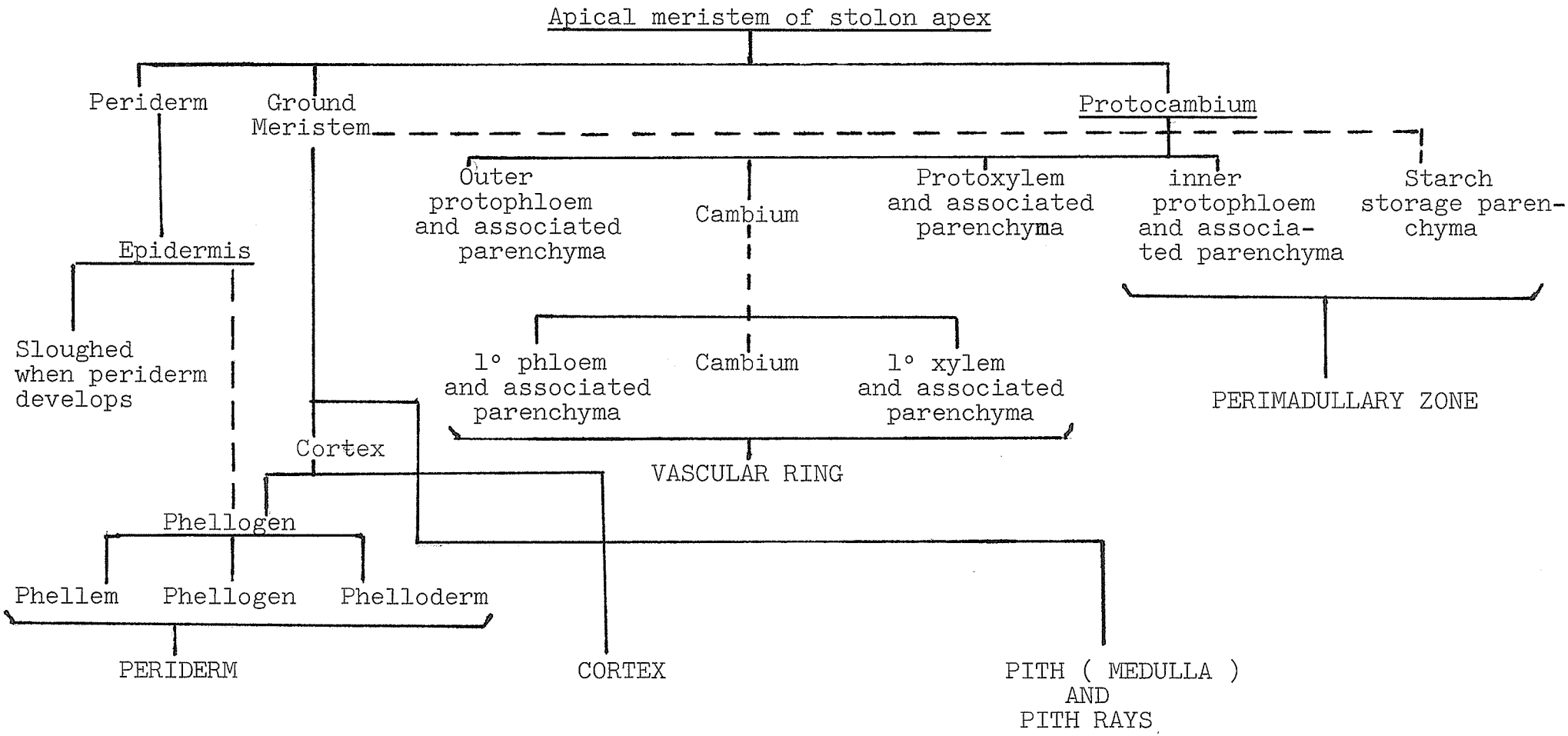

Apical meristem of stolon apex
Periderm
Ground Meristem
Protocambium
Outer protophloem and associated parenchyma
Cambium
Protoxylem and associated parenchyma
inner protophloem and associated parenchyma
Starch storage parenchyma
Epidermis
Sloughed when periderm develops
1° phloem and associated parenchyma
Cambium
1° xylem and associated parenchyma
PERIMADULLARY ZONE
Cortex
VASCULAR RING
Phellogen
Phellem
Phellogen
Phelloderm
PERIDERM
CORTEX
PITH ( MEDULLA ) AND PITH RAYS

Figure 6. Internal structure of potatoes, tuber cross section.

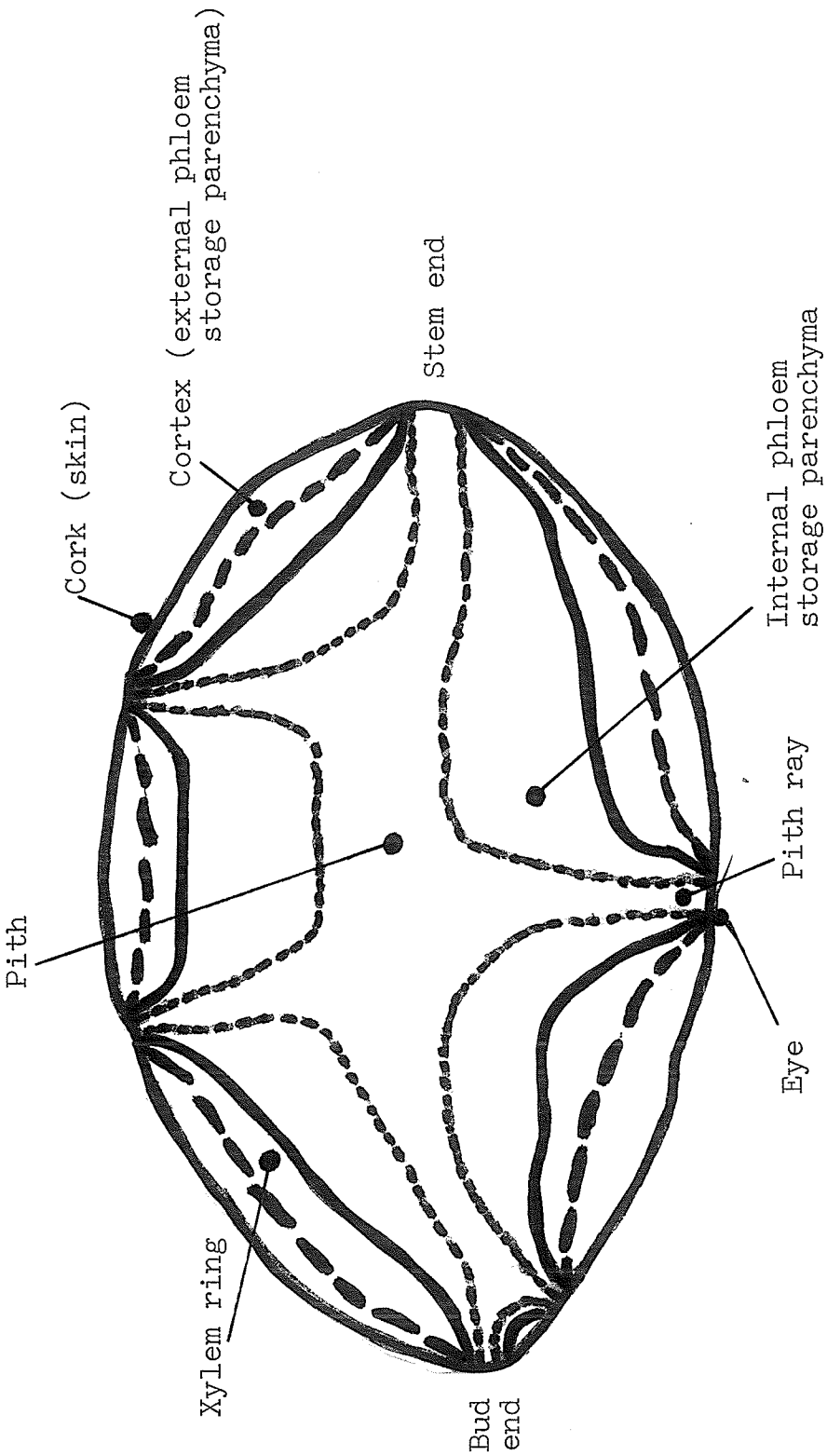

Cork (skin)
Cortex (external phloem storage parenchyma)
Stem end
Internal phloem storage parenchyma
Pith
Pith ray
Eye
Xylem ring
Bud end

TABLE 6. Synonymity of terms applied to mature potato tuber tissues compared with common misapplications.

| Zone* | Tissues* | Synonyms* | Common mis/applications* |
|---|---|---|---|
| Periderm | Phellem | Skin | Epidermis, phelloderm |
| | Phellogen | Cork, Skin | Phellogen, phelloderm |
| | Phelloderm | Cork cambium | Cambium, phellem, phelloderm |
| | | Cells produced inwardly by phellogen | |
| Cortex | Cortical parenchyma | Outer storage tissue | Skin, vascular zone |
| Vascular "ring" | Outer protophloem and associated parenchyma, protoxylem and associated parenchyma, some inner protophloem and associated parenchyma, and other primary phloem and xylem tissues | Primary vascular bundles, xylem "ring" | Cambium, cortex |
| Perimedullary "zone" | Inner phloem and associated phloem parenchyma | Markkrone, storage parenchyma | Vascular "ring" |
| | Medullary rays | Pith rays, eye branches | |
| Pith | Pith parenchyma | Medulla, Mark, water core | |

*Reeve et al (1969a)

## 2.10 Discoloration Reactions

The most obvious manifestation of deterioration in peeled and processed potatoes is browning, which may be accompanied by the impairment of flavor, texture and nutritive value (Smith, 1958). Four mechanisms in browning were reviewed by Eskin et al, 1971 and are presented in Table 7.

TABLE 7. Mechanisms of browning reactions.

| Mechanism | Requires oxygen | Requires amino group in initial reaction | pH Optimum |
|---|---|---|---|
| Maillard | - | + | alkaline |
| Caramelization | - | - | alkaline, acid |
| Ascorbic acid oxidation | + | - | slightly acid |
| Phenolase | + | - | slightly acid |

Heisler et al (1962) observed that stem end blackening was associated with low potassium content. On the other hand, non-enzymatic browning is due to interaction between reducing sugars and amino acids (Maillard), but other formation of soluble brown colors are due to organic acids, metals and phosphate ion (Schwinmer et al, 1957; Ross, 1948; Hughes and Swain, 1962a, b, c).

Rendleman (1978a) found that chlorogenic acid plays an important role in the blackening of potatoes due to the oxidation of complexes between iron and chlorogenic acid.

Reducing substances such as ascorbic acid, prevent the enzymatic browning by reducing the quinones formed in diphenol oxidation (Simon

et al, 1955; Ross, 1948).

Sweeney (1969) found that varieties highest in free tyrosine content had the greatest enzymic browning when exposed to air.

### 2.10.1 Browning Inhibition Using Sodium Bisulfite

Tyrosine is initially oxidized by polyphenol oxidase (phenolase) to a reddish-orange "dopachrome" pigment. Further oxidation and polymerization reactions result in changes from brown to black melanin pigments (Muneta, 1981). The most common commercial method of inhibiting enzymatic blackening of peeled potatoes is by the use of sodium bisulfite or a combination of bisulfite and citric acid. Bisulfite alone is effective as an inhibitor of 3,4-dihydroxyphenyl alanine oxidation, the first product of tyrosine oxidation. Bisulfite may also reduce the quinones formed in the oxidation process, or it may form colorless addition products with the quinones (Muneta and Wang, 1977; Green, 1976). Sulfite applied gave somewhat better protection against non-enzymatic browning (Hendel et al, 1955) and marked protection was achieved at low moisture (Hanning and Hunsader, 1957).

Peeled potatoes of medium size, dipped in a 1% solution of metabisulfite for 2 min had an $SO_2$ content of 50 ppm; the uptake increased both with the concentration of the solution and the time of soaking. It was also influenced by the physical condition of the cut surface, a rough surface absorbing more sulphite than a smooth one (Furlong, 1961).

### 2.10.2 Browning Inhibition by Other Methods

Mapson and Tomalin (1961) inactivated phenolase activity using heat, infrared radiation and radio-frequency power, but these methods have a major disadvantage since production of off-flavors were present

during subsequent storage. Simon et al (1955) reported that calcium chloride was effective against non-enzymatic browning and in conjunction with sulfite was more effective than either of the two used individually. They suggested that the inhibitory effect was due to the chelation of calcium with amino acids.

Addition of adenosine triphosphate (ATP) to potatoes inhibits the browning produced by enzymic oxidation of phenols (Makower, 1964a), the mechanism by which ATP prevents browning is not known. Makower (1964b) also found that diphosphopyridine nucleotide inhibited enzymic browning. Other methods were reviewed by Eskin et al (1971).

## 2.11 Potato Peeling

Peeling is one of the most important steps in processing of potatoes. Effectiveness and efficiency of peeling to a great extent determines yield of finished product, labor costs of subsequent inspections, amount of waste, and the cost of waste disposal.

Under ideal conditions, peeling would require removal of only a very thin outer layer of the potato; it would leave no peel, eyes or other material to be removed subsequently by hand trimming and, above all, it would leave the newly exposed surface of the potato unchanged by contact with heat or chemicals. Unfortunately, in actual commercial operations, ideal conditions are never achieved (Talburt and Smith, 1975).

Commercially, potatoes are peeled by three processes: 1) abrasive, 2) steam and 3) caustic. Caustic peeling is the most widely used (Orr et al, 1980).

### 2.11.1 Abrasion Peeling

Abrasion peeling removes peel by rasping or rubbing the potatoes against a carborundum surface, while spraying with water. However, in the case of russeted varieties and those with deep eyes, abrasion usually involves excessive peeling loss and considerable trimming to produce an acceptable product (Feustel and Harrington, 1957).

### 2.11.2 Steam Peeling

Steam peeling conditions usually used are live steam at 690 kPa for 25 sec (Orr et al, 1980). When steam peeling is used a cooked surface is formed and it is very susceptible to spoilage and discoloration (Feustel and Harrington, 1957).

### 2.11.3 Caustic Peeling

Basically the caustic peeling process consists in immersing the potatoes in a hot (80 to 102°C) concentrated (15 to 25 wt%) solution of sodium hydroxide (NaOH). Typical residence times range from 3 to 8 minutes. Caustic peeling is a mass transfer limited process until the outer peel has been penetrated. At this point it becomes a chemical reaction rate controlled process (McFarland and Thomson, 1972).

Powers et al (1977) reported that peeling losses in Russet Burbank potatoes, using lye, appear to be in the 8 to over 17% range.

Hot lye solution, penetrates the periderm and breaks down the inter cellular pectic substances, swells and gelatinizes the starch granules and reacts with chlorogenic acid forming a yellowing color (Orr et al, 1980; McFarland and Thomson, 1972; Reeve, 1976). Ideally, lye penetration only as far as the phelloderm beneath the phellogen, or cork cambium, should suffice. Such penetration perhaps would average about

0.3 mm in depth for the Russet Burbank variety (Reeve, 1976).

### 2.11.4 Morphological Characteristics of Potato Peel Removed by Various Techniques

The morphological characteristics of potato peel removed by various techniques were reported by Orr et al (1980) and are presented in Table 8.

## 2.12 Cooking Methods Applied in Potatoes

Methods applied for cooking potatoes are: boiling, water, steam, microwave and baking.

Boiling water has the disadvantage that intercellular material will diffuse reducing the nutritive value; steam and microwave are believed to prevent diffusion of the intercellular material improving the maintenance of the original value of the potato (Talburt and Smith, 1975).

### 2.12.1 Engineering Factors Involved in Boiling Water and Steam Cooking

When these processes are applied, heat transfer is the dominant phenomenon involved. When the rate of heat transfer is dependent on time it is described as unsteady-state or transient heat transfer (Charm, 1963). A key factor involved in the evaluation of unsteady-state heat transfer is the relative importance of internal and external resistance to heat transfer and a dimensionless number called Biot is used (Heldman and Singh, 1981).

When potatoes are cooked, both the internal resistance and convective heat-transfer coefficient at the surface must be accounted for in determining the temperature distribution during heating and time necessary for cooking. In this case, the Biot number falls between 0.1 and 40 (McCabe and Smith, 1967; Earle, 1966; Merkel, 1974).

TABLE 8. Morphological characteristics of potato peel removed by various techniques.

| Characteristics | Hand peeled | Abrasive | Steam | Caustic |
|---|---|---|---|---|
| Starch granules | + + + +[1] | + + + | + + | + |
| Intactness of intercellular junctions | present | present | present to partial | partial to complete destruction and disorganization |
| Cellular arrangement | definite pattern for Pe[2] and P[3] | definite pattern for Pe | slight change of Pe; some cellular collapse | complete change of Pe; much cellular collapse |
| Overall damage to peel | none | slight | slight (intercellular and intracellular tearing) | extensive |
| Shape of peridermal cells | normal | normal | slightly expanded with cracks | elongated collapsed cells with amorphous starch granules |

[1] + = Amount of starch granules with increasing trend in sign.

[2] Pe = Peridermal cells.

[3] P = Parenchymal cells.

### 2.12.2 Microwave Heating

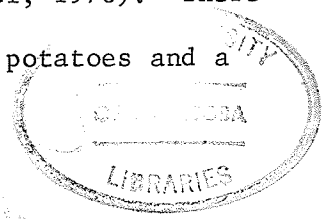
Microwaves are electromagnetic waves of very short wavelengths (1 m to 0.1 mm) working at two frequencies (2,450 MHz and 915 MHz) (Kalafat and Kroger, 1973).

Since all materials are made up of atoms and molecules and these molecules can be ionized or electrically neutral, then when an electrical field is applied to the polar molecules in foods these molecules tend to behave like miniature magnets and attempt to line up with the field. In an attempt to line up in the electrical field such molecules oscillate rapidly as the electrical field created by microwaves keeps changing millions of times per second. Friction between the molecules as they rotate in the field causes the production of heat. Molecules and ions alike rotate in the microwave field causing heat by the energy of their collisions. As a result, foods high in water content are readily heated by microwave energy (Copson, 1975).

## 2.13 Changes in the Tuber During Cooking

It appears that two fundamental changes are necessary for converting raw potato into cooked tissue: (1) gelatinization of the starch and (2) a marked decrease in the cell adhesion of the tissue (Parsonius and Sharp, 1939b; Pyke and Johnson, 1940; Hoff, 1972).

In general, cooking has major effects on the pectic materials of the potato. The most obvious is a solubilization effect causing separation of the cells (Freeman and Ritchie, 1940; Parsonius and Sharp, 1939a). Pectic materials become more soluble as a result of de-polymerization, breakage of hydrogen bonds and higher temperature of solution (Bettelheim and Sterling, 1955a; Ooraikul et al, 1974; Moledine et al, 1978). There is also a decrease in the calcium content of the cooked potatoes and a



decrease in intrinsic viscosity (Reeve, 1972; Bettelheim and Sterling, 1955b; Pyke and Johnson, 1940). Much of the solubilized pectic substance diffuses into the cooking medium. A constant effect, is a lower methoxyl content in the cooked potatoes, this may be due to the activity of enzymes in the first few minutes of heating, perhaps to a direct heat-induced de-esterification or to removal of fractions of higher ester content by the cooking water (Bettelheim and Sterling, 1955a).

Upon cooking of potatoes all the starch granules are rapidly gelatinized, large granules gelatinizing more easily than the small ones (Alsberg, 1938; Cheng and Hadziyev, 1980). Microscopic examination of cooked potato tissue showed that the large swollen granules completely filled the cells and also that almost all of the cell walls remained intact after cooking, although the tissue cells became distended by the swollen gel and tend to separate, particularly in mealy tubers (Parsonius and Sharp, 1938a), due to the degradation of pectic substances between and in the cell wall (Jericevic and Ooraikul, 1977; Ooraikul et al, 1974).

Swelling of the gelatinized starch is the major factor tending to cause "rounding-off" of cells and thus cell separation (Bettelheim and Sterling, 1955b). However, Bretzloff (1970) did not support this idea.

In normal cooking, potato tissue permeability was increased most sharply at a temperature slightly above 60°C (140°F). Holding potato tissue at 48°C (118.4°F) for 27 hours destroyed the semi-permeability properties of the potato tissue (Parsonious and Sharp, 1938b).

### 2.13.1 Pre-Cooking of Potatoes and its Effect

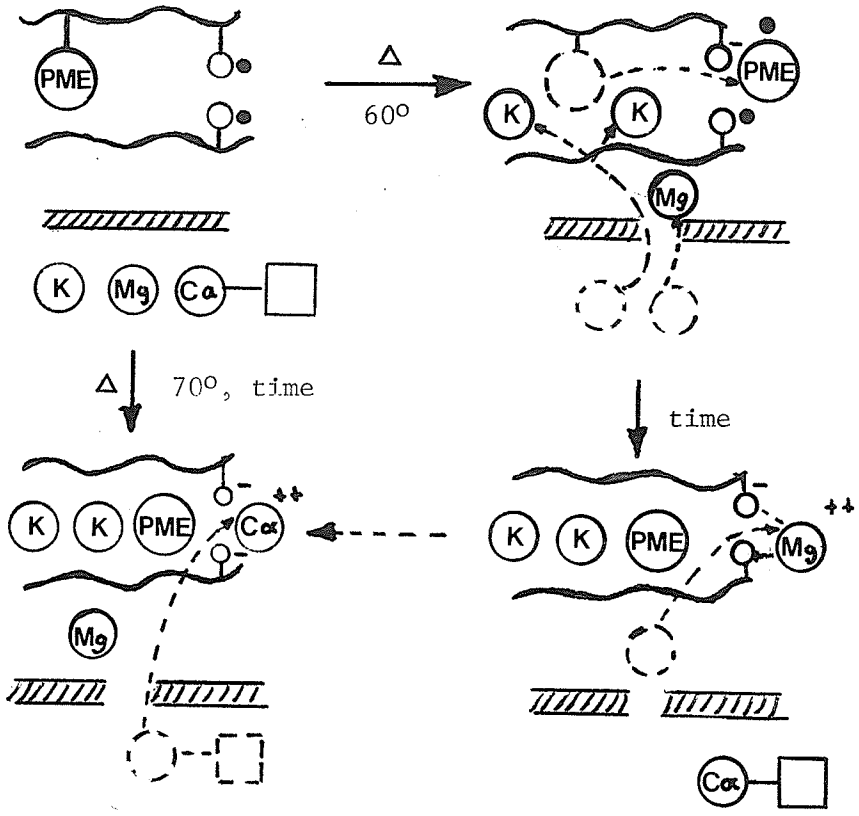
When potato tissue is held for some time at moderate temperatures

(50 to 80°C) and subsequently boiled, it attains a firmer texture than potatoes that are boiled without pre-treatment. Porter et al. (1959) believed that the effect is due to starch retrogradation which results in decreased swelling power of the starch granules. Linehan and Hughes (1969) and later Suzuki and Hizukuri (1979) postulated migration of amylose from the starch granules to the middle lamella. Infiltration by amylose into the cell wall fabric was believed to result in reinforcement of mechanical strength of the cell wall and middle lamella. Bartolome and Hoff (1972b) believed that when the cell membrane is disrupted by heating above 50°C, solutes from the cytoplasm and probably also from vacuoles diffuse into intercellular space and activate the enzyme pectin methylesterase. Given sufficient time, the enzyme interacts with accessible methyl ester groups on the polyuronide chains to produce additional free carboxyl groups. Diffusing divalent ions, either magnesium or calcium, finally establish cross-linkages between chains and render the tissue more resistant to further thermal degradation (Figure 7). Since a major proportion of the total calcium of potato tubers is bound in the starch (Hadziyev and Steele, 1979), it is likely that the relative proportions of these metals interacting with uronide depend on the state of the starch granules.

### 2.13.2 Texture of the Tubers After Cooking

Several broad indications can be made concerning potato texture (Bettelheim and Sterling, 1955b): a) the starch content is the principal determining factor in potato texture, its role is to bring about a slight distension of the cell walls during gelatinization, inducing a tendency in the cells to separate from each other; b) cell separation is the

Figure 7. Proposed mechanism to account for the firming effect (Bartolome and Hoff, 1972b).




polyuronide chain
ester group
free carboxyl
methanol
cell membrane
ruptured membrane

K potassium ion
Mg magnesium
Cα calcium ion
starch grain
gelatinized starch

principal physical attribute of a mealy potato and the degree of cell separation is a measure of the degree of mealiness; c) certain characteristics of the pectic materials play a role in the development of a textural quality. Mainly, their effect is opposed to that of the starch. Where the starch tends to cause cell rounding and separation, these characteristics of the pectic materials counterpose an adhesive force tending to prevent cell separation.

Studies of potatoes cooked to "doneness" (Nonaka, 1980) have positively related potato texture to specific gravity of the tubers, starch content of the tubers, chemical properties of the starch, objectively measured textural characteristics, cell wall material, cell adhesion or cohesion, intercellular cement, mineral content of the tuber and interaction of phytic acid with polyuramide (Wager, 1963). Hester and Bennet (1956) found that the degree of sloughing was greater for whole potato than for potato slices.

## 2.14 Changes in the Nutritional Composition During Cooking

The influence of cooking on retention of vitamin C is a subject of many conflicting reports. Leichsenring et al (1957) found as much as a 100% increase in ascorbic acid (vitamin C) as a result of boiling and assumed that there was a release of a bound form of the acid. Somogyi (1975) found losses of 27% for potatoes cooked under pressure and 16% for those boiled in water.

Jaswal (1973) found that the extent of damage to total, bound and free amino acids was significantly lower during cooking. Huang et al (1981) found that proteinase inhibitors were partially inactivated during cooking and Carboxypeptidase inhibitor was stable during cooking.

Cooking caused a 12.9% loss of the total lipids, with the greatest lost in neutral and phospholipid fractions, and the least in galactolipids (Pun and Hadziyev, 1978). The fatty acid composition of total and individual lipids in cooked potatoes did not change appreciably from raw potatoes. Nawar (1969) theorized that these could be formed by the heating process. The loss of lipids was highest in potatoes cooked in a microwave oven, least in boiled tubers and intermediate in steamed potatoes. Mondy and Mueller (1977) explained this as follows: during boiling, heat penetrates the potato gradually from the external to the internal tissue. The pattern of heating causes the starch granules in the outer tissue to gelatinize and form a barrier which may inhibit the escape of components from within the center of the tuber. During microwave cooking, heat is generated throughout the entire tuber within a relatively short period of time. Water within the cell is converted rapidly to steam and the rapidly expanding and escaping steam ruptures the cells thus forcing free lipid material from the inner tissues.

True et al (1979) obtained data in which the cooking of potatoes had a negligible effect on the mineral content. Cooking potatoes resulted in a decrease on phenolic compounds (Mondy et al, 1971).

## 2.15 Flavoring Constituents of Cooked Potatoes

The term "flavor" has been used to denote a whole complex of sensations including not only taste, but aroma, mouth feel, texture and even appearance (Mondy et al, 1971).

### 2.15.1 Non-Volatile Constituents

Phenolic compounds, ascorbic acid and glycoalkaloids have been considered significant in potato flavor development, although the

majority of these compounds have been associated with bitter off-flavor (Mondy et al, 1971; Hadziyev and Steele, 1979).

### 2.15.2 Volatile Constituents

These compounds are the essence of potato flavor; among them the most notorious are: pyrazines, sulfur containing compounds, carbonyls and thiazoles (Sapers et al, 1971; Buttery et al, 1973; Guadagni et al, 1971; Marce and Hadziyev, 1977; Koehler et al, 1969; Self et al, 1963; Coleman and Chi-Tang Ho, 1980; Seaman et al, 1952).

## 2.16 Principles of Dehydration

There are two fundamental processes which occur simultaneously in the dehydration process (Williams-Gardner, 1971; Treybal, 1973; Slade, 1967): 1) transfer of heat to raise the wet solids temperature and to evaporate the moisture (heat transfer) and 2) transfer of mass in the form of internal moisture to the surface of the solid and its subsequent evaporation (mass transfer). Heat transfer in the drying operation occurs through three basic mechanisms: convection, conduction or radiation. In some cases, it occurs as a result of a combination of any of these efforts.

Industrial driers differ in type and design and are dependent on the principal method of heat transfer employed (Van Arsdel et al, 1973a). Regardless of the type that is utilized, heat is required to be transferred to the surface of the solid and thence to its interior (Treybal, 1973).

Mass transfer in the drying of a wet solid depends on two mechanisms: 1) movement of moisture internally within the solid which is a function of the internal physical nature of the solid and its moisture

content and 2) movement of water vapour from the material surface which is a result of external conditions such as air temperature, humidity, air flow rate and area of exposed surface (Heldman and Singh, 1981; Williams-Gardner, 1971).

When foods are dehydrated, they do not lose water at a constant rate all the way down to dryness. On the contrary, as drying progresses, the rate of water removal drops off under any fixed set of conditions. The curve illustrated in Figure 8 is a plot of moisture content at any time in a given material undergoing drying. Utilizing the slopes of the curve from Figure 8 permits one to develop a theoretical drying curve (Figure 9) (McCabe and Smith, 1967; Charm, 1963; Van Arsdel et al, 1973a; Heldman and Singh, 1981; Treybal, 1973).

## 2.17 Potato Granule Production

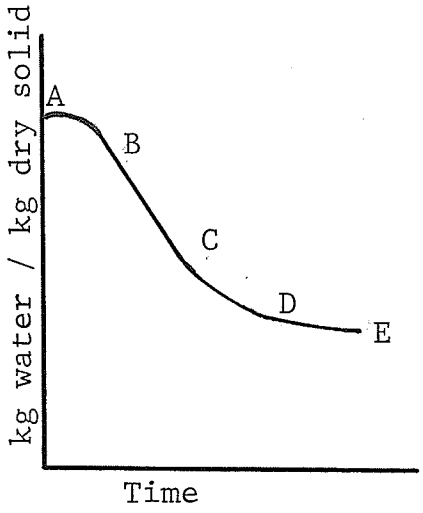
### 2.17.1 Add-Back Process

The add-back process technology has been widely reported (Olson et al, 1953, 1959; Neel et al, 1954; Olson and Harrington, 1955a, b; Cooley et al, 1954; Noyes, 1969; Van Arsdel, 1973b; Talburt and Smith, 1975; Moledina et al, 1978). Its outline is depicted in Figure 10.

An essential pre-preparation of potato for the add-back process is precooked at 70°C for 20 minutes and to cool in cold water prior to steam cooking. This serves to render the cell wall less degradable by cooking, thereby enabling the potato cells to withstand the forces generated by compression, mixing and rubbing during the continuous mash-mixing step (Potter et al, 1959). In the mash-mixer about two parts by weight of dry granules are recycled to be mixed with freshly cooked tissue. After mash-mixing the product enters the conditioner where it

Figure 8. Constant conditions of drying.

Figure 9. Drying curve at constant conditions.




A-B Equilibrium period
B-C Constant drying rate
C-E Falling drying rate

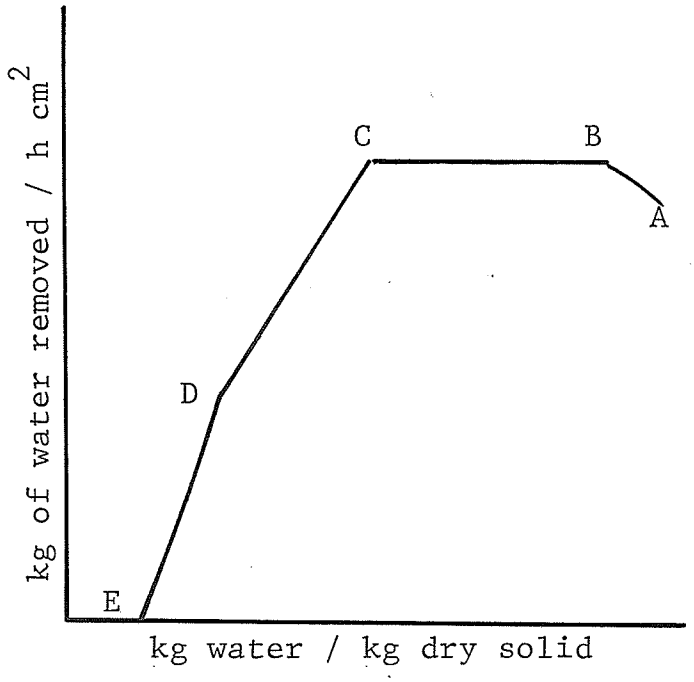
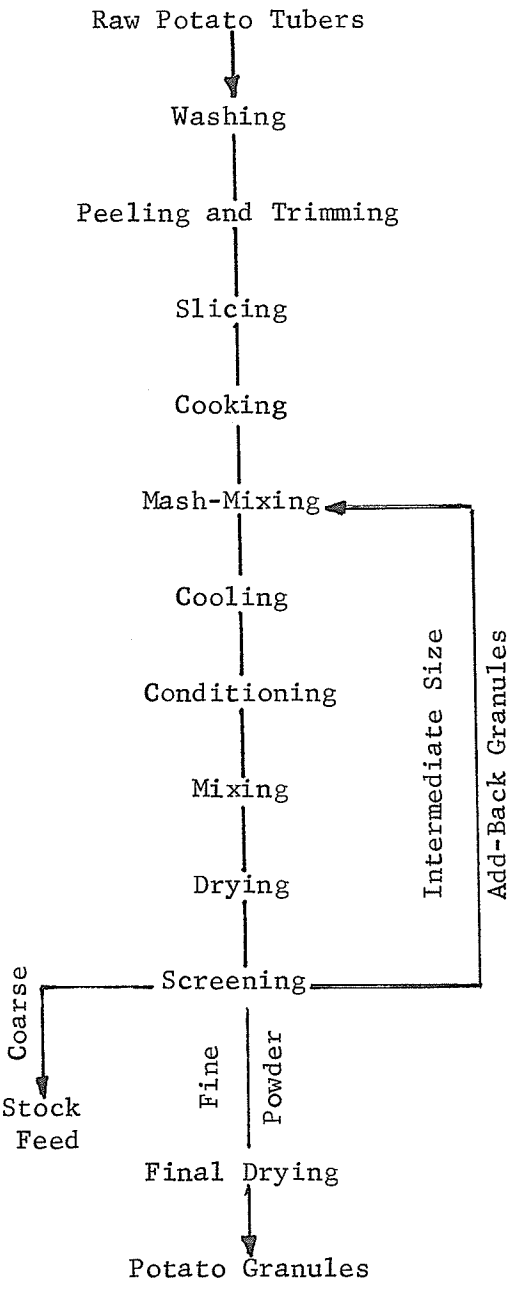


Figure 10. Schematic outline of the add-back process for manufacture of potato granules.


Raw Potato Tubers
Washing
Peeling and Trimming
Slicing
Cooking
Mash-Mixing
Cooling
Conditioning
Mixing
Drying
Screening
Intermediate Size
Add-Back Granules
Coarse
Stock Feed
Fine
Powder
Final Drying
Potato Granules

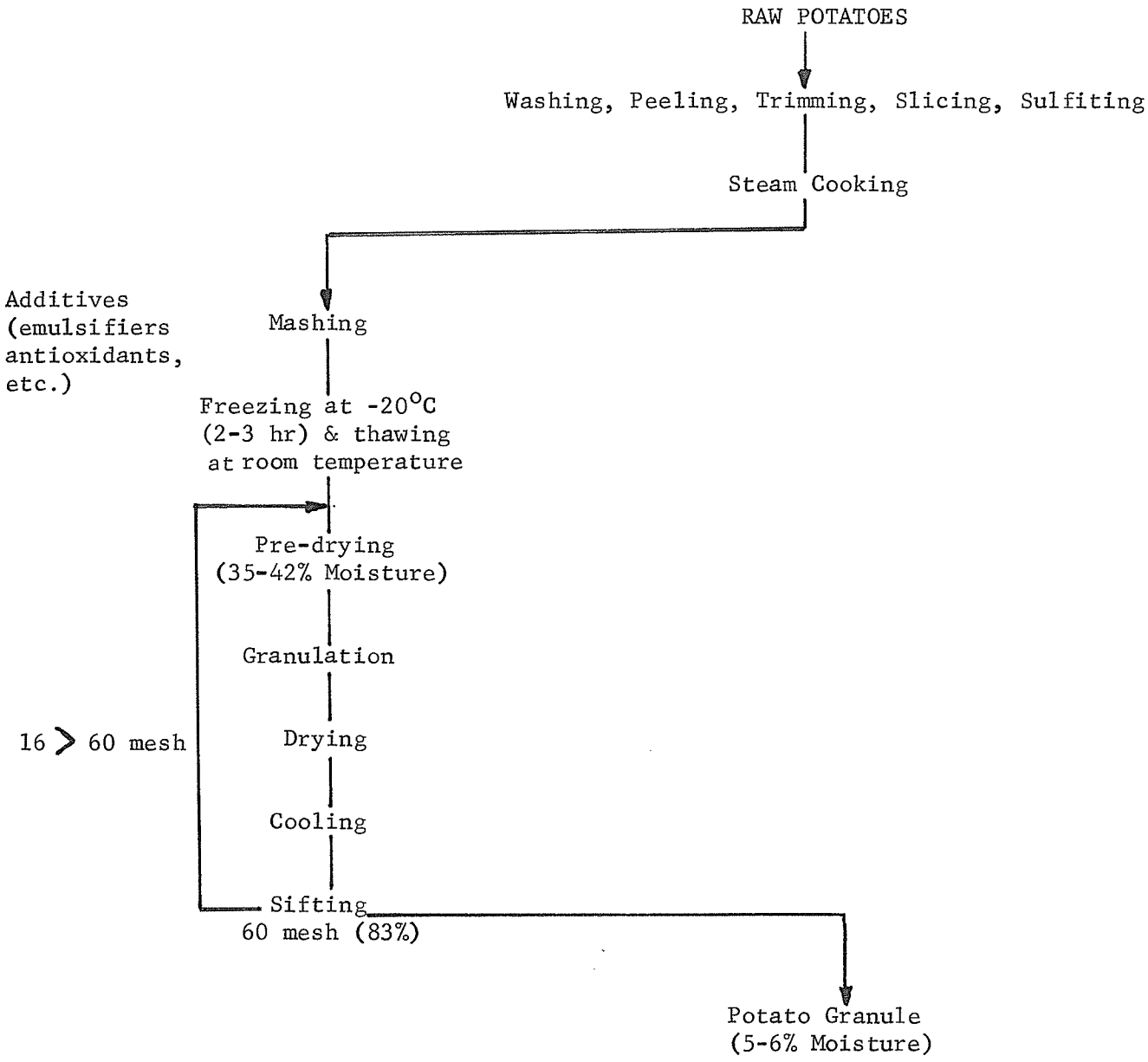
is tumbled along a tunnel through which warm air at about 45°C is blown. The conditioning took about 45 minutes during which starch gel partially retrograded and the moisture content was reduced from 35% to about 31%. The product at this stage was still largely in the form of single cells and cell aggregates. The product was dried in an air lift dryer, where the moisture was reduced to about 15%, then in a fluid bed dryer and a cooler where the moisture was lowered to about 8%. The dried product was then passed through a series of sieves where the particles bigger than mesh 10, consisting mainly of unbroken tissue or large aggregates were discarded. The intermediate sized particles (between 10 and 80 mesh) were recycled together with some initial product to the mash-mixer. The final product (smaller than 80 mesh) consisted mainly of single cells and aggregates of a few cells. Most granules were round and had fairly smooth surfaces, with cell walls forming ridges and folds due to dehydration.

### 2.17.2 Freeze-Thaw Process

A freeze-thaw process for the production of potato granules minimizes some of the major problems (precooking, recycling, etc.) of the add-back process (Harrington, Olson and McCready, 1951; Hadziyev and Steele, 1979).

The flow chart of the freeze-thaw process is portrayed in Figure 11 (Ooraikul and Hadziyev, 1974). The potatoes were prepared by peeling, slicing, washing and soaking in 0.5% $NaHSO_3$ solution for 5 minutes, after which they were steam-cooked for 35 minutes, mashed and frozen in an air-blast freezer. The frozen mashed potatoes were thawed at room temperature to about 0 to 5°C before drying, then were pre-dried,

Figure 11. Flow chart for straight through freeze-thaw potato granule process.


RAW POTATOES
Washing, Peeling, Trimming, Slicing, Sulfiting
Steam Cooking
Additives (emulsifiers antioxidants, etc.)
Mashing
Freezing at -20°C (2-3 hr) & thawing at room temperature
Pre-drying (35-42% Moisture)
Granulation
16 > 60 mesh
Drying
Cooling
Sifting 60 mesh (83%)
Potato Granule (5-6% Moisture)

granulated and dried (Ooraikul, 1978).

Pre-drying and granulation are the two most crucial steps in the freeze-thaw process. For the potato tissues to be subdivided to fine granules successfully without excessive damage, the moisture content of the mash must first be reduced to about 45 to 35% (Olson and Harrington, 1955).

During freezing, the intracellular water was drawn out osmotically. Thus, ice crystals were formed both outside and inside the cells, leaving most of them visibly shrunken. The starch gel also retrograded more fully under these conditions (Jericevic and Ooraikul, 1977).

Particles retained on 18 mesh consisted mainly of unmashable tissue and were rejected during this process. The intermediate size granules (18 > 60) normally consisted of aggregates comprising several cells which failed to separate during granulation, or which might have been reformed after granulation. Product passing through mesh 60 was acceptable (Moledine et al, 1978).

# 3. MATERIALS AND METHODS

Netted Gem potatoes (Russet Burbank), grown by the Plant Science Department, University of Manitoba in 1980, were used in this study. Approximately 150 Kg of potatoes selected for a specific gravity within a range of 1.093 to 1.098 were used between September and April 1981. The Netted Gem variety was selected because it is widely used by the industry and has become the standard by which new cultivars are evaluated.

## 3.1 Experimental Design

The experiments conducted were designed with the following objectives:

1. To conduct preliminary studies on the original material, i.e. finding out the proximal analysis of the potatoes, specific gravity and the microstructure of raw potatoes.

2. To study changes in composition and microstructure of potatoes during different cooking methods.

3. To compare the two techniques applied for the production of granules and their effects in the composition and microstructure of potatoes.

4. To conduct the final evaluation of the granules produced by the two processes utilizing the different methods of cooking.

## 3.2 Preparation of Potatoes Before Analysis

The potatoes were stored in a cabinet with a temperature of 10°C

and a relative humidity of 75%. Specific gravity of each potato was determined using the air-water method and calculated by the following formula:

$$\text{Sp. Gr.} = \frac{\text{weight in air}}{\text{weight in air - weight in water}}$$

## 3.3 Potato Analysis

### 3.3.1 Moisture Content

Most samples were held at 105°C in a Blue M forced draft oven for 12 hours, cooled in a dessicator and weighed. The samples used to assess the drying pattern for processes used in this study were held at 105°C for 3 hours, cooled and weighed (AOAC, 1975). All calculations for moisture content are on dry weight basis.

### 3.3.2 Nitrogen Content

Total nitrogen was determined by micro-kjeldahl method as described in A.O.A.C. (1975).

### 3.3.3 Vitamin C Determination

Ascorbic acid was determined by the indophenol titration method as described in A.O.A.C. (1975).

### 3.3.4 Fat Determination

Fat content was analyzed by Soxhlet procedure as described in A.O.A.C. (1975).

## 3.4 Preparation of Potatoes for Scanning Electron Microscopy

The following methods and equipment were used. Raw potato tubers were cut into halves along the minor axis. The parallel cuts obtained were then further sliced with a razor blade radially towards the center

of the pith. Sections of about 3 $mm^3$ corresponding to periderm and cortex, outer medulla and pith were then cut. These were rinsed in distilled water and fixed for 12 hours at 4°C in 3% glutaldehyde in 0.1 M K-phosphate buffer; pH 6.86. After rinsing in buffer, the fixed sections were treated overnight at 4°C in 2% Osmium tetroxide in the same buffer. The sections were once again rinsed in buffer and then dehydrated by successive treatments at 30 minute intervals at room temperature in 50, 70 and 90% and then twice in absolute ethanol. The sections then were frozen by immersion in liquid nitrogen and then transferred into a Virtis 10-146 MP-BA freeze-drier. After drying the samples then were attached in the scanning electron microscopy stand or base using silver paste and spattering with gold using a Balzer Sputter Coater and then the pictures were taken using a Cambridge S.E.M. and a ISI Scanning Electron Microscope.

With the previously mentioned preparation, certain unfavorable defects were detected in the samples, therefore a more simple preparation procedure was used for subsequent studies. The raw potato was immersed in liquid nitrogen and then freeze-dried using a Virtis 10-146 MP-BA mobile freezer. The samples were then prepared for microscopy using silver paste and gold as described above.

### 3.5 Ash Determination

Potato samples (raw, mashed granules) weighing 2 to 10 g were dry ashed in an ashing crucible. After initial charring on a hot plate, samples were placed in an oven at 550°C for 2 hours. After cooling, then wetting with a few drops of concentrated $HNO_3$, the dishes were returned to the oven for an additional 1 hour. The residues were then cooled on a dessicator and weighed. The mineral composition of the ashes was

determined after solubilization in 6N HCl under gentle boiling for 30 minutes. The solutions were made up to volume and a diluted aliquots were analyzed in the presence of lanthanum chloride for calcium and magnesium using an Atomic Absorption Spectrophotometer, Shandon Sonther Analytical A3000 (Haydar et al, 1980).

### 3.6 Total Starch Determination in Potatoes

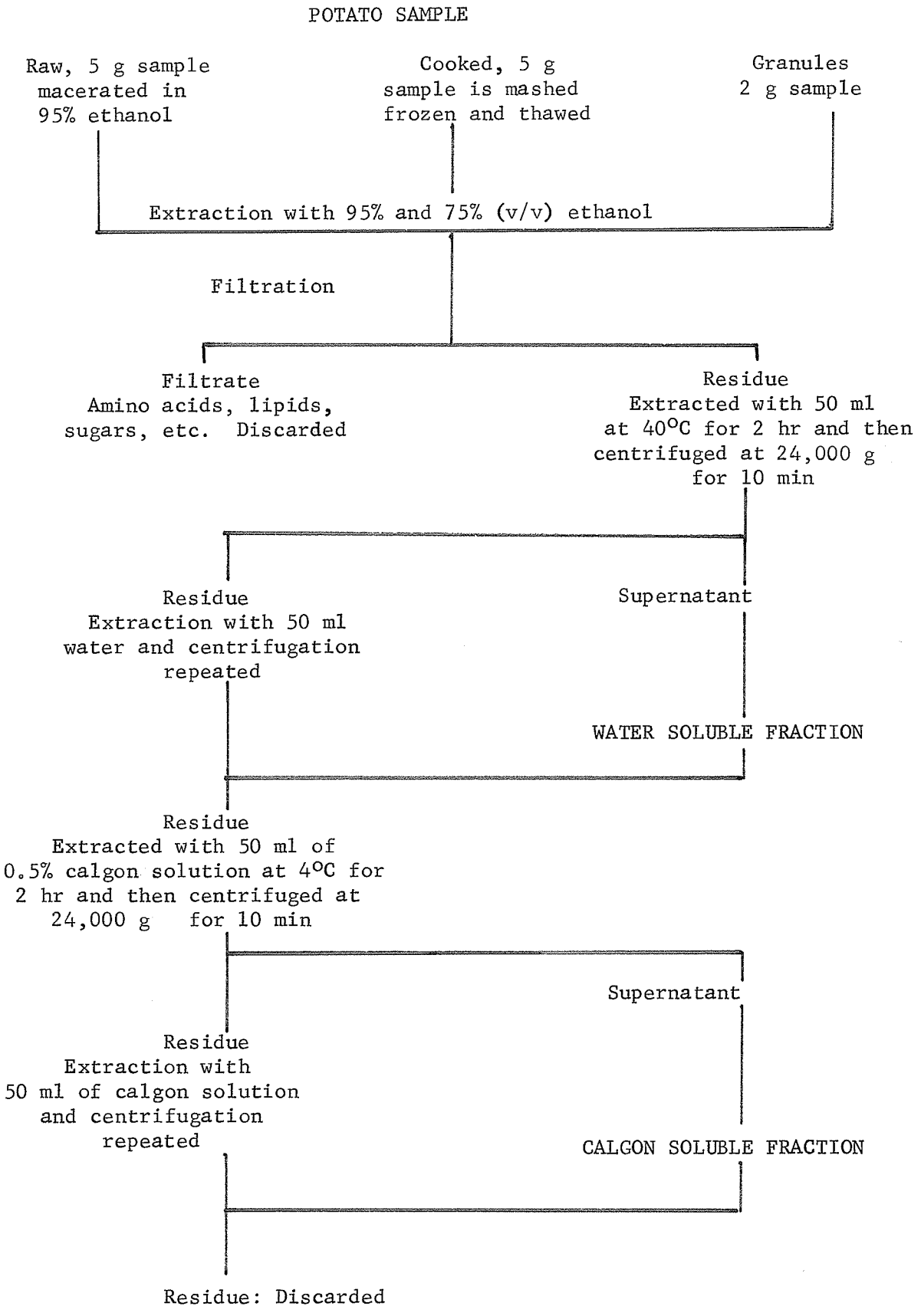
Washed and peeled tubers were immersed in ice-cold water containing 100 ppm $NaHSO_3$, diced and then homogenized in a blender with two volumes of ice-cold deionized water with 1% ammonium oxalate. The slurry was squeezed through a 100-mesh sieve and the homogenate was centrifuged in a Sorvall Superspeed RC2-B Automatic Refrigerated Centrifuge at 4,500 g for 10 minutes. The upper light brown layer of protein was removed from the sediment and the lower layer of starch was resuspended in water and recentrifuged. This was repeated several times until no impurity was evident under the light microscope. This preparation was then freeze-dried in a Virtis 10-146 MP-BA Freeze Mobile and weighed (Fedec et al, 1977).

### 3.7 Analysis of Pectic Substances

The method of McComb and McCready (1952) was applied with Ooraikul et al (1974) modification to avoid interference of free water-soluble starch in carbazole reaction for both water and calgon-soluble fractions of pectic substances.

The potato samples were macerated in ethanol in a cold room ($5^{o}C$) using an Oster Blender at low speed. Subsequent extraction steps with water and a 0.5% calgon solution (sodium-hexametaphosphate) are depicted in Figure 12. From a total of 100 ml potato extract, 2.5 ml aliquots

Figure 12. Flow chart for extraction of pectic substances from potatoes. All extraction steps except the first ethanol step were performed in cold room. All centrifugations were performed on a Sorvall Superspeed RC2-B Refrigerated Centrifuge.


POTATO SAMPLE
Raw, 5 g sample macerated in 95% ethanol
Cooked, 5 g sample is mashed frozen and thawed
Granules 2 g sample
Extraction with 95% and 75% (v/v) ethanol
Filtration
Filtrate
Amino acids, lipids, sugars, etc. Discarded
Residue
Extracted with 50 ml at 40°C for 2 hr and then centrifuged at 24,000 g for 10 min
Residue
Extraction with 50 ml water and centrifugation repeated
Supernatant
WATER SOLUBLE FRACTION
Residue
Extracted with 50 ml of 0.5% calgon solution at 4°C for 2 hr and then centrifuged at 24,000 g for 10 min
Supernatant
Residue
Extraction with 50 ml of calgon solution and centrifugation repeated
CALGON SOLUBLE FRACTION
Residue: Discarded

were taken for determination of free starch and 2 ml for determination of uronide contents as described by McComb and McCready (1952).

The starch content was determined by mixing the aliquot with 7.5 ml distilled water, heating the solution at 100°C for 5 to 10 minutes and cooling at room temperature. Then 0.2 ml of 0.02 N $KI_3$ solution was added and the absorbance of the blue color read at 640 nm using a Spectronic 20 Baush and Lomb.

### 3.8 Total Free Starch Determination

A 2.5 g sample of cooked, mashed or freeze-thaw potatoes or 0.5 g granulated potatoes was agitated 5 minutes in 500 ml of water heated to 65.5°C. The slurry was filtered and from clear filtrate an aliquot of 5 ml was transferred to a 125 ml Erlenmeyer flash containing 1 ml of 0.02 N $KI_3$ and 44 ml of distilled water. The absorbance of the blue color developed in the dark at room temperature for 3 hours, was read at 640 nm using a Spectronic 20 Baush and Lomb and expressed as blue value index (Mullins et al, 1955).

### 3.9 Production of Potato Granules Using Freeze-Thaw Technique

Potatoes were washed after specific gravity determination and peeled using sodium hydroxide with a concentration of 20% at a temperature of 95°C for 1 minute. Then the potatoes were washed again then cut to a dimension of 3 $cm^3$ approximately. The potato portions were then immersed in a 0.5% $NaHSO_3$ solution for 3 minutes.

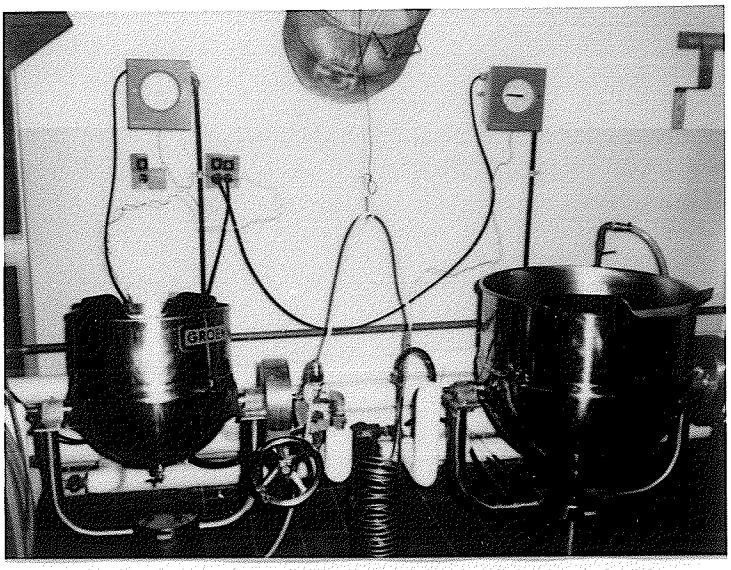
The potato dices were cooked using the following variation:

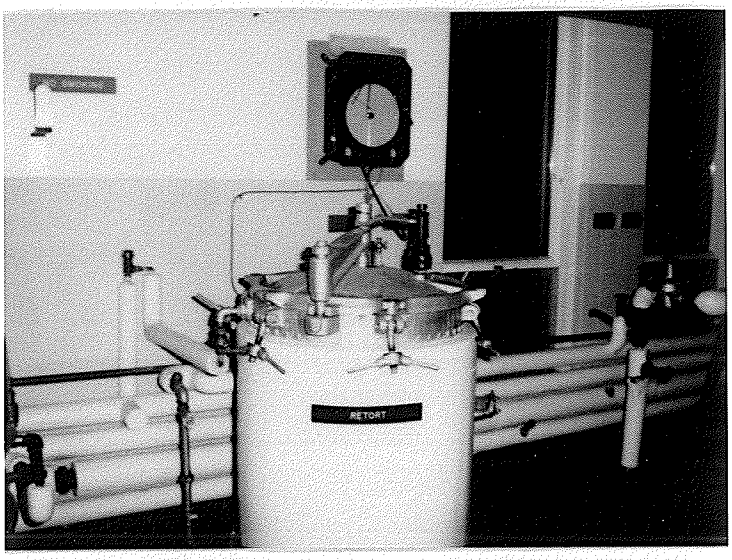
- boiling water (Figure 13),
- boiling water with 100 ppm calcium,

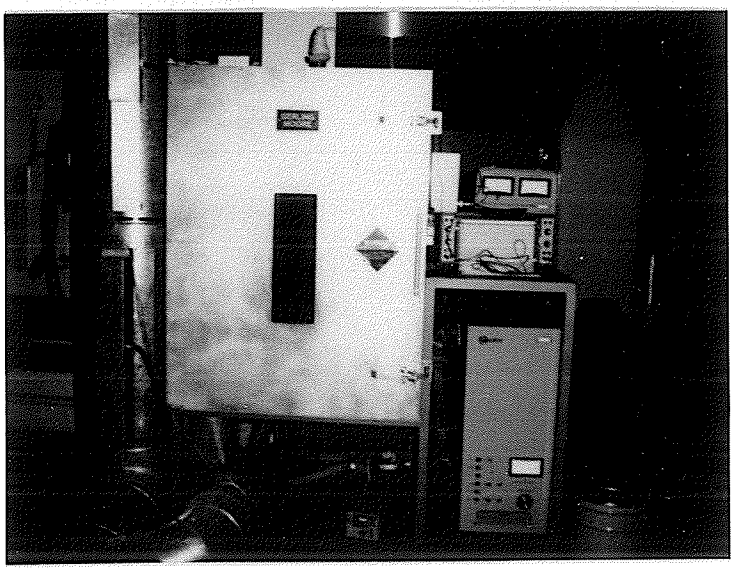
Figure 13. Pilot plant kettles used for cooking potatoes in boiling water with and without calcium.

Figure 14. Retort used for cooking potatoes by steam.

Figure 15. Microwave unit used for cooking potatoes.




RETORT



- pre-cooking in boiling water and final cooking in steam,

- pre-cooking in boiling water with 100 ppm calcium and final cooking in steam,

- cooking in steam (Figure 14),

- cooking with microwave energy (Figure 15).

After cooking, potatoes were mashed through a mesh 8 and then frozen in a cold room to a temperature of -20°C approximately and subsequently thawed to a temperature of 0 to 5°C. The freeze-thaw mashed potatoes were filled into a Hi-Speed fluid bed dryer (Lab-Line Instruments, Inc.), fixed with a stirrer device as illustrated in Figure 16.

The mashed potatoes (500 g/batch) were pre-dried at 70°C for 10 minutes with an air flow of 73 m/minute measured in an Air Velocity Meter Thermo-Systems Inc. Model 1650 and the moisture content at this state was reduced from 76 to 40% approximately. Granulation was performed at a temperature of 50°C for 15 minutes with air flow of 73 m/minute. Final dehydration was carried out at a temperature of 80°C for 8 minutes and an air flow of 56 m/minute.

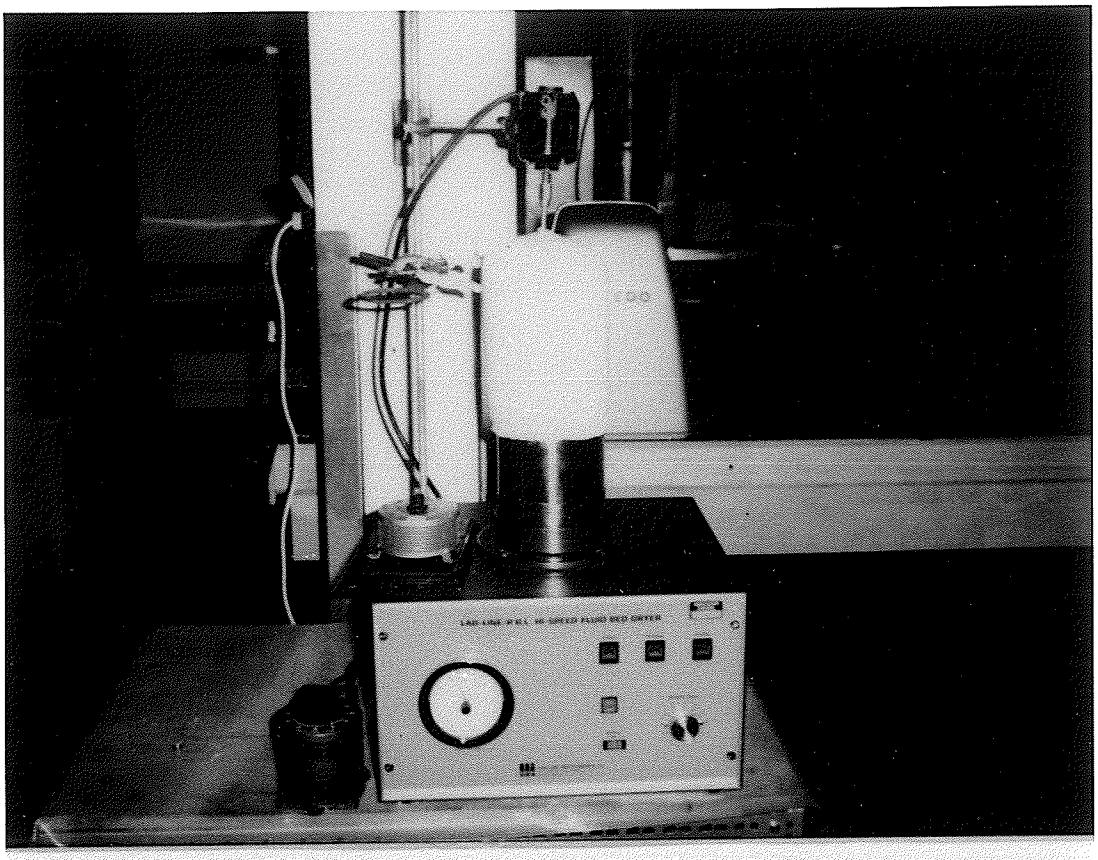
After drying was completed, the granules were classified according to granule size using a series of sieves (RO-TAP Testing Sieve, Shaker W.S. Tyler Co. of Canada Ltd.) accepting those granules passing through mesh 50 and rejecting those that did not pass through mesh 20; granules between the above limits were recycled.

The flow chart is depicted in Figure 17.

### 3.10 Production of Potato Granules Using Continuous Technique

The same conditions that were applied for the freeze-thaw process

Figure 16. Fluidized bed batch dryer adapted with a stirrer device used for granulation and final drying of potatoes.



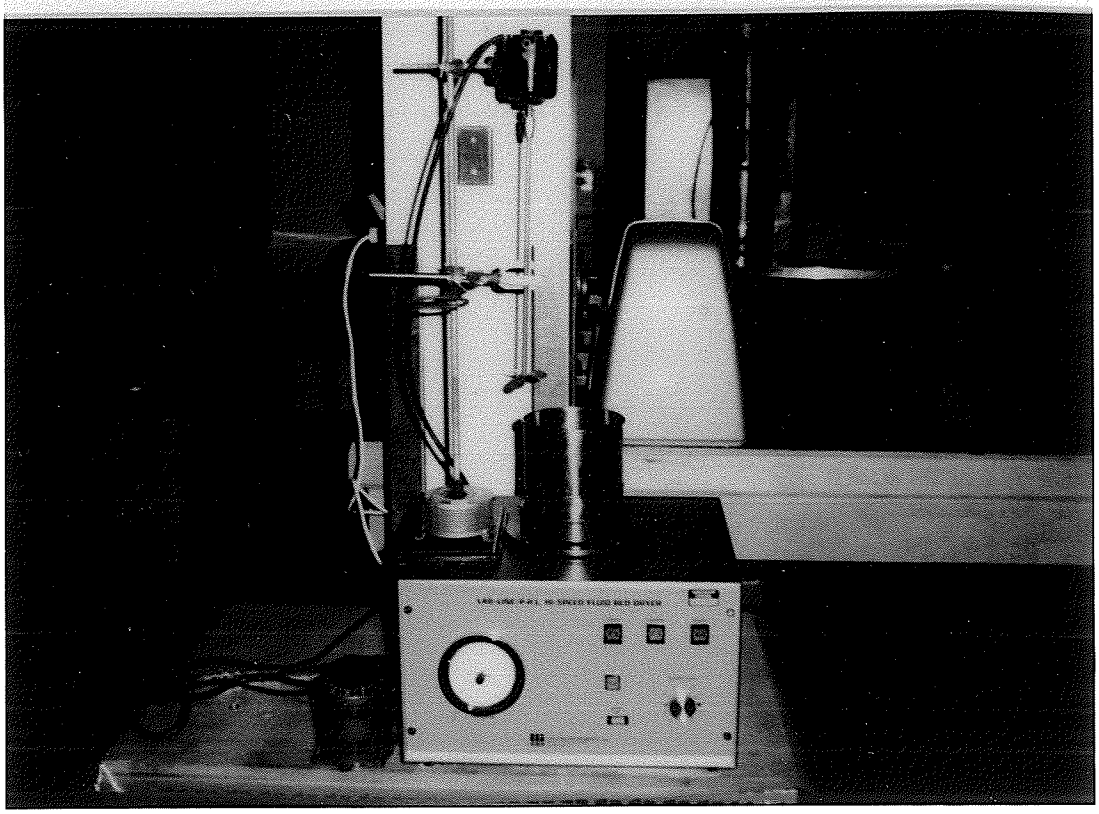
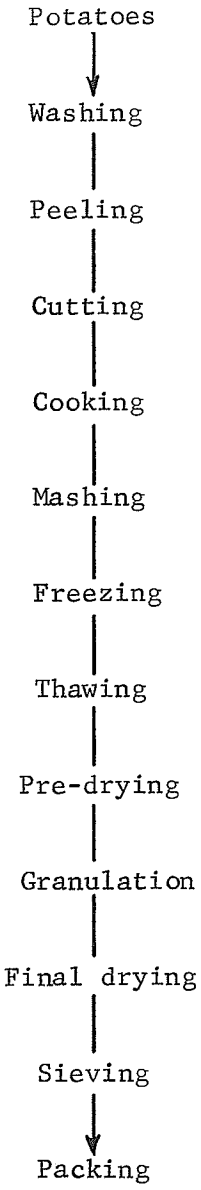


Figure 17. Flow chart of the freeze-thaw process.


Potatoes
Washing
Peeling
Cutting
Cooking
Mashing
Freezing
Thawing
Pre-drying
Granulation
Final drying
Sieving
Packing

were applied in the continuous process with the difference that the freeze-thaw step was eliminated and a period in which retrogradation was performed was used. The other change applied was in the dehydration step, in which pre-drying was carried out with a Drum Dryer (General Food Package Equipment Corp. G43) working at 2-8 kg/cm$^2$ of vapour inlet and 10 rpm (Figure 18a).

The flow diagram is shown in Figure 18b.

## 3.11 Potato Granules Evaluation

### 3.11.1 Swelling Power of Potato Granules

The method described by Potter (1954) with minor modifications by Ooraikul and Moledine (1981) was used to determine the swelling power values of potato granules. Granule samples weighing 1 g were placed in 15 ml graduated centrifuge tubes and mixed with sufficient distilled water at 25°C to make 10 ml of homogeneous slurry. The tubes were stoppered and agitated for 1 hour in a Fisher shaker at room temperature, then centrifuged in a IEC International Centrifuge CS for 30 minutes at 2,000 g. The supernatant was swiftly decanted, then 5 ml of distilled water was carefully pipetted into the tubes and the total volume determined. The volume of the swollen material, designated as SP, was calculated from (total volume - 5) 10, expressed on the basis of 10 g dry solids.

### 3.11.2 Water Holding Capacity of Potato Granules

The method of Medcalf and Giles (1965) as modified by Morrow and Lorenz (1974) was used to determine the percentage of water holding capacity of potato granules. A sample of 0.5 g granules was added to

Figure 18a. Drum dryer used in the continuous process for pre-dried potatoes.

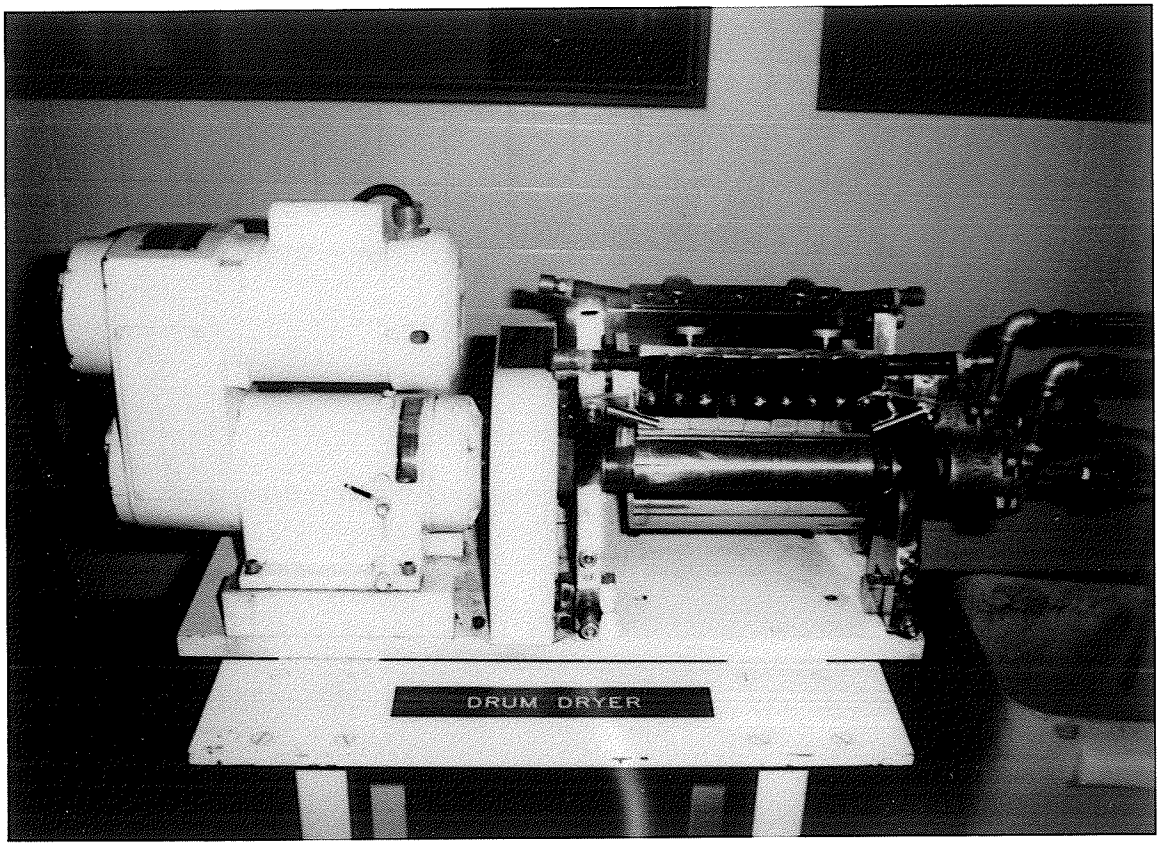
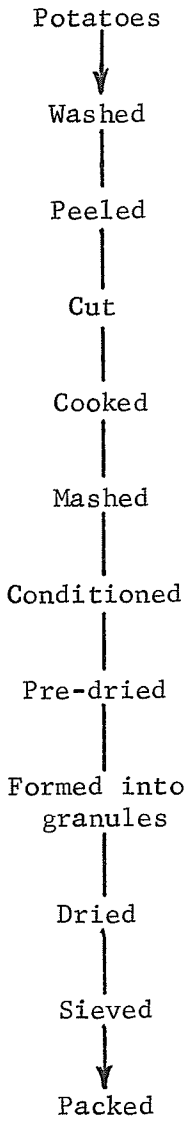

DRUM DRYER

Figure 18b. Flow chart of the continuous process for the production of potato granules.


Potatoes
Washed
Peeled
Cut
Cooked
Mashed
Conditioned
Pre-dried
Formed into granules
Dried
Sieved
Packed

10 ml distilled water in a tared 15 ml tapered centrifuge tube. The tube was stoppered and agitated for 1 hour in a Fisher shaker at room temperature, then centrifuged for 30 minutes at 4,000 g using a Sorvall Superspeed RC2-B Automatic Refrigerated Centrifuge. The supernatant was carefully decanted and excess water wiped dry with paper tissue. The tube was weighed to determine percent water holding capacity, expressed as weight of water retained per 100 g dry matter.

3.11.3 Determination of Rehydration Rate

Petri dishes were used as containers. A very thin layer of potato granules, approximately 3 g, was placed into the dish and weighed.

The bottom section of the dessicator was filled with water and the sample placed in the dessicator at room temperature; the atmosphere of the dessicator was considered 100% relative humidity. The samples were weighed at certain time intervals as described by Jericevic and Le Maguer (1975).

# 4. RESULTS AND DISCUSSION

## 4.1 Potato Characteristics

Netted Gem potatoes, specific gravity 1.093 to 1.098 whose proximate composition is given in Table 9, were used since varying specific gravities result in fluctuations in potato nutritional value. Furthermore, total solids will fluctuate during storage, thus standard conditions are required to minimize variations among tubers.

### 4.1.1 Potato Microstructure

Three regions are readily observed microscopically when a tuber is disected; these regions are namely as follows: Cortex (external phloem, storage parenchyma and Xylem ring), Outer Medulla (internal phloem, storage parenchyma) and Pith area (Figure 6).

Cork cells shown in Figure 19 are enlarged. Cell walls are heavily suberized. These walls were much thicker than those found among parenchyma cells. Since cork cells are dead cells, they do not contain starch or protein grains. The parenchyma cells in the cortex are presented in Figure 20. The cells normally contain numerous round and oval-shaped starch grains. The thickness of these parenchyma cell walls was less than those of the cork cells.

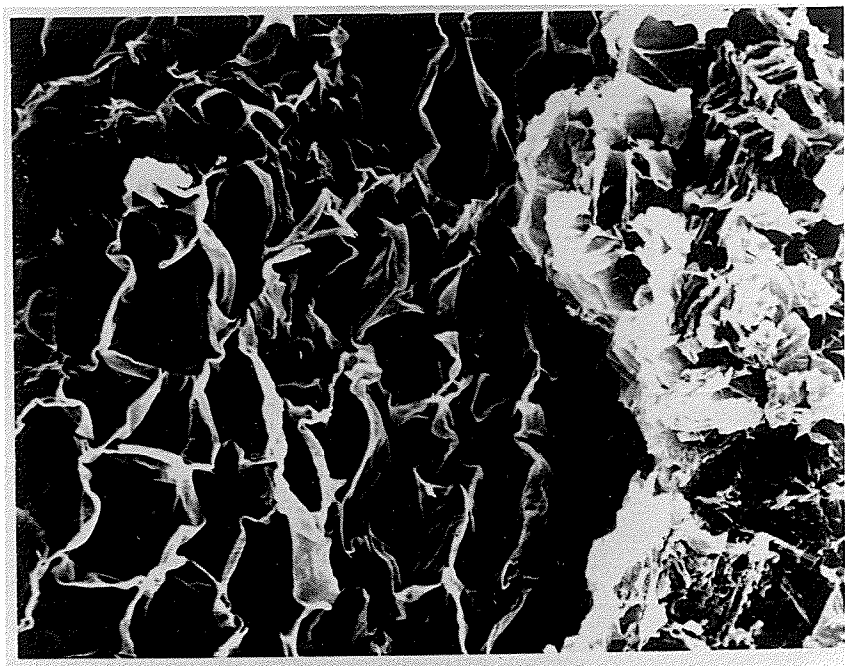
The outer medulla occupied close to 75% of the total tuber volume. This zone contains starch grains similar in size to those of the cortex (Figure 21a). The pith cells are presented in Figure 21b. The main difference between these cells and adjacent tissue was that they appeared

TABLE 9. Proximate analysis of Netted Gem potatoes.

| | |
|---|---|
| Moisture | 75.6% |
| Protein | 2.3% |
| Carbohydrates | 19.6% |
| Crude Fat | 0.2% |
| Crude Fiber | 0.9% |
| Ash | 1.3% |
| Specific Gravity 1.093 - 1.098 | |

Figure 19. Scanning electron microscopy micrograph showing potato cork cells at a magnification of 200 X.

Figure 20. Micrograph of parenchyma cells in the cortex tissue of potatoes at a magnification of 200 X.



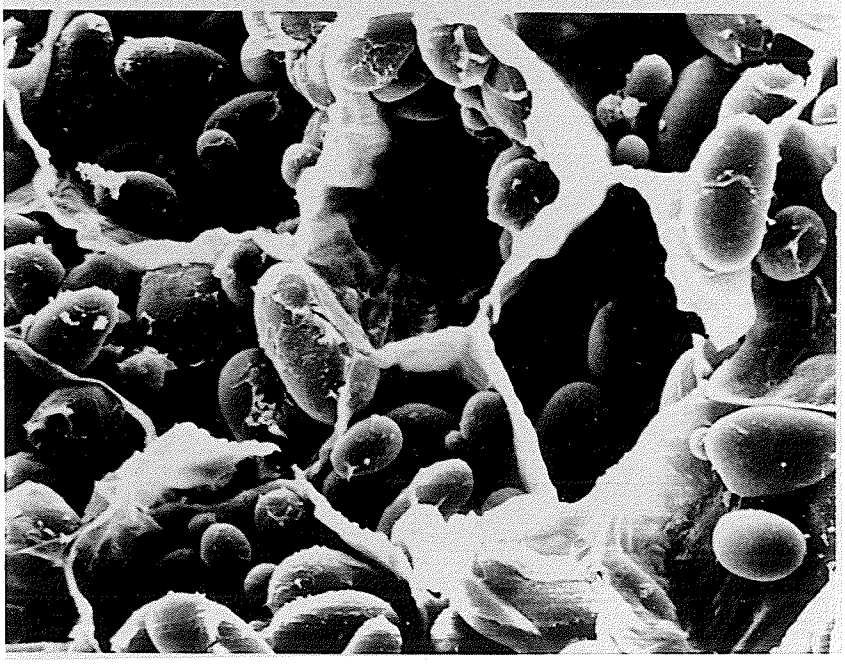
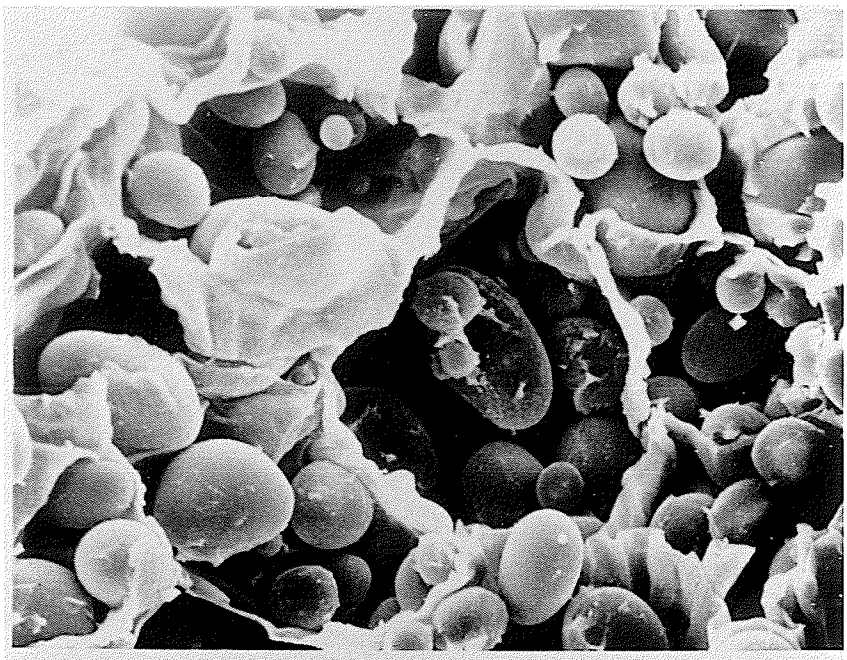
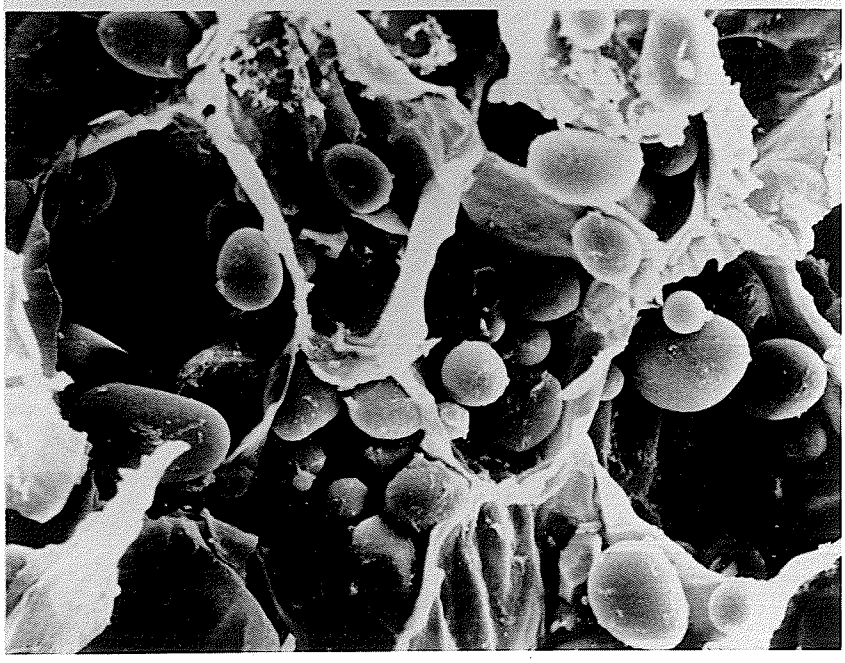


Figure 21. Micrographs of outer medulla tissue (a) and pith area (b) with a magnification of 200 X.



A

B



smaller and had a lower starch content. It was also found that the method of preparation for the samples could induce changes in the potato microstructure. The changes found were collapse of the cells, possibly caused during fixation or during alcohol treatment by weakening the cell walls and empty cells whose starch granules washed out during fixation. These changes were responsible for altering the preparation method to other simple techniques which were fast and did not cause appreciable change.

### 4.1.2 Changes in Vitamin C Content With Specific Gravity

Table 10 shows changes in vitamin C content in tubers according to different specific gravities used. Increases in specific gravity, correlated to an increase in vitamin C content. However, this does not mean that further increases in specific gravity will necessarily result in an increase of ascorbic acid content or vice versa.

### 4.1.3 Distribution of Mineral Content (Approximate Analysis) Between Tuber Region and Between Specific Gravity Ranges

The statistical analysis used here was a split-plot design with 96 total observations for determination of mineral distribution (approximate analysis). Data are presented in Table 11. The statistical analysis shows significant differences between specific gravities, tissues and tissues-specific gravity interaction as depicted in Appendix 1.

In Figure 22 the ash content of the cortex tissue shows a well defined pattern, in which increases in mineral content in this particular region are noticeable with increases in the specific gravity. These results suggest that mineral accumulation occurs on the outer tissues of the tuber. On the other hand, the inner tissues did not show a defined

TABLE 10. Changes in vitamin C content according to specific gravity.

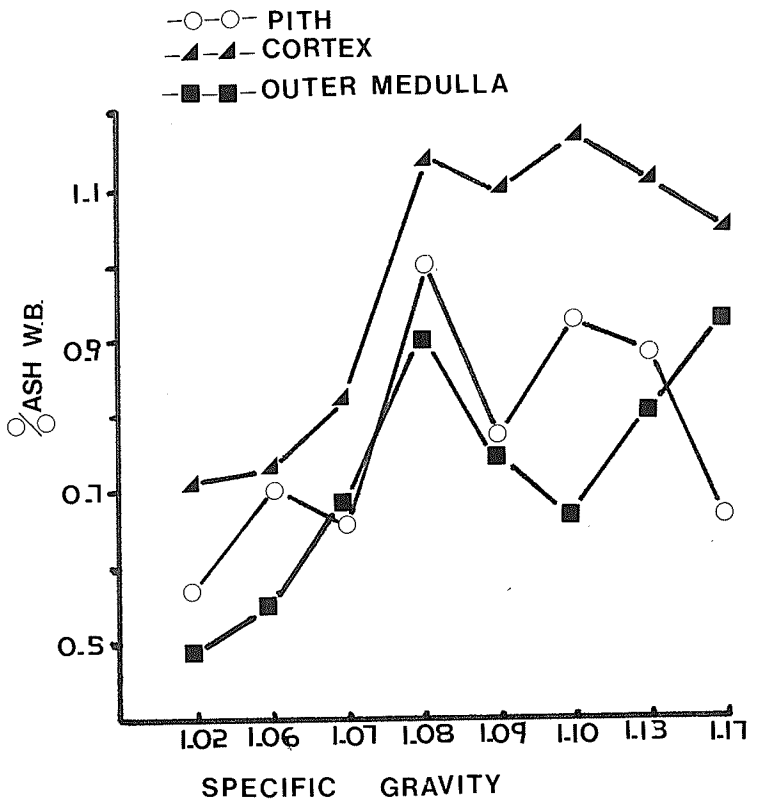
| Specific gravity | mg/100 g Potatoes (DB) av.* ± st. dev. |
|---|---|
| 1.093 | 7.87 ± 0.29 |
| 1.095 | 8.62 ± 0.13 |
| 1.097 | 9.30 ± 0.84 |
| 1.098 | 11.23 ± 1.50 |

*Average of six observations for each specific gravity.

TABLE 11. Ash distribution on potato tissues.

| Specific gravity | Tissue | Mean of three observations |
|---|---|---|
| 1.02437 | Cortex | 0.71 |
| | Outer Medulla | 0.4935 |
| | Pith | 0.576 |
| 1.06417 | Cortex | 0.72925 |
| | Outer Medulla | 0.55 |
| | Pith | 0.71425 |
| 1.07589 | Cortex | 0.826 |
| | Outer Medulla | 0.69325 |
| | Pith | 0.66875 |
| 1.0830 | Cortex | 1.14 |
| | Outer Medulla | 0.9175 |
| | Pith | 1.01125 |
| 1.0920 | Cortex | 1.000 |
| | Outer Medulla | 0.742 |
| | Pith | 0.7875 |
| 1.09932 | Cortex | 1.1775 |
| | Outer Medulla | 0.67175 |
| | Pith | 0.92125 |
| 1.13842 | Cortex | 1.03825 |
| | Outer Medulla | 0.8125 |
| | Pith | 0.88025 |
| 1.17281 | Cortex | 0.937 |
| | Outer Medulla | 0.92075 |
| | Pith | 0.65775 |

Figure 22. Distribution of ash content between tuber region and specific gravity ranges.


PITH
CORTEX
OUTER MEDULLA
% ASH W.B.
1.1
0.9
0.7
0.5
1.02
1.06
1.07
1.08
1.09
1.10
1.13
1.17
SPECIFIC GRAVITY

pattern, suggesting that these tissues are responsible for the mineral variations of the mineral content in the tuber; possibly cells in pith area and outer medulla are less compacted leaving more intercellular space causing no correlation with specific gravity.

Figure 23 depicted the total ash content versus specific gravity. In general, ash content increases when the specific gravity increases to certain values, with further increases in specific gravity a decrease in ash content is observed. Ash content increased with specific gravity up to 1.083 then levelled off and remained almost constant throughout specific gravity 1.09 to 1.17.

### 4.1.4 Starch Determination

Starch content of tubers whose specific gravity varies between 1.093 to 1.098 is approximately 55 to 56% (D.B.). Data presented in Figure 24 portray the variability of starch content with specific gravity. The interesting point is that almost a constant percent of starch is observed when the specific gravity lies between the limits chosen for this study. This is a basic reason for selecting potatoes between 1.093 and 1.098.

## 4.2 Potato Processing

Two main processes were studied: the Freeze-thaw process and the Continuous process. Six different methods of cooking were applied and the principal microstructural and compositional changes in potato tubers were followed. The granular properties of products from these processes were compared with ones obtained from the add-back process furnished by a commercial source.

Figure 23. Total ash content in potato tubers according with specific gravities.

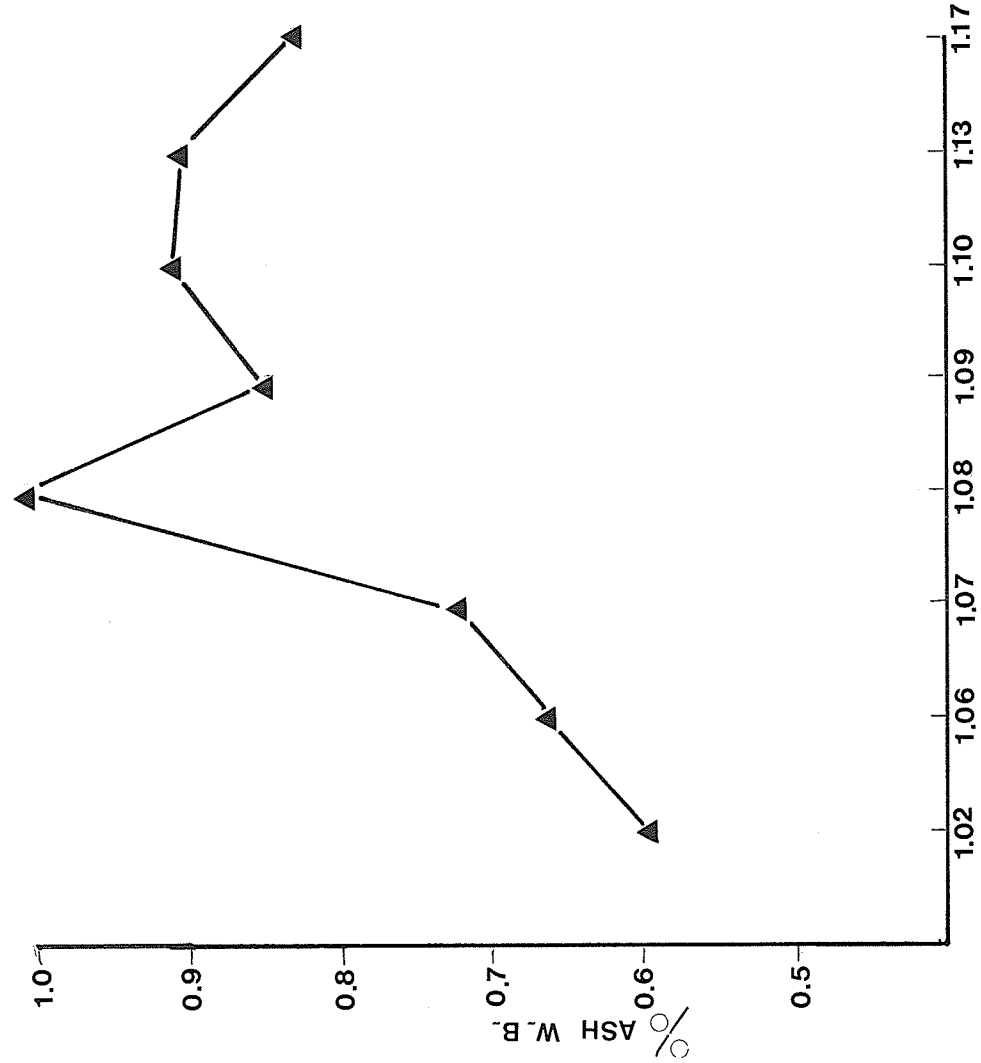
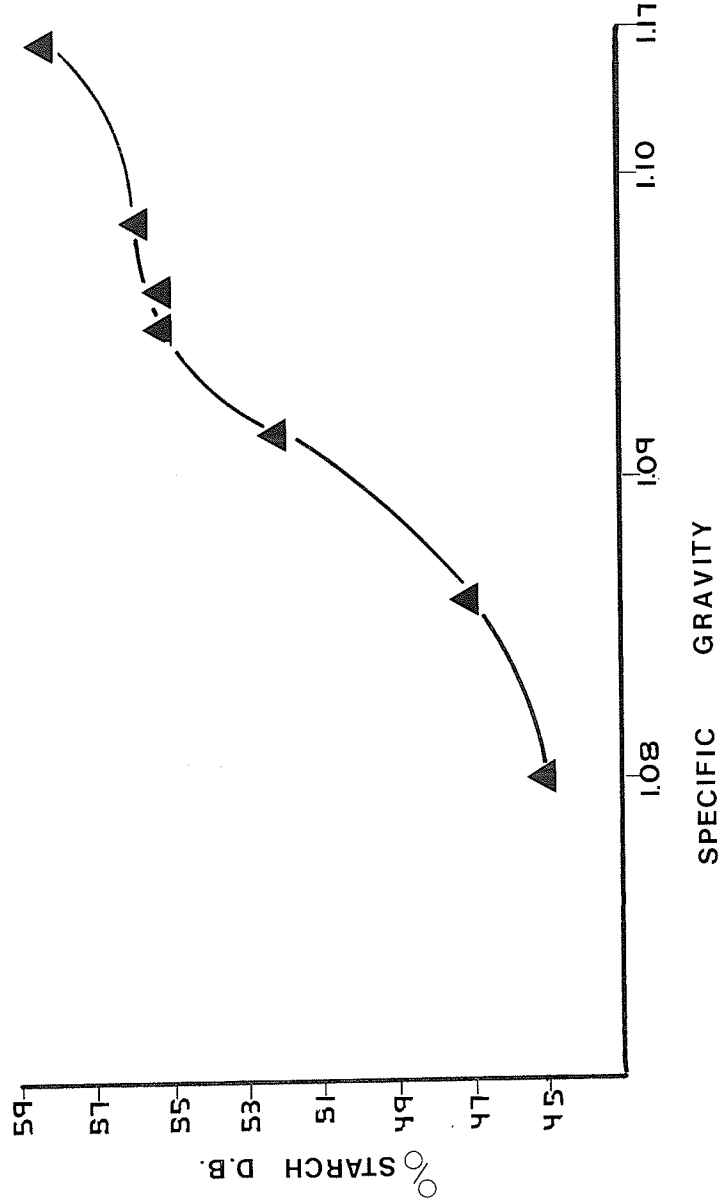

1.0
0.9
0.8
0.7
0.6
0.5
% ASH W. B.
1.02
1.06
1.07
1.08
1.09
1.10
1.13
1.17
SPECIFIC GRAVITY

Figure 24. Variation of starch content in potato tubers with specific gravity.


% STARCH D.B.
59
57
55
53
51
49
47
45
1.08
1.09
1.10
1.11
SPECIFIC GRAVITY

4.2.1 Methods of Cooking, Conditions and Effects

Six methods of cooking were used under the following conditions:

a) Cooking in boiling water at 100°C for 30 minutes.

b) Cooking in boiling water in the presence of 100 ppm Calcium at 100°C for 30 minutes.

c) Pre-cooking in boiling water at 87°C for 15 minutes and final cooking by steam at 100°C for 15 minutes.

d) Pre-cooking in boiling water in the presence of 100 ppm Calcium at 87°C for 15 minutes and final cooking by steam at 100°C for 15 minutes.

e) Steam cooking at 100°C for 30 minutes.

f) Cooking by microwave using 1 Kw forward power for 10 minutes.

The reason for applying these distinctive methods of cooking was that during cooking two main effects were produced in the potato tissue: 1) gelatinization of the starch (Figure 25) and 2) softening of the tissue which was due to solubilization of the cementing materials between cell walls and related with the presence of ions (Figure 26). It is possible to obtain a desirable effect in the tuber when the degree of change for each cooking method is known.

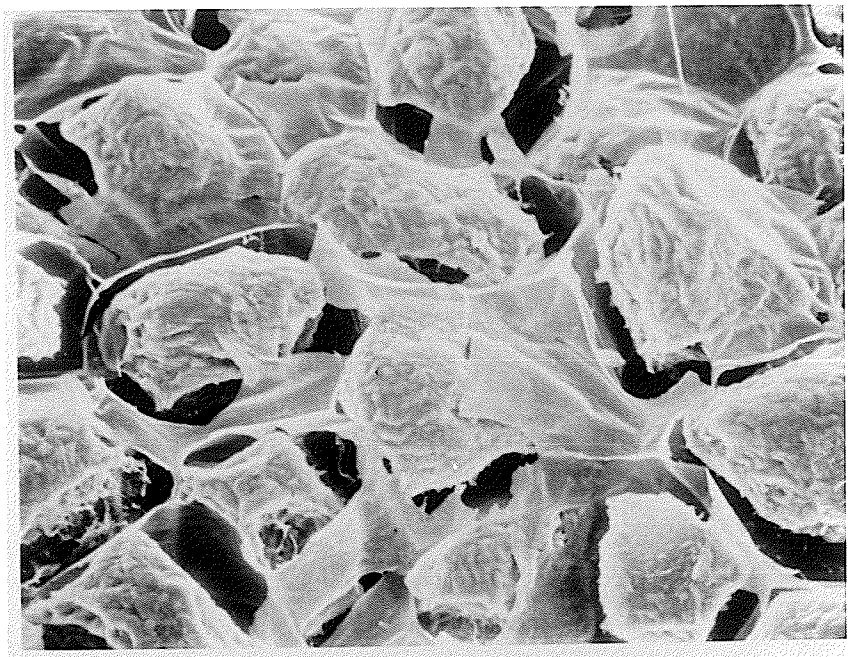
Proximate composition of cooked potatoes is depicted in Table 12. Ash and protein content did not change appreciably with the different cooking methods. Vitamin C content (an important nutrient) was recorded and all the cooking methods demonstrated a loss of this nutrient. Raw potato contained about 68 mg/100 g dry matter, while cooked tubers contained a vitamin C content of 55 to 56 mg/100 g dry matter. Microwave cooking caused a greater loss in vitamin C content (51 mg/100 g dry matter); the reason for this is not known at

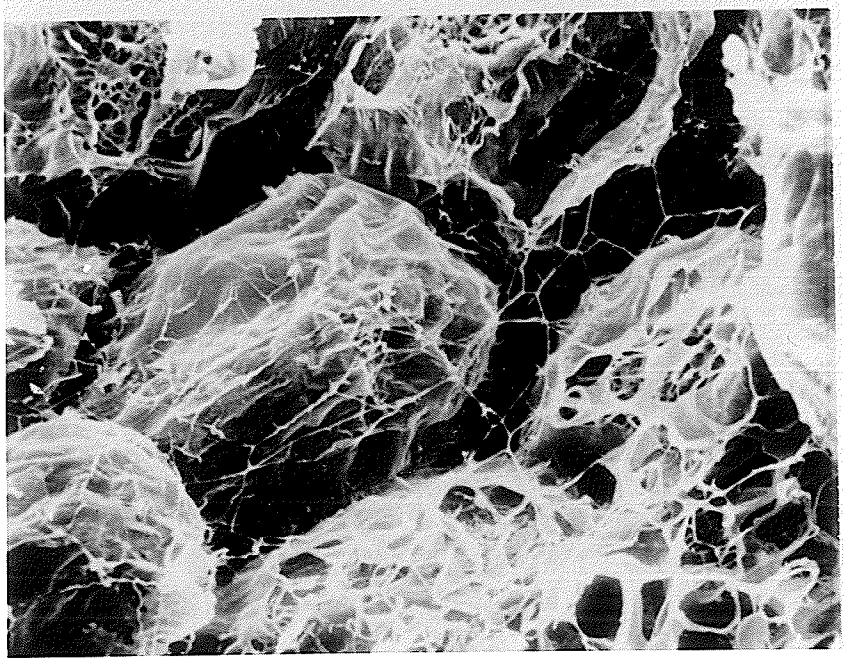
TABLE 12. Proximate composition of 100 g peeled, raw and cooked potatoes (WB).

| | % Dry matter | % Ash | % Protein | Vitamin C mg/100 g |
|---|---|---|---|---|
| Raw | 22.00 | 0.93 | 2.00 | 15.00 |
| Boiling water | 20.20 | 0.85 | 1.90 | 11.50 |
| Steam | 21.80 | 0.89 | 1.95 | 12.20 |
| Microwave | 25.80 | 1.18 | 2.16 | 13.20 |
| Boiling water with 100 ppm calcium | 20.70 | 0.87 | 1.90 | 11.60 |
| Boiling water with 100 ppm Ca & steam | 21.10 | 0.86 | 1.92 | 11.80 |
| Boiling water & steam | 21.40 | 0.89 | 1.94 | 12.00 |

Figure 25. Micrograph in which gelatinization of the starch is depicted at a magnification of 200 X.

Figure 26. Solubilization of the cementing material upon cooking (magnification 400 X).





this point.

4.2.2 Cooked Potato Microstructure

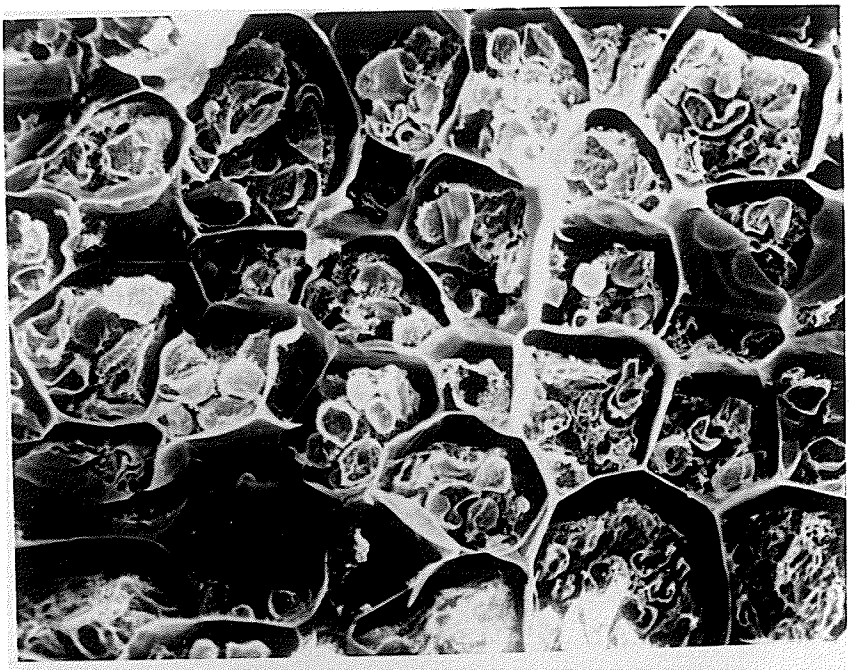
The starch granules in cooked potato tissue were large, swollen and completely filled the cells; almost all of the cell walls remained intact after cooking (Figures 27c, 28, 29, 30, 31 and 32). However, the tissue cells became distended by the swollen gel and tended to separate, due to degradation of pectic substances between and within the cell wall. It is believed that pre-cooking serves to render the cell wall less degradable by cooking, thereby enabling the potato cells to withstand compression and shear forces during the mashing step (Moledina et al, 1978).

Potatoes cooked by boiling water in the presence of 100 ppm calcium are shown in Figure 27. The micrographs depict in Figure 27a, b, those cells cooked for 5 minutes at 100°C with a magnification of 200X and 1000X, respectively, showing the initial changes of the starch granules during this method. The starch granules shrink because the calcium ions promote retrogradation by freeing the water bound in the starch chains and possibly forming complexes with amylose.

Figure 27c shows the starch matrix after complete cooking by this method. The pitting of the starch matrix is easily seen.

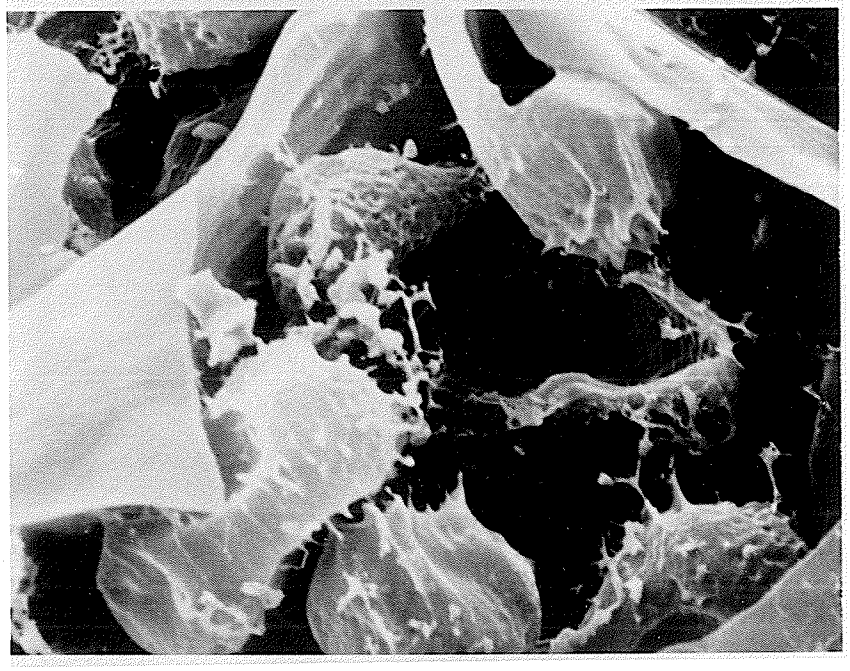
A surprising effect was found when tubers were cooked by microwave. Figure 28a, b, c and d show gelatinization of the starch granules in which disintegration did not occur in the same way than other cooking methods as seen in Figure 28e. Since added water in the microwave case is absent the starch could not swell at the same rate as when it was present. All the starch granules adhered together leaving fractures throughout the matrix.

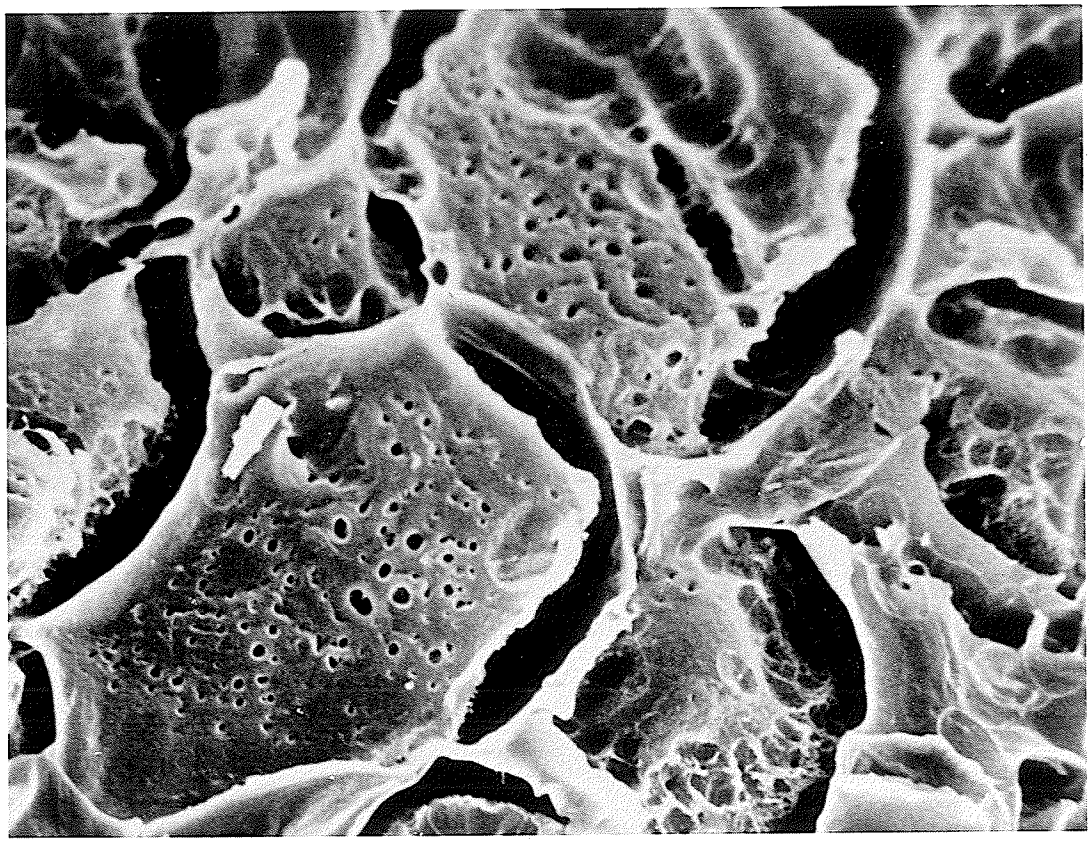
Figure 27. Micrographs of potato cells cooked by boiling water in the presence of calcium: a) 5 minutes at 100°C with a magnification of 200 X; b) 1,000 X in which the starch granules have shrunk and c) cells in which final cooking was achieved (magnification of 400 X).



A

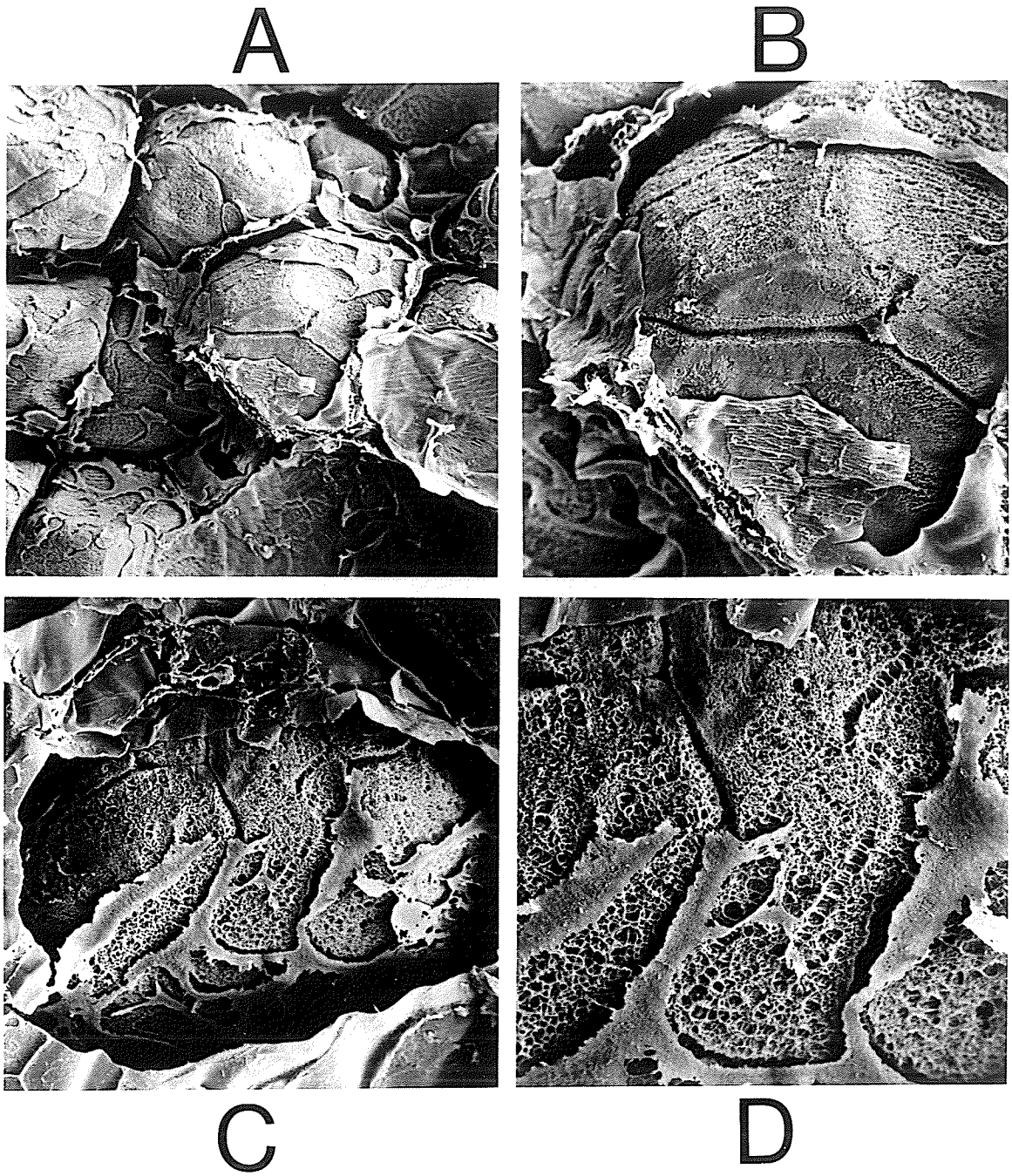
B

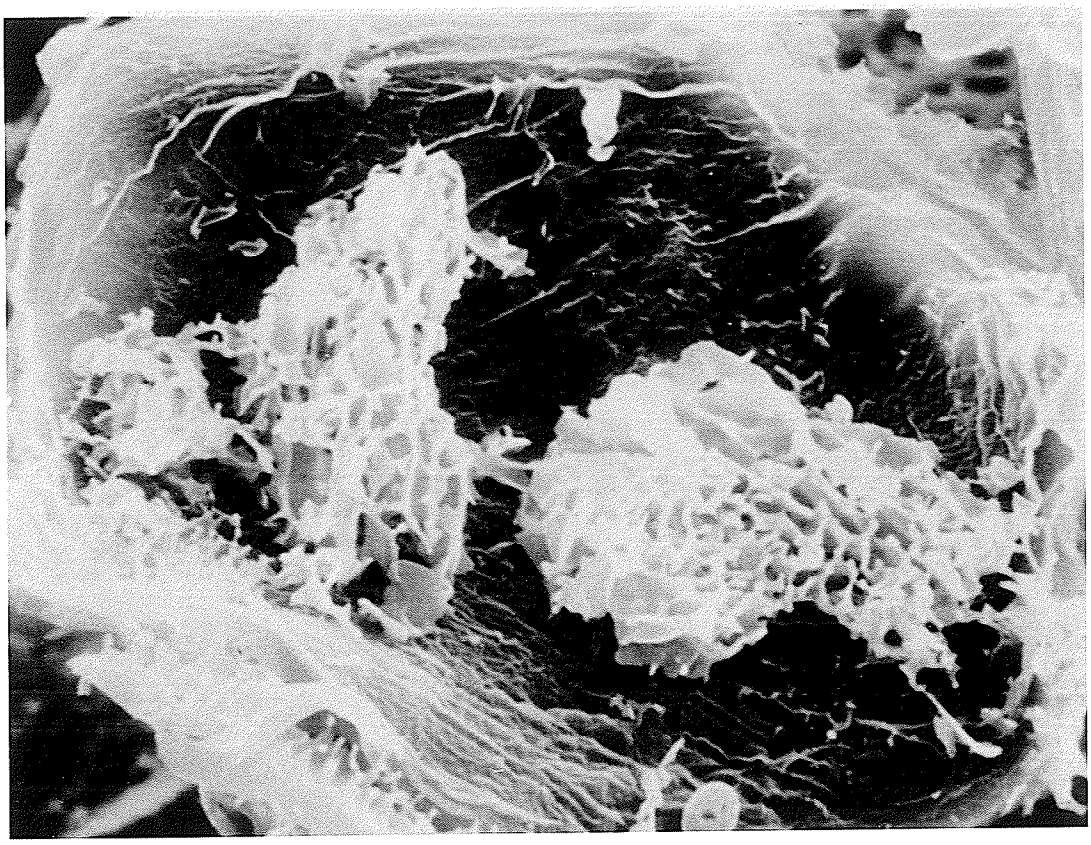




C

Figure 28. Scanning electron micrographs of potatoes cooked by microwave; a and b (500 X and 1,000 X) samples were cooked 5 minutes with 1 Kw forward power in which the starch did not desintegrate as in the other methods (Figure e). Figure c and d (500 X and 1,000 X) are micrographs in which final cooking was achieved. Figure e is at a magnification of 1,000 X.


A
B
C
D



E

In Figures 28a and b, the surface of the matrix is quite smooth because total cooking was not achieved at this time (cooking for 5 minutes using 1 Kw forward power). Figures 28c and d show a matrix which is cracked and pitted. Also, some denatured protein or cytoplasmic material can be distinguished. A cooked texture was achieved at this point.

Cooking by boiling water is shown in Figures 29a and b. As predicted, this cooking method produced complete solubilization of the pectic substances, thereby causing some breakdown of the cell walls. Precooking in boiling water with final cooking by steam is shown in Figure 30. The cells are packed together without any significant disruption of the cell walls. This could mean that the method prevents, to some extent, weakening of the cells.

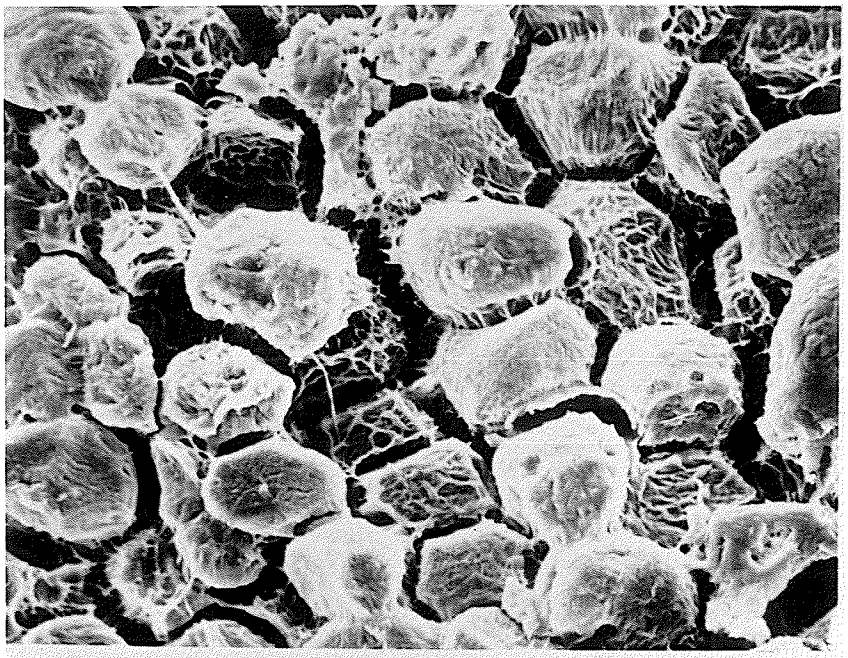
Steam cooked potatoes are shown in Figures 31a, b and c. The starch matrix has practically filled the entire cell. The cell wall is well defined, suggesting that minimal changes occur during this special cooking method. The starch matrix is extremely fisured, possibly due to internal pressures created by the steam cooking.

Pre-cooking in boiling water in the presence of calcium and final cooking by steam are displayed in Figures 32a and b. This method presented the combined effect of the boiling water in the presence of 100 ppm calcium and steam cooking. The cells are completely filled by the gelatinized starch and the cell walls look quite firm.

### 4.2.3 Freeze-Thaw Process

This process involves controlled freezing and thawing of the cooked mashed potatoes before dehydration. Preliminary requirements were

Figure 29. Potato cells cooked by boiling water; the micrographs show that the cell walls are weakened probably due to solubilization of the pectic substances, 200 X (a) and 400 X (b).



A

B

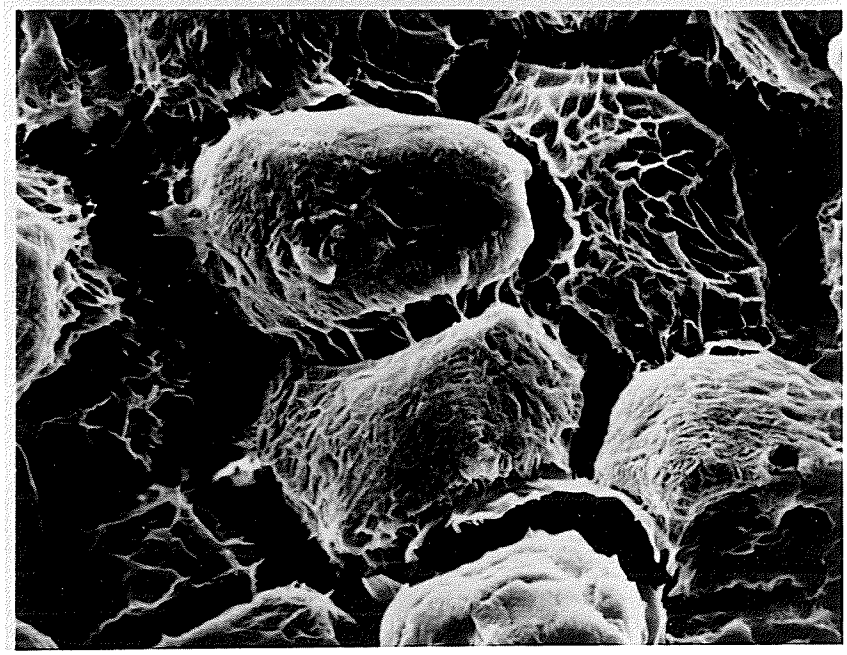
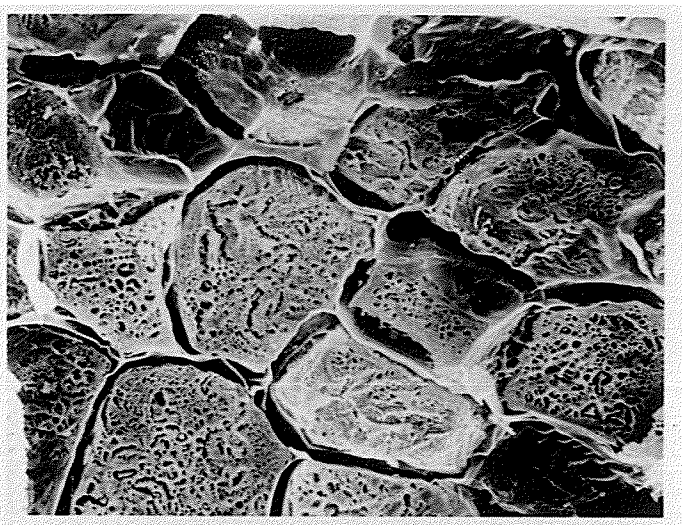
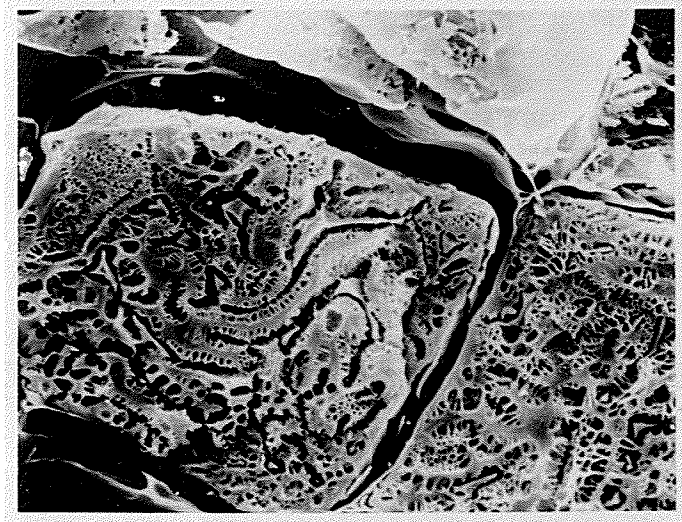


Figure 30. Scanning electron micrograph of cells pre-cooked in boiling water with final cooking by steam at a magnification of 200 X.

Figure 31. Steam cooking in which the starch matrix is pitted due to the internal forces developed by this method, a (400 X), b (800 X) and c (1,000 X).

A





B

C

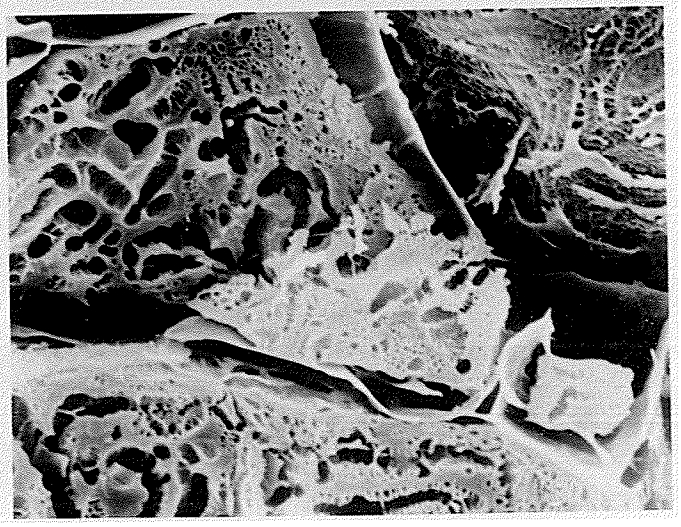
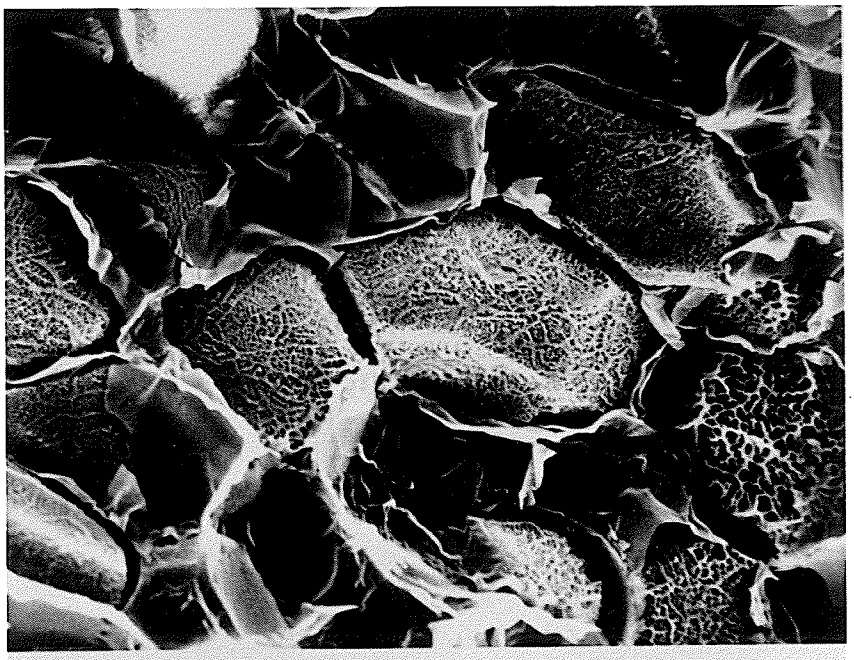
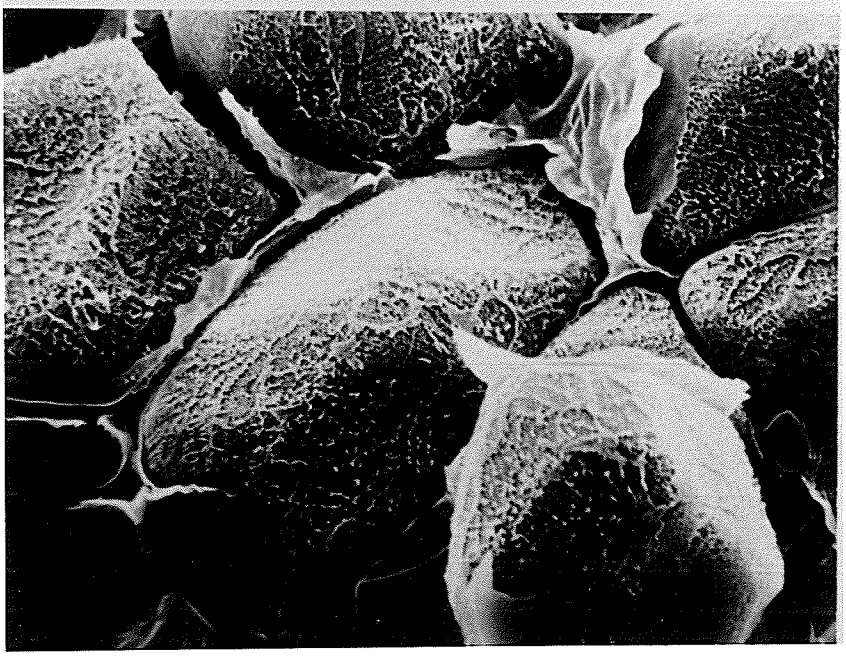


Figure 32. Scanning electron micrographs at magnifications of 200 X (a) and 400 X (b) of cells pre-cooked in boiling water in the presence of 100 ppm calcium with final cooking by steam.



A

B



pointed out in materials and methods section 3.9. After cooking, potatoes were mashed and then frozen in a cold room to a temperature of -20°C for approximately 20 minutes. The frozen mashed tubers were thawed to about 0 to 5°C, predried, granulated and dried.

4.2.3.1 Changes in Calcium Content During the Freeze-Thaw.Process. It is believed that the presence of ions (especially calcium) will strengthen the cells forming pectic complexes, thus avoiding softening during cooking. The calcium content of raw potatoes was approximately 42.2 mg/100 g dry matter (Table 13). During cooking with boiling water calcium pectic complexes are disrupted and calcium difuses into the cooking medium, thus explaining the slight decrease in calcium content observed when potatoes were cooked using this method.

Microwave and steam cooking produced little change in calcium content. Pre-cooking in boiling water and final cooking by steam did not show a change in calcium content even using water as a medium of pre-cooking. In this case, pre-cooking probably gelatinized the outer cells forming a type of barrier, thereby preventing the escape of calcium from the inner tissues to the cooking medium.

The calcium content of potatoes that were pre-cooked in boiling water in the presence of 100 ppm of calcium with final cooking by steam increased slightly. This suggested that the calcium in the medium in some way reacted with the soluble pectin, thus avoiding to some degree the sloughing of the tissues. On the other hand, cooking tubers in boiling water in the presence of 100 ppm of calcium showed a tremendous uptake of calcium, suggesting that calcium not only reacted with soluble pectins but also with starch granules. The calcium complexed with starch displacing water and inducing the shrinkage observed in

TABLE 13. Changes in calcium content during granule production.

| Treatment | Ca mg/100 g dry matter* | |
|---|---|---|
| | Granules | Mashed (F-T) |
| Raw control | 42.20 ± 2.20 | 42.20 ± 2.20 |
| Microwave | 31.94 ± 3.37 | 38.07 ± 10.48 |
| Boiling water with 100 ppm calcium | 107.94 ± 12.07 | 160.40 ± 18.58 |
| Steam | 41.94 ± 4.60 | 38.50 ± 5.20 |
| Boiling water & steam | 34.87 ± 2.41 | 49.09 ± 13.95 |
| Boiling water with 100 ppm calcium & steam | 67.14 ± 4.34 | 59.52 ± 16.85 |
| Boiling water | 32.40 ± 5.50 | 31.07 ± 9.05 |

*Mean of 4 observations.

Figure 27b.

4.2.3.2 Changes in Magnesium Content During Granule Production. Magnesium content did not vary between the different cooking methods. The magnesium content in raw potato is approximately 127 mg/100 g dry basis and a significant change on cooking was not observed. Thus, magnesium is probably not a reactant or did not form associations with the pectic substances (Table 14). Depression of magnesium was not noticeable when calcium was added.

4.2.3.3 Changes in Pectic Substances. The parameter which has more importance in determining the strength of the cells is the pectic substances, since these are found in the middle lamella and are responsible for the cementing effect among cells. The assay method used was based on the colorimetric reaction of carbazole with pectins. The calibration curve presented in Figure 33 was used for the calculation of the amount of pectin without interference caused by the presence of starch. The intersection X is the original absorbance evaluated in which pectic and starch reacted with carbazole reagent, the point Y is the point in which the starch interference was measured, by subtraction (X-Y) the true pectin content was determined.

The water-soluble pectin content of cooked mashed potatoes increased during cooking (Table 15). The water-soluble pectic substances in raw potato is 20 mg/100 g dry basis. It is probable pectins in raw potato form complexes with other components such as sugars, rather than calcium alone and upon cooking these break down to increase the pectic content.

The content of calgon-soluble pectic substances in raw potatoes was found to be approximately 8 mg/100 g dry basis, lower than those values

TABLE 14. Determination of magnesium content during granule production.

| Treatment | Mg mg/100 g dry matter* | |
|---|---|---|
| | Granules | Mashed (F-T) |
| Raw control | 127.0 ± 11.30 | 127.0 ± 11.30 |
| Microwave | 126.3 ± 11.77 | 129.8 ± 0.97 |
| Boiling water with 100 ppm calcium | 107.2 ± 1.80 | 139.5 ± 0.80 |
| Boiling water & steam | 113.7 ± 3.40 | 123.9 ± 0.10 |
| Steam | 103.2 ± 3.14 | 114.5 ± 5.13 |
| Boiling water with 100 ppm calcium & steam | 95.4 ± 7.40 | 120.4 ± 2.55 |
| Boiling water | 104.9 ± 5.13 | 138.3 ± 3.53 |

*Mean of 4 observations.

Figure 33. Calibration and correction curves used in pectic substances determination.

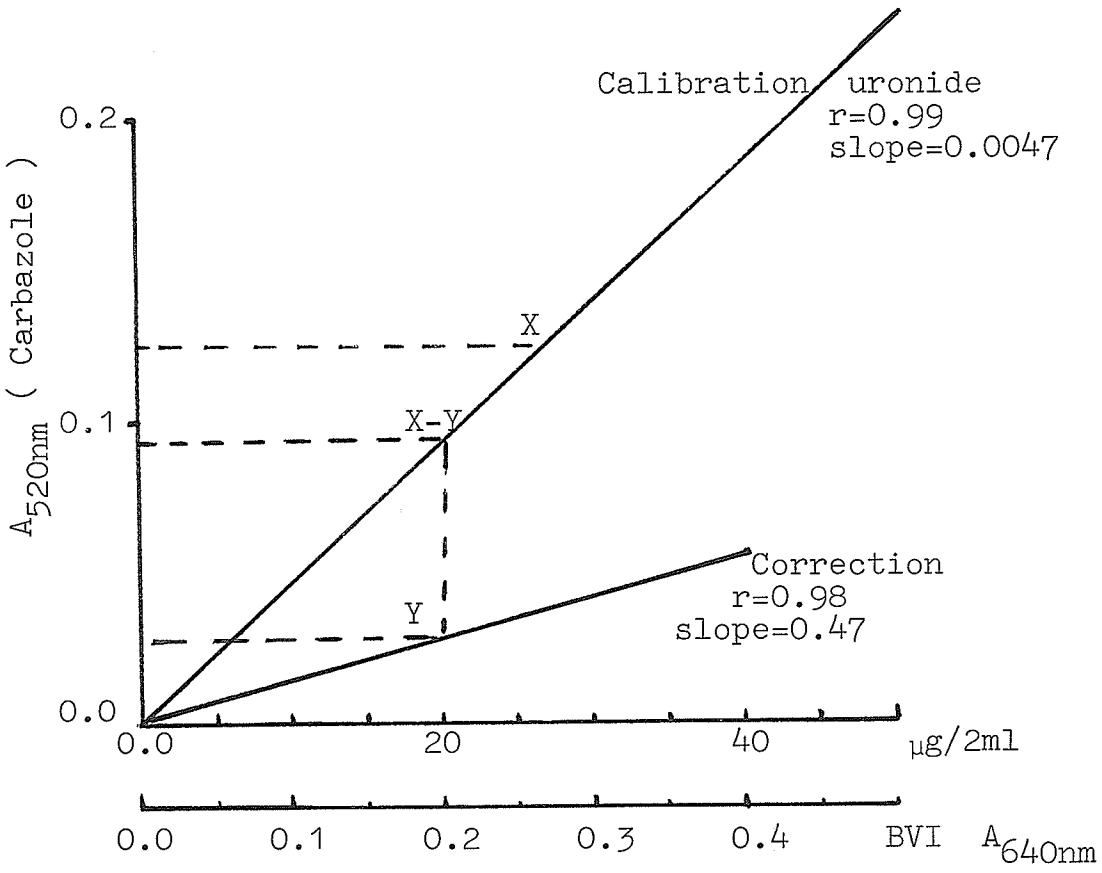

Calibration uronide
r=0.99
slope=0.0047
Correction
r=0.98
slope=0.47
X
X-Y
Y
0.2
0.1
0.0
A520nm ( Carbazole )
0.0
20
40
µg/2ml
0.0
0.1
0.2
0.3
0.4
BVI A640nm

TABLE 15. Water soluble pectic substances in cooked mashed potato.

| Treatment | Starch BVI $A_{640nm}$ | Total pectic subst. | µg/2 ml extract | mg/100 g WB | mg/100 g DB |
|---|---|---|---|---|---|
| Boiling water with 100 ppm calcium | 0.065 | 0.205 | 37.23 | 37.23 | 148.92 |
| Microwave | 0.265 | 0.390 | 56.47 | 56.47 | 218.87 |
| Boiling water & steam | 0.270 | 0.256 | 27.46 | 27.46 | 109.46 |
| Boiling water with 100 ppm Ca & steam | 0.389 | 0.330 | 31.48 | 31.48 | 125.92 |
| Boiling water | 0.376 | 0.320 | 30.59 | 30.59 | 122.36 |
| Steam | 0.298 | 0.342 | 42.97 | 42.97 | 171.88 |

of cooked potatoes. This may suggest that pectic substances in the potato analyzed are mainly in tightly bound forms. The observation that the quantity of calgon-soluble fraction of pectic substances was low and that cooking increased the apparent total considerably (Table 16) suggests that ionic bonds are not important in the structure of protopectin in Netted Gem potatoes. Instead, it appears that physical enmeshing of the polyuronides in the cellulosic fibres of the cell walls and other bonds existing in cell walls and middle lamella are more important. This fraction of enmeshed polyuronides could be solubilized completely by HCl at higher temperatures as found by Bettelheim and Sterling (1955). However, this was not analyzed in this study because the excessive starch hydrolysis and extraction caused by the HCl resulted in extracts to which the starch carbazole correction curve could not be applied satisfactorily.

4.2.3.4 Dehydration of the Freeze-Thawed Mash Potato. After cooking, the potatoes were mashed separating the cells with little damage. The mashed potatoes were then frozen at -20°C. As the potatoes were being frozen part of the intercellular water was drawn out osmotically due to the freezing concentration of the cell mass. Thus, ice crystals were formed both outside and inside the cells. The starch gel also retrograded more fully under these conditions. Thawing, however, must be controlled so that the temperature of the mash should not be higher than 5°C when predrying starts or the benefit of freezing will be substantially lost through readsorption of water and softening of cell walls. By freezing and thawing a remarkable toughening of the cell wall occurs which makes cell separation during granulation more easily accomplished.

TABLE 16. Calgon soluble pectic substances in cooked mashed potato.

| Treatment | Starch BVI $A_{640nm}$ | Total pectic subst. | µg/2 ml extract | mg/100 g WB | mg/100 g DB |
|---|---|---|---|---|---|
| Boiling water with 100 ppm calcium | 0.030 | 0.059 | 9.570 | 9.57 | 38.28 |
| Microwave | 0.036 | 0.051 | 7.250 | 7.25 | 28.10 |
| Boiling water & steam | 0.097 | 0.127 | 17.320 | 17.32 | 69.20 |
| Boiling water with 100 ppm Ca & steam | 0.121 | 0.139 | 17.540 | 17.54 | 70.10 |
| Boiling water | 0.075 | 0.049 | 2.958 | 2.95 | 11.83 |
| Steam | 0.090 | 0.093 | 10.850 | 10.85 | 43.40 |

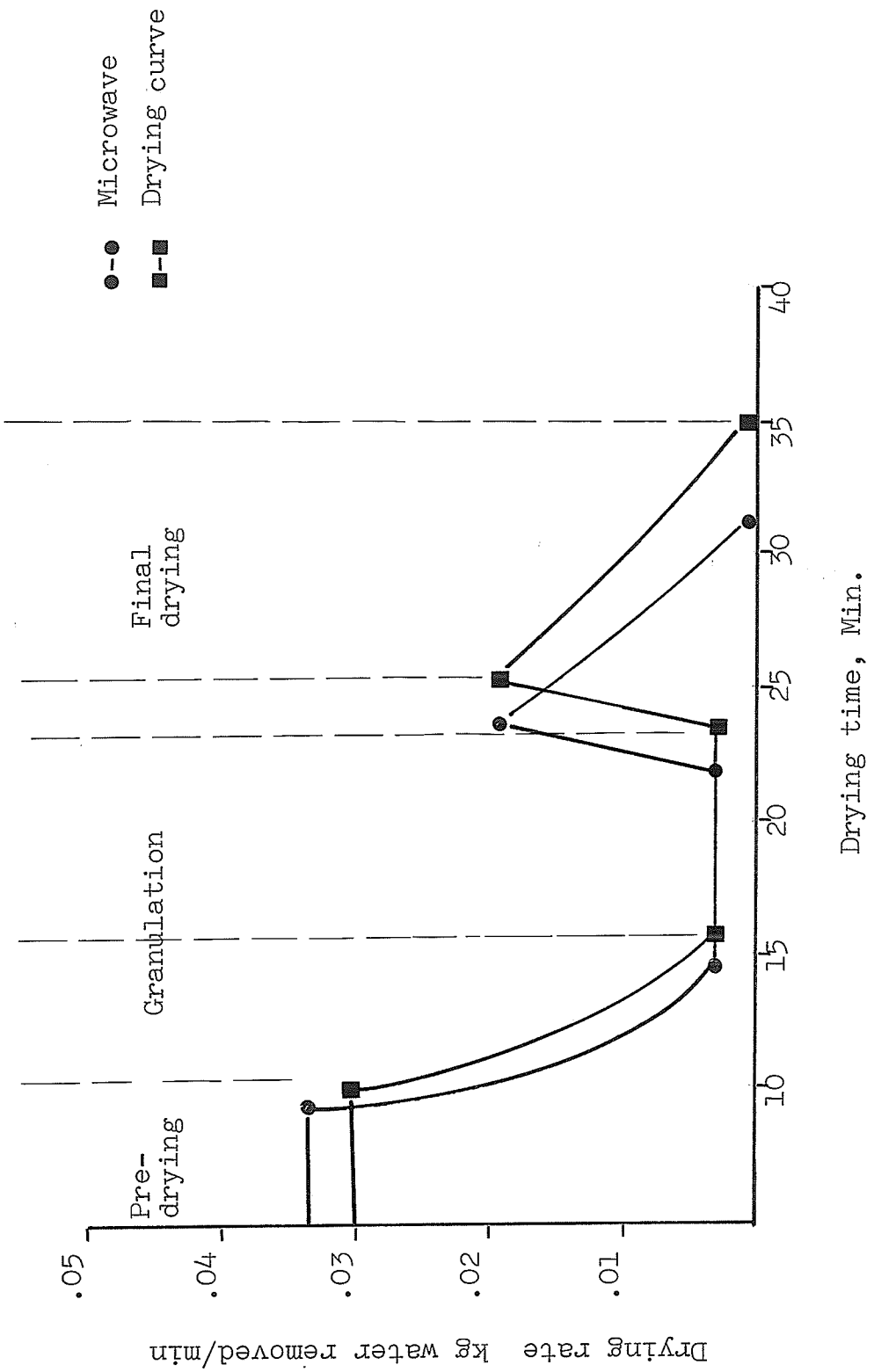
The thawed mash assumed the consistency of granular materials, e.g. wet sand with a substantial portion of the moisture being extracellular (Moledina et al, 1978). Materials of such a consistency exhibit a significant period of constant drying rate where the moisture can be rapidly evaporated from the material (Treybal, 1973; Labuza, 1972). Increased initial moisture levels and increased load weights will increase the time required to dry the material.

The freeze-thawed mash was first pre-dried using a bath fluidized bed dryer adapted with a stirrer. Mashed potatoes (500 g) were pre-dried under 70°C for 10 minutes with an air flow of 73 m/minute. The initial moisture content of the freeze-thawed mash dropped from approximately 76 to 40% in this step, excepting the freeze-thawed mash which was cooked by microwave that required 8 minutes under the same conditions since the initial moisture content was 74.2%.

During granulation the temperature was reduced to 50°C and the air velocity remained constant, the velocity of the stirrer was increased to high speed for 15 minutes. It is believed that at a moisture range of 45 to 35% the potato cells are most resistant to rigorous compression and shear due to the high speed of the stirrer; this also produces higher yields of fine granules, lower amounts of discards and less broken cells than when the potatoes are granulated at higher or lower moisture contents (Ooraikul, 1978). It is also apparent from Figure 34 that the drying enters the falling rate period during the granulation step. The moisture content in the granulation step dropped from 40 to 30%.

After the granules were produced, the final drying took place under falling rate conditions dropping the moisture content from 30 to 8% in 8 minutes at a temperature of 80°C and an air velocity of 56 m/minute.

Figure 34. Drying pattern during dehydration of potatoes.


Microwave
Drying curve
Pre-drying
Granulation
Final drying
.05
.04
.03
.02
.01
10
15
20
25
30
35
40
Drying rate kg water removed/min
Drying time, Min.

After drying, the product was sieved and the granules retained on mesh 20, consisting mainly of unmashable tissue, were rejected during the process. Intermediate size granules (higher than mesh 20 and lower than mesh 50) normally consisted of aggregates comprising several cells that failed to separate during granulation or which might have been formed during granulation. These aggregates of granules were recycled for further granulation. Granules which passed through mesh 50 were accepted. The percentage of granule production is portrayed in Table 17. These data illustrate that microwave cooking produced the higher yield while those granules cooked in water as a medium showed the lower yield, excepting where calcium was present. This is possibly explained as follows; boiling water weakened the cell walls exposing the starch that during dehydration formed agglomerates, otherwise calcium strengthened the cell walls too much so that during mashing the cells have to be disrupted producing high amounts of rejected granules as seen in the data shown in Table 17. Steam granules indicate that few changes, besides gelatinization of the starch and dissolution of pectic substances, occurred. Microwave granules indicate that the degree of swelling during gelatinization of the starch is less than in the other methods of cooking and thus did not subject the cell wall to stress forces and, therefore avoided weakening them.

4.2.3.5 Granule Microstructure. The granule microstructure of freeze-thaw processed material is shown in Figure 35. Most of the granules are shrunken with a wrinkled cellulosic wall surrounding the dried cell content and very angular in comparison to the Add-back granules which are largely round (Figure 36). It is not unusual to have

TABLE 17. Granule yield using the freeze-thaw technique.

| Granules cooked by | Retained in mesh 20 | Retained in mesh 50 | Accepted granules |
|---|---|---|---|
| Steam | 9% | 28-27% | 63-64% |
| Boiling water with 100 ppm calcium | 29% | 11-10% | 60-61% |
| Microwave | 8-9% | 8-6 % | 84-86% |
| Boiling water | 30% | 25-23% | 45-47% |
| Boiling water and final cooking by steam | 29% | 26-24% | 45-47% |
| Boiling water with 100 ppm calcium and final cooking by steam | 30% | 25-23% | 45-47% |

Figure 35. Scanning electron micrographs of potato granules produced by the freeze-thaw process at a magnification of 500 X.

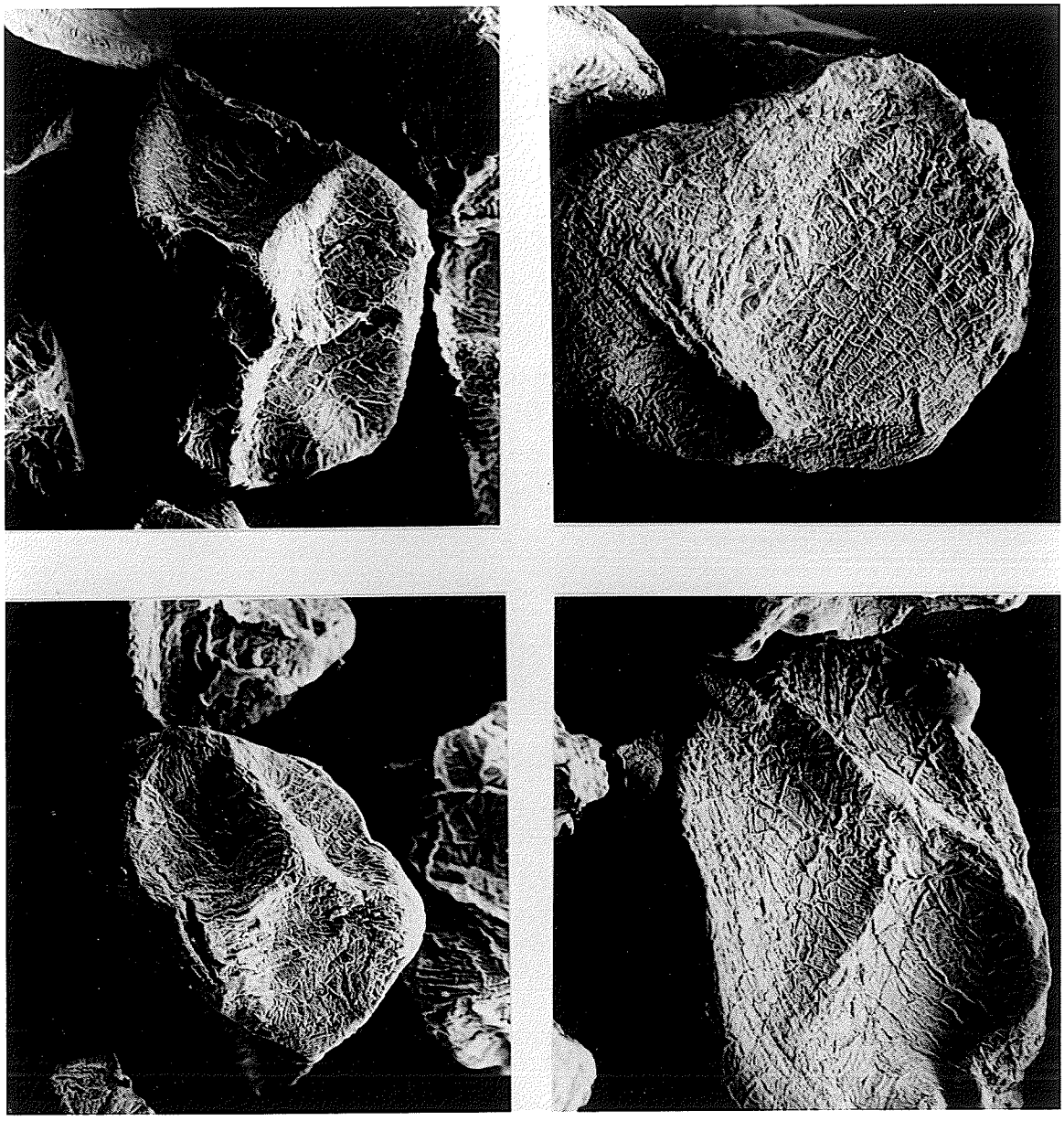
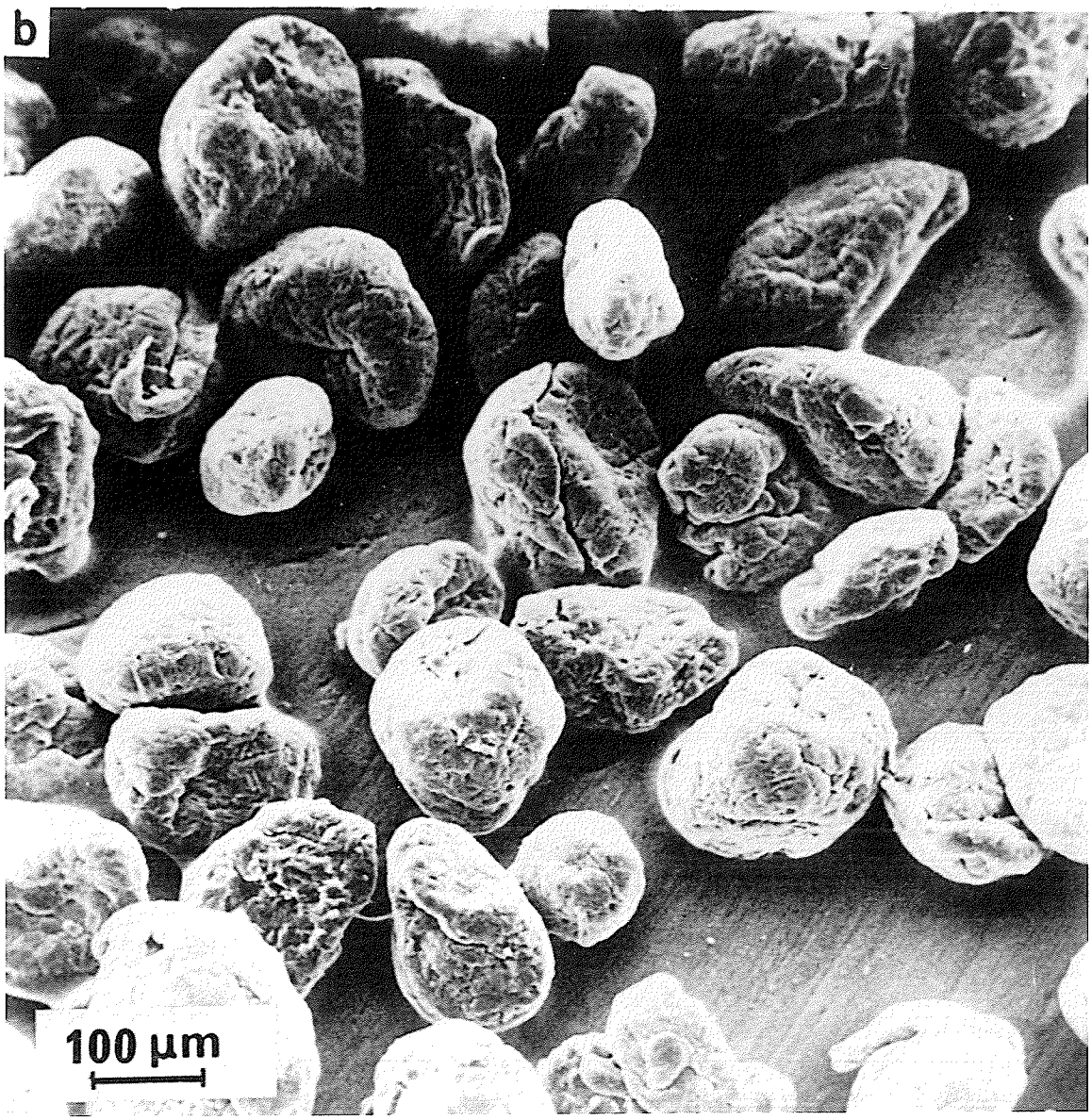


Figure 36. Scanning electron micrograph of potato granules obtained by the add-back process (Hadziyev and Steele, 1979).


b
100 µm

angular-shaped potato cells in the final product, since that is their original natural appearance. Reeve et al (1969b) pointed out that potato cells remain angular and polyhedral as in their original raw state when frozen par-fries were thawed and soaked in cold water, or in cooked potatoes prior to the point of cell sloughing.

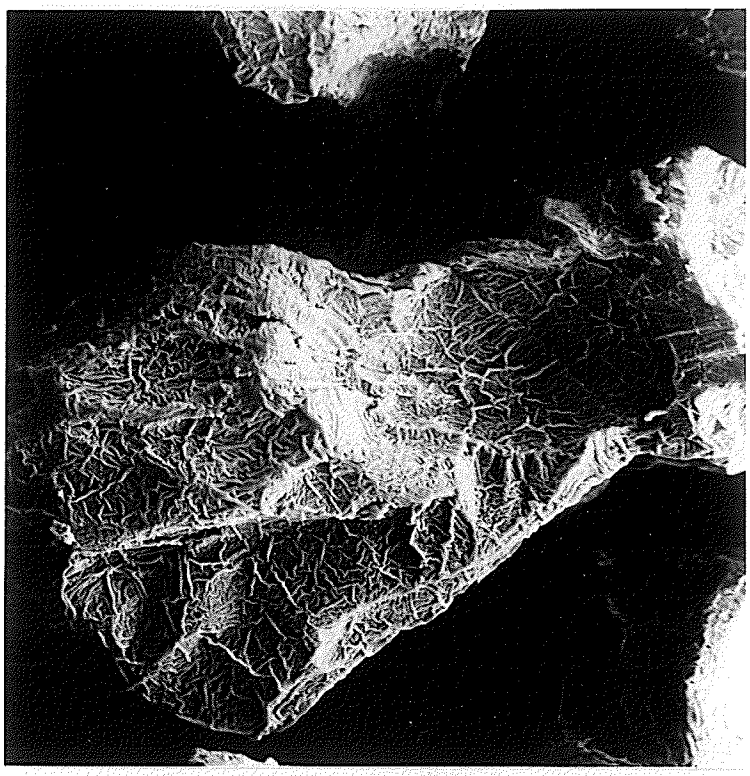
Also, from Figure 35 some fissures can be distinguished. These fissures obviously assist the penetration of water towards the internal surface of the granules during reconstitution. However, if granules consist mainly of separated cells, the total surface area of contact between granules and water would be larger. This could result in different textural and organoleptic impressions of reconstituted products (Jericevic et al, 1977).

A small number of cells were found aggregated, usually around a ruptured cell (Figure 37).

4.2.3.6 Physicochemical Properties of the Freeze-Thaw Granules. The rehydration experiments were plotted as kg water per kg wet granules versus time in seconds (Figure 38). The results obtained are an average of three determinations. This allows a more uniform rehydration and mixing on reconstitution of the granules with water than the add-back granules.

In Table 18 water holding capacity, free starch determination and swelling power are reported. With respect to free starch and water holding capacity properties, the granules obtained by the freeze-thaw process are quite similar to those obtained by the add-back process. Regarding swelling power, all the granules obtained by the freeze-thaw process show higher values possibly due to the shrunken cells that

Figure 37. Micrographs of agglomerates produced by the freeze-thaw process due to leached starch at a magnification of 500 X.



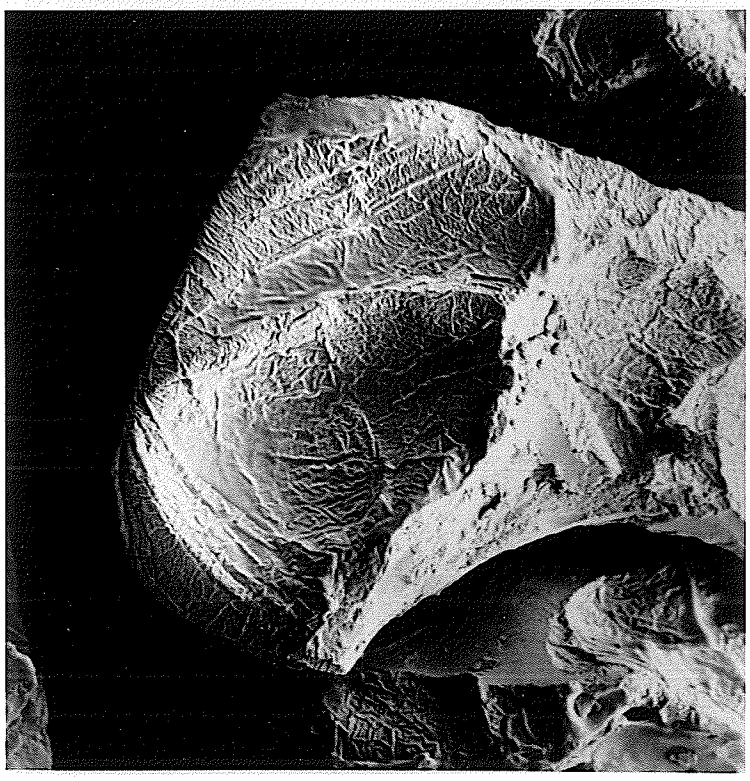


Figure 38. Rehydration curve of potato granules.

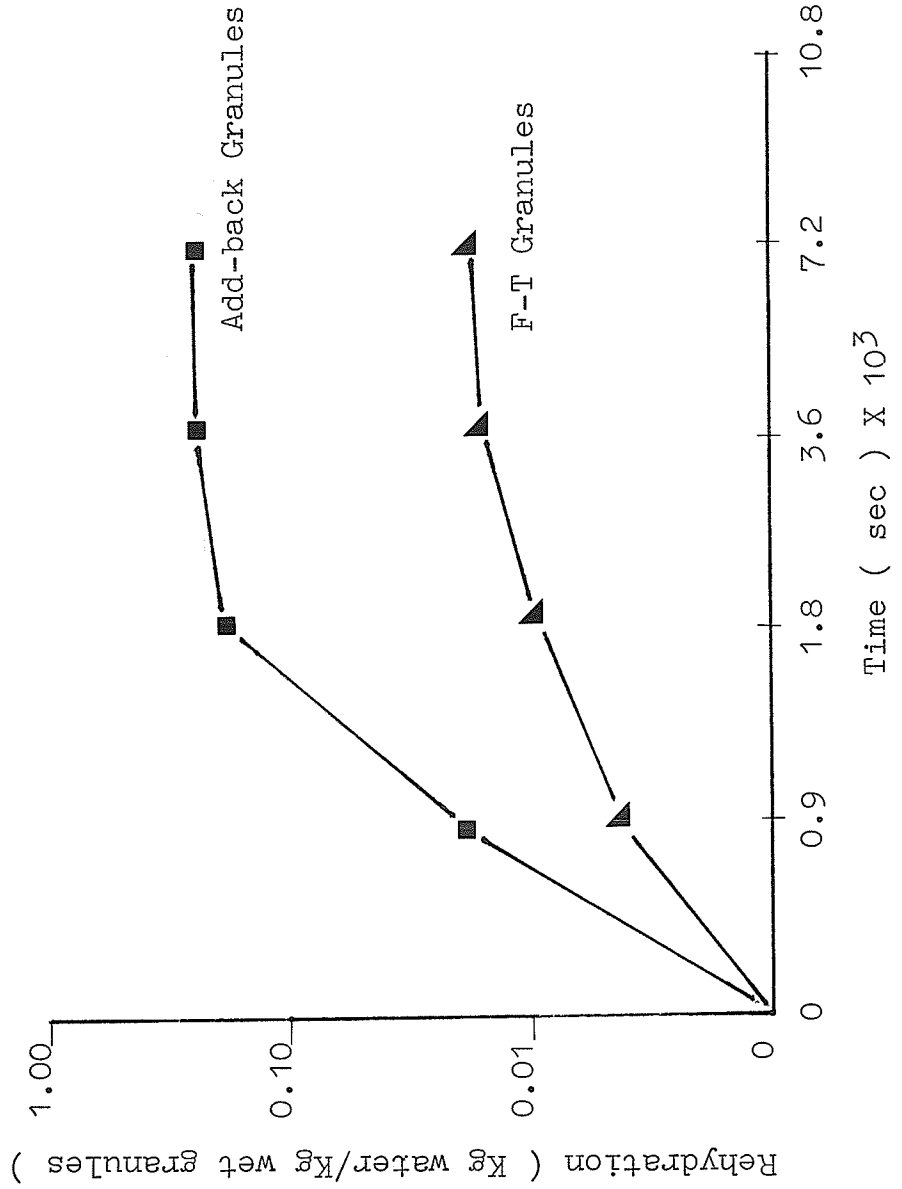

Add-back Granules
F-T Granules
1.00
0.10
0.01
0
0
0.9
1.8
3.6
7.2
10.8
Time ( sec ) X 10³
Rehydration ( Kg water/Kg wet granules )

TABLE 18. Physicochemical properties of potato granules.

| Treatment | Free starch[1] BVI ($A_{640nm}10^3$) | WHC[1] g water/ 100 g dry matter | Swelling[1] power (ml/10 g dry matter) |
|---|---|---|---|
| Add-back | 158 ± 3.2 | 398 ± 13.20 | 26.0 ± 0.6 |
| Freeze-Thaw | | | |
| Boiling water & steam | 154 ± 4.3 | 435 ± 11.50 | 49.5 ± 0.5 |
| Boiling water | 130 ± 5.1 | 393 ± 12.80 | 49.0 ± 0.2 |
| Steam | 160 ± 3.7 | 295 ± 25.90 | 47.5 ± 0.1 |
| Microwave | 169 ± 2.5 | 386 ± 9.35 | 41.5 ± 0.3 |
| Boiling water with 100 ppm calcium | 157 ± 2.8 | 413 ± 15.60 | 48.0 ± 0.2 |
| Boiling water with 100 ppm calcium & steam | 140 ± 4.2 | 273 ± 22.40 | 44.0 ± 0.3 |

[1]Mean of 6 observations.

could resist more expansion when water was added.

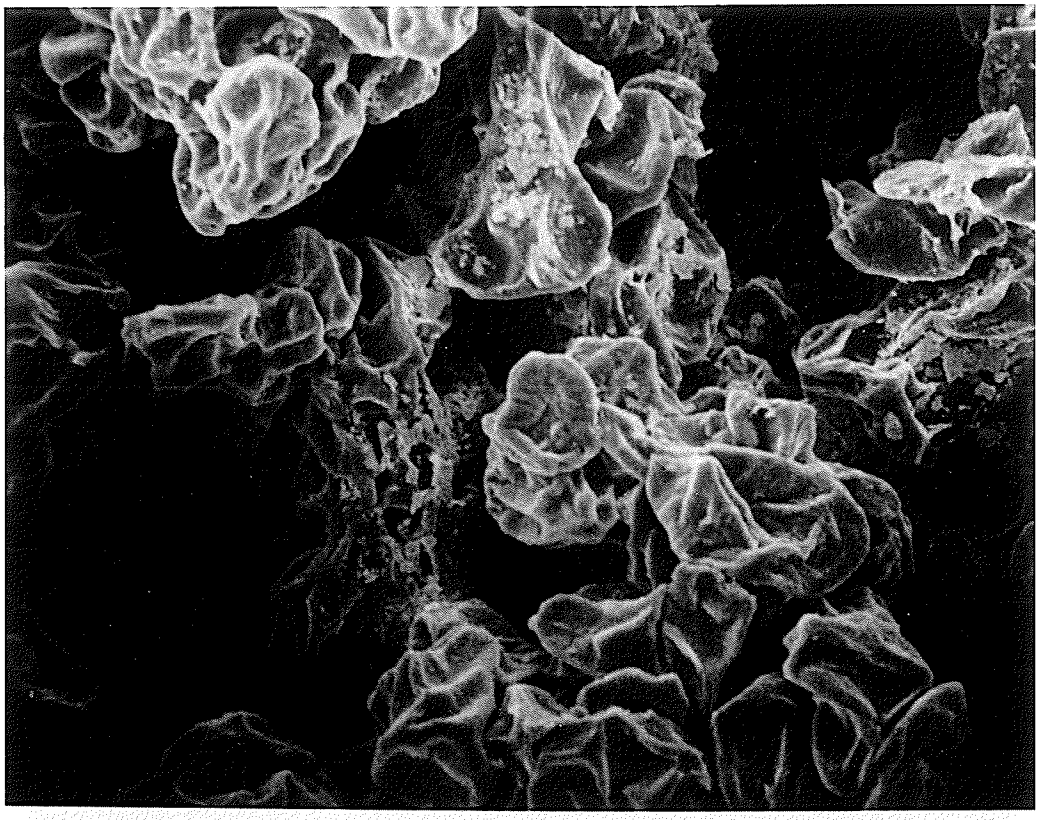
4.2.4 Continuous Process

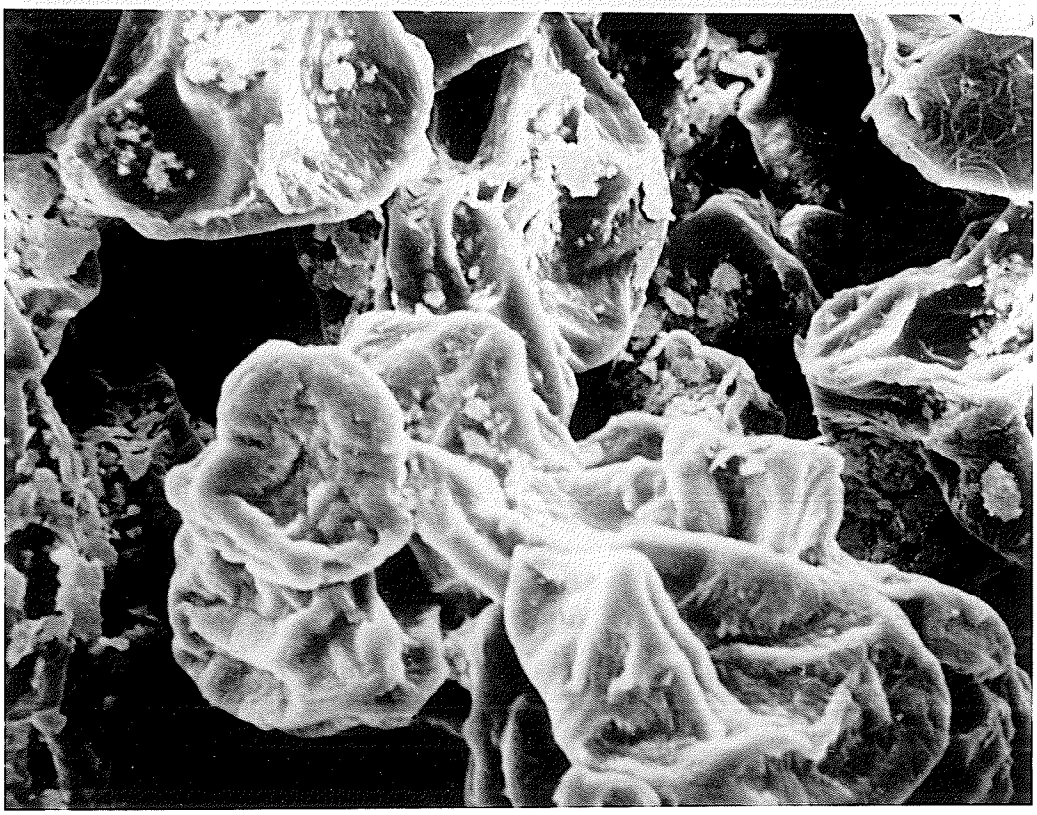
This process mainly consisted of the following steps: the potatoes were washed, peeled, cut, cooked, conditioned, pre-dried, granulated and dried. The cooking methods applied to the freeze-thaw process and the analytical tests applied on the final products were also used in the continuous process. The results obtained with this process were similar to those with the freeze-thaw products. After cooking, the potato was subjected to a conditioning period in which the cooked tubers were left at room temperature for half an hour in order to ensure that starch retrogradation was fully achieved as performed in the add-back process.

Conditioning was thought to release water from the gelatinized starch matrix to the surrounding. The sample was then pre-dried in a drum drier working at 2.8 $kg/cm^2$ and a temperature of 130°C, formed a flake type product with a moisture content of 36%. Then granulation was carried out in a fluidized bed batch dryer adapted with a stirrer device as done in the freeze-thaw process. Finally, the product was dried to 8% moisture content. In Figure 39, the granules obtained by this process are shown, agglomeration of granules occurred by this process rather than individual granules. This agglomeration can be explained as a physical phenomenon rather than a chemical one. In the freeze-thaw process internal water or physically bound water probably migrated from the cell, thereby avoiding: 1) expansion and rupture of the cell walls and 2) exposure of the starch matrix which causes agglomeration during evaporation.

In the continuous process, retrogradation occurs to some extent, but the free water liberated by the starch did not migrate extracellularly,

Figure 39. Granules produced by the continuous process. Lumps can be distinguished easily demonstrating the failures of this process; magnifications are 200 X and 400 X.





therefore during dehydration the cell walls were open by the forces caused when water was evaporated. The physicochemical results obtained (Table 19) show that this method is not adequate or recommended for the production of potato granules. Mullins et al. (1955) established that potato granules with B.V.I. ranging from 80 to 190 units were acceptable. Potato granules with large B.V.I. readings had a pasty texture caused by free starch. This effect occurs when the cellular matrix is destroyed leaching starchy material out. The water holding capacity of granules from the continuous process (210-225 g D.B.) is also much lower than those from the add-back process (398 g D.B.).

TABLE 19. Physicochemical properties of potato granules produced by the continuous process.

| Treatment | Free starch BVI ($A_{640nm}10^3$) | WHC g water/ 100 g D.B. | Swelling power (ml/10 g D.B.) |
|---|---|---|---|
| Add-back | 158 ± 3.2 | 398 ± 13.20 | 26.0 ± 0.6 |
| Continuous: | | | |
| Boiling water & steam | 235 ± 2.5 | 215 ± 15.3 | 60.0 ± 0.5 |
| Boiling water | 270 ± 3.0 | 210 ± 12.2 | 82.0 ± 0.7 |
| Steam | 233 ± 1.5 | 220 ± 8.0 | 52.0 ± 0.5 |
| Microwave | 225 ± 2.0 | 225 ± 5.0 | 49.5 ± 0.5 |
| Boiling water with 100 ppm calcium | 255 ± 3.0 | 215 ± 10.0 | 52.5 ± 1.0 |
| Boiling water with 100 ppm calcium & steam | 250 ± 4.0 | 217 ± 10.5 | 51.3 ± 1.5 |

# 5. CONCLUSION

Various cooking methods applied in the production of potato granules have shown different effects upon microstructural and processing characteristics of the final potato products. The rupture of cells, a consequence of boiling water, appeared to be due to cell wall distension. Cell wall distension in pre-cooking was not pronounced as the size of the raw cell was retained. Boiling water in the presence of calcium yield granules in almost the same amount as steam, possibly because calcium reacted with pectic substances responsible for the cohesiveness of the cells, protecting the cell walls from distension. Also, ions are thought to be related with the retrogradation of the starch when water is liberated from it. Steam appeared to cause less distension than boiling water. These findings are in agreement with those obtained by Reeve (1972) and Bretzloff (1970).

Microwave cooking caused less cell wall distension, since the gelatinized starch did not swell during cooking as much as in the other methods and expansion did not occur explaining the higher production obtained.

The advantages found in the freeze-thaw process in comparison with the add-back process are as follows: several mixing, pre-cooking, conditioning and recycling steps, as usually applied in add-back process, were eliminated and replaced by only freezing, thawing and predrying steps.

Granulation in the add-back process was accomplished by the recycled dry granules being passed and embedded into newly cooked tissue, thereby separating the cells (Van Arsdel et al, 1973b). Since the solubilization of cell binding material was reduced due to the pre-cook treatment, cell separation might not be complete, leaving some unbroken lumps which would later be discarded. Moreover, starch released when some of the cell walls are torn apart might cause formation of aggregates or might remain in the final product and cause stickiness on reconstitution.

Freezing and thawing increased the porosity of cell walls and caused partial separation of water from individual cells, thus resulting in rapid dehydration in the pre-dried step. The resultant add-back granules were largely round and more compact with a relatively smooth surface, while the freeze-thaw granules were mostly angular with considerable shrinkage and their surface was covered with minute holes or pores.

The continuous process failed because during pre-drying, water evaporated forcing the cell walls to distend causing opening of the cells and leaking starch forming great amounts of agglomerates. This confirmed that the state of the water present on the cells played a definite role in the production of potato granules, relating to some extent to the method of cooking applied.

# 6. RECOMMENDATIONS FOR FUTURE RESEARCH

1. Further studies on the retrogradation of starch are required; particularly the effect of ions. It may be possible to study the role of phosphate ions during retrogradation by enzymatic or other means. This may help to explain the role of calcium ions during the collapse of starch granules as observed in this study.

2. Microstructure analyses in this study indicated that various cooking techniques inhibited differing effects on the starch molecule. Further studies, i.e. by using column chromatography to determine changes in molecular weight may help to evaluate these changes.

3. An assessment of the energy requirements of the freeze-thaw process as compared with the add-back process is necessary in order to evaluate their adaptability at the commercial level.

4. Further studies are required at the process engineering level in order to modify the freeze-thaw and continuous processes, thereby making them more efficient for commercial application. For example, the predrying stage could be carried out using microwave energy, thereby increasing the efficiency of granulation.

5. Sensory evaluation of the final products that come from the freeze-thaw, add-back and continuous processes should be carried out. This will assist in assessing the textural quality of these products and help to evaluate the physical parameters that were observed in the granules under the microscope. This evaluation was not possible in this current study since the potatoes used had a distinct bitterness indicating high levels of glycoalkaloid were present.

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# APPENDIX

APPENDIX 1. Analysis of variance for potato ash as split-plot design.

| Specific gravity | Tissues | Repetitions | | | | Total |
|---|---|---|---|---|---|---|
| 1.02437 (A) | Cortex | 0.75 | 0.67 | 0.73 | 0.69 | 2.840 |
| | Outer Medulla | 0.49 | 0.50 | 0.48 | 0.48 | 1.974 |
| | Pith | 0.55 | 0.60 | 0.53 | 0.62 | 2.304 |
| | | 1.798 | 1.782 | 1.743 | 1.795 | 7.118 |
| 1.06417 (B) | Cortex | 0.71 | 0.72 | 0.74 | 0.73 | 2.917 |
| | Outer Medulla | 0.61 | 0.55 | 0.53 | 0.51 | 2.200 |
| | Pith | 0.69 | 0.72 | 0.74 | 0.70 | 2.857 |
| 1.07589 (C) | Cortex | 0.83 | 0.79 | 0.84 | 0.82 | 3.304 |
| | Outer Medulla | 0.73 | 0.60 | 0.74 | 0.70 | 2.773 |
| | Pith | 0.61 | 0.69 | 0.70 | 0.66 | 2.675 |
| | | 2.182 | 2.100 | 2.285 | 2.185 | 8.752 |
| 1.08300 (D) | Cortex | 1.28 | 1.18 | 1.00 | 1.10 | 4.560 |
| | Outer Medulla | 0.87 | 0.99 | 0.92 | 0.89 | 3.670 |
| | Pith | 1.05 | 1.02 | 0.99 | 0.98 | 4.045 |
| | | 3.200 | 3.190 | 2.915 | 2.970 | 12.275 |
| 1.09200 (E) | Cortex | 0.71 | 0.82 | 1.25 | 1.22 | 4.000 |
| | Outer Medulla | 0.54 | 0.70 | 0.83 | 0.88 | 2.968 |
| | Pith | 0.60 | 0.80 | 0.82 | 0.93 | 3.150 |
| | | 1.858 | 2.327 | 2.901 | 3.032 | 10.118 |
| 1.09932 (F) | Cortex | 0.89 | 1.22 | 1.35 | 1.25 | 4.710 |
| | Outer Medulla | 0.64 | 0.68 | 0.69 | 0.67 | 2.687 |
| | Pith | 0.89 | 0.90 | 0.89 | 1.00 | 3.685 |
| | | 2.425 | 2.802 | 2.935 | 2.920 | 11.082 |
| 1.13842 (G) | Cortex | 0.95 | 1.17 | 1.05 | 0.97 | 4.153 |
| | Outer Medulla | 0.77 | 0.84 | 0.82 | 0.81 | 3.250 |
| | Pith | 0.87 | 0.87 | 0.88 | 0.89 | 3.521 |
| | | 2.601 | 2.887 | 2.753 | 2.683 | 10.924 |

(continued)

APPENDIX 1. (continued)

| Specific gravity | Tissues | Repetitions | | | | Total |
|---|---|---|---|---|---|---|
| 1.17281 (H) | Cortex | 0.93 | 0.95 | 0.94 | 0.91 | 3.748 |
| | Outer Medulla | 0.91 | 0.93 | 0.92 | 0.90 | 3.683 |
| | Pith | 0.55 | 0.67 | 0.68 | 0.72 | 2.631 |
| | | 2.395 | 2.566 | 2.557 | 2.544 | 10.062 |
| | Cortex | 7.068 | 7.536 | 7.914 | 7.714 | 30.232 |
| | Outer Medulla | 5.586 | 5.822 | 5.939 | 5.858 | 23.205 |
| | Pith | 5.828 | 6.286 | 6.248 | 6.506 | 24.868 |
| | | 18.482 | 19.644 | 20.101 | 20.078 | 78.305 |

Correction factor $= \frac{(78.305)^2}{96} = 63.87$

Total sum $(X)^2$ = 67.52 - C.F. = 3.65

(Sum of reps)$^2$/n = 63.94 - C.F. = 0.072 n = 24

(Sum of Sp. Gr.)$^2$/n = 65.60 - C.F. = 1.735 n = 12

(Sum of tissues)$^2$/n = 64.71 - C.F. = 0.84 n = 32

(Sum reps x Sp. Gr.)$^2$/n = 66.00 - C.F. - Reps - Sp. Gr. = 0.33 n = 3

(Sum reps x tissues)$^2$/n = 0.015 n = 8

(Sum Sp. Gr. x tissues)$^2$/n = 0.45 n = 4

ANALYSIS OF VARIANCE (SPLIT-PLOT DESIGN)

| Source of variation | DF | SS | MS | F |
|---|---|---|---|---|
| Specific gravity | 7 | 1.7355 | 0.2479 | 15.89** |
| Reps. | 3 | 0.7205 | 0.0240 | 1.53ns |
| Error a | 21 | 0.3291 | 0.0156 | |
| Main Plot Total | 31 | 2.1367 | | |
| Tissues | 2 | 0.8428 | 0.4214 | 93.64** |
| Tiss x Sp. Gr. | 14 | 0.4560 | 0.0325 | 7.22** |
| Error b | 48 | 0.2161 | 0.0045 | |
| Grand Total | 95 | 3.6518 | | |

(continued)

APPENDIX 1. (continued)

MEAN YIELDS FOR MAIN EFFECTS AND SIMPLE EFFECTS

| Tissues | Specific gravity | | | | | | | | Tissues main effects |
|---|---|---|---|---|---|---|---|---|---|
| | A | B | C | D | E | F | G | H | |
| Cortex | 0.71 | 0.72 | 0.82 | 1.14 | 1.00 | 1.17 | 1.03 | 0.93 | 0.94 |
| Outer Medulla | 0.49 | 0.55 | 0.69 | 0.91 | 0.74 | 0.67 | 0.81 | 0.92 | 0.72 |
| Pith | 0.57 | 0.71 | 0.66 | 1.01 | 0.78 | 0.92 | 0.88 | 0.65 | 0.77 |
| Sp. Gr. main effects | 0.59 | 0.66 | 0.72 | 1.02 | 0.84 | 0.92 | 0.91 | 0.83 | |

Comparison #1 - Between means of Specific Gravities over all levels of tissues tested.

$$S\bar{x} = \frac{Ea}{r \text{ Tissues}} = \frac{0.0156}{4(3)} = 0.0013 = 0.036$$

Tukey's w test  p = 8
n2 = 21
q = 4.75

| Sp. Gr. | Mean |
|---|---|
| A | 0.593 a |
| B | 0.664 a |
| C | 0.729 ab |
| H | 0.838 bc |
| E | 0.843 bc |
| G | 0.910 cd |
| F | 0.923 cd |
| D | 1.022 d |

$$w_{.05} = q \times S\bar{x}$$

$$w_{.05} = 4.75\ (0.036) = 0.171$$

Comparison #2. Between means of tissues tested over all levels of specific gravity.

$$S\bar{x} = \frac{Eb}{r \text{ Sp. Gr.}} = \frac{0.0045}{4(8)} = 0.00014 = 0.0118$$

Tukey's test  p = 3
n2 = 48
q = 3.42

| Tissues | Mean |
|---|---|
| Cortex | 0.944 a |
| O. Medulla | 0.725 c |
| Pith | 0.776 b |

$$w_{.05} = q\ S\bar{x}$$

$$w_{.05} = 3.42\ (0.0118) = 0.0405$$

APPENDIX 2. Water soluble pectic substances in potato granules.

| | Starch BVI $A_{640nm}$ | Total pectic subst. | µg/2 ml Extract | mg/100 g WB | mg/100 g DB |
|---|---|---|---|---|---|
| Freeze-thaw | | | | | |
| Boiling water with 100 ppm calcium | 0.325 | 0.900 | 159.14 | 397.85 | 418.79 |
| Microwave | 0.330 | 0.580 | 90.42 | 226.05 | 237.94 |
| Boiling water & steam | 0.225 | 0.950 | 179.78 | 449.45 | 473.10 |
| Boiling water with 100 ppm Ca & steam | 0.383 | 0.373 | 41.17 | 102.92 | 108.34 |
| Boiling water | 0.395 | 0.929 | 158.29 | 393.72 | 416.55 |
| Steam | 0.185 | 0.965 | 186.80 | 467.00 | 491.57 |
| Add-back | 0.353 | 0.820 | 139.29 | 348.22 | 366.55 |

APPENDIX 3. Calgon soluble pectic substances in potato.

| Granules | Starch BVI $A_{640nm}$ | Total pectic subst. | µg/2 ml Extract | mg/100 g WB | mg/100 g DB |
|---|---|---|---|---|---|
| Freeze-thaw | | | | | |
| Boiling water with 100 ppm calcium | 0.076 | 0.131 | 20.23 | 50.57 | 53.23 |
| Microwave | 0.079 | 0.114 | 16.36 | 40.90 | 43.07 |
| Boiling water & steam | 0.054 | 0.082 | 12.00 | 30.00 | 31.57 |
| Boiling water with 100 ppm Ca & steam | 0.106 | 0.194 | 30.68 | 76.70 | 80.73 |
| Boiling water | 0.100 | 0.099 | 11.06 | 27.65 | 29.10 |
| Steam | 0.096 | 0.175 | 27.63 | 69.07 | 72.71 |
| Add-back | 0.115 | 0.118 | 13.61 | 34.02 | 35.81 |