CHEMICAL AND PHYSICAL PROPERTIES AFFECTING THE COOKING OF POTATOES

By

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AN ABSTRACT

Submitted to the School for Advanced Graduate Studies of
Michigan State University of Agriculture and
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DOCTOR OF PHILOSOPHY

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MAHENDRA KUMAR SHARMA

ABSTRACT

Katahdin potatoes of three specific gravity groups 1.065 - 1.070, 1.074 - 1.076, and 1.080 - 1.085 were stored at 40° and 70° F. to determine the effect of specific gravity and storage temperatures on the hardness of the tubers after cooking as measured by mechanical pressure tester. Fourteen varieties in 1956 and 15 varieties in 1957 were used to examine the specific gravity and cooking characteristics of different parts of tuber before storage, and analysis of pectic compounds and hemicelluloses of hard-cooking Onaway tubers was correlated with hardness both before and after storage.

(1) Initially, the internal region (pith) had more resistance to pressure after cooking than surface region (cortex). As storage period increased both surface and internal areas cooked soft. Changes in pressure resistance after cooking were greater in the internal area than in the surface area. The change from hard to soft was accelerated by increasing temperature.

(2) Within single tubers of any variety the specific gravity of the pith was characteristically lower than that of the cortex and outer medulla, while cortex and outer medulla differed only slightly in specific gravity. These differences were greatest in tubers of high specific gravity. Such high specific gravity potatoes also exhibited marked differences in resistance to pressure between surface and internal

areas at eight weeks of storage at 70° F. Low specific gravity potatoes exhibited less pronounced differences. Differences in specific gravity between variety were not related to the resistance to pressure after cooking of each variety.

(3) Excessive deposit of calcium pectate, protopectin and hemicelluloses were the cause of hardness in the internal area of cooked tubers. Upon reduction in the amount of these substances after five to six weeks of storage at 70° F., these tubers cooked soft. With the fall of pectic substances and hemicelluloses to levels which no longer caused hard cooking, the penetration resistance of tuber tissue was dependent on starch content.

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INTRODUCTION

Culinary quality of potatoes has been related to the appearance, texture and taste of cooked tubers. For highest quality it is generally agreed that boiled or baked potatoes should be creamy white in color, have a moderately dry to dry and mealy texture, and a good natural potato flavor. An additional quality characteristic is the time required to cook potatoes to "done-ness" by boiling. Frequent complaints are made where tubers do not cook uniformly and quickly, and it was the purpose of this study to examine the reasons for this lack of uniformity in cooking.

This difficulty is not invariably associated with any one variety, but occurs at times in at least several of our standard varieties. In 1955, the variety Sebago furnished our best experimental material. In 1956, Katahdin exhibited this characteristic, while in 1957 an early variety, Onaway, harvested when tops were dry, was found to contain about 80% of tubers that cooked very slowly. Fifteen other standard varieties, both early and late, were grown in the same trial and no other variety was found which cooked particularly hard. This year 10 to 80 percent of tubers in samples of Onaway from several locations were found to be unacceptable. A few years ago the variety Menominee was found to cook hard. In 1957 it cooked without difficulty, which indicated that one variety which may cook hard one year may cook differently another year. No theories were found in the literature to explain the occurrence of this phenomenon.

Practically no work has been reported on the physical and chemical properties which influence the time required to cook potatoes. During cooking of potatoes two obvious changes take place. Starch is gelatinized, and owing to a marked decrease in cell adhesion, the tissue is softened and cells separate so that the tuber can be readily mashed. Upon completion of these changes the tuber tissue is judged to be cooked.

The role of pectic substances in the architecture of plant cell walls has been well demonstrated. It has been shown that pectic substances are present in the primary cell wall. They are also found as a cementing material in the middle lamella between adjoining cells. It is assumed that they are made up principally of calcium salts of pectic acid and pectinic acid, insoluble "glues" which bind the cells together. The cellulose is so intermingled with pectic substances, hemicelluloses and other materials in the walls that when these substances are removed or modified, the walls are weakened and become fragmented and lamellate.

A study of changes in cooking properties with increasing storage was conducted. Differences in response to cooking of various tuber tissue areas were investigated, as were physical differences between the areas. Finally, the association of various pectic constituents with cooking characteristics, and the relationship of changes of pectic materials to changes in cooking properties were studied.

REVIEW OF LITERATURE

There are many aspects of potato quality which have been studied in the past. Among those receiving most attention have been the problems of post-cooking darkening, the development of color in potato chips, the mechanism of cooking, and the relationship between specific gravity and mealiness of cooked tubers. Less work has been reported on the role of pectic compounds in regard to cooking.

The work on darkening was reviewed recently by Smith and Muneta (1954) whose theory related the presence of iron and o-diphenols to the occurence of dark pigments in tubers after boiling. The chemistry of chip color and the occurrence of the reactants in raw tubers was discussed by Shallenberger and Smith (1955) who postulated that products of condensation between amino acids and reducing sugars were responsible for the brown pigment of fried potato slices. These considerations constitute major areas of investigation, each with voluminous literature. The literature pertaining to the phenomena of texture and hardness in cooking is reported in the following review.

The mechanism of cooking. Knowledge of the changes which occur during cooking has been incomplete and results as interpreted have often been contradictory. There has been a general misconception of the physical changes developed within a potato tuber during cooking. Atwater (1895) thought that on boiling the starch swelled and the cells burst open. Gilmore (1905) and East (1908) believed that mealy potatoes were those containing sufficient starch to rupture the cell walls during boiling. In 1917 Langworthy attributed the bursting of the cell walls to internal steam pressure. These investigators overlooked the possibility that disintegration of the cells may have been due to the mechanical operation of mashing rather than to cooking itself. Day (1909) on examination of cooked potatoes found no breakage of the cell walls. She postulated that: "The middle lamella which holds the cells together had dissolved and the cells separated from each other". She did not find that bursting of cells was associated with mealiness. Sweetman (1933) agreed with Day, and conjectured that the cooking process of potatoes was characterized by such physico-chemical changes as partial gelatinization of the starch, the solution of some of the pectic substances, the increased digestibility of cellulose, the coagulation of most of the protein and more or less caramelization of the sugars.

Reeve (1954) claimed that histologically, tissue softening, starch gelation and swelling, cell separation and cell wall distention and rupturing were interdependent changes caused by cooking potatoes. This was essentially in agreement with the conclusion of Personius and Sharp (1938, 1939a, 1939b) that neither failure of cell cohesion nor starch gelation, alone or in combination, was a casual factor for cooked texture in potatoes, but rather both were mechanisms of structural changes. Reeve's histological observations on heated slices of potatoes showed that cell separation, caused by weakening of the adhesive properties of the middle lamella and aided by swelling of the gelled starch within the cells, was not directly responsible for the difference between mealy and non-mealy cooked potatoes. Roberts and Proctor (1955) discovered that in aqueous medium, the middle lamellae of the parenchymatous starch-containing cells of the potato tuber were altered at 55°-60° C. and pectic substances in the walls were altered at 70° C. The cellulose of the walls was not destroyed at this temperature but was so weakened that the walls were fractured and no longer retained the starch grains which had gelatinized and were released as a sticky mass.

A general relationship between extent of sloughing from boiled tubers and specific gravity of raw tubers was observed by Whittenberger and Nutting (1950). Considerable variation both in extent of sloughing and in specific gravity occurred in different regions of the same tuber, in different tubers of the same lot, and different lots of the same variety. These investigators thought that the principal cause of sloughing was associated with the swelling of starch gelatinization, which developed pressure within cells sufficient to fracture mechanically the intercellular cement.

It is now generally accepted that cooking of potatoes does not cause bursting of cell walls but permits ready mechanical separation of cells. The starch grains swell (55°-65° C.) during cooking to fill the cell more or less completely and the cell separates more or less readily due to the dissolution of pectic substances at higher temperatures. Ruptured cell walls are not necessarily characteristic of cooked potatoes. Rupturing of cells, as distinct from separation of cells, is also caused by swelling of gelled starch.

<u>Specific gravity as related to mealiness in potatoes</u>. There are many factors such as variety, date of planting and of harvest, growing conditions (soil moisture, soil and air temperature) soil type, fertility and cultural practices which affect mealiness in potatoes. Numerous

investigators have shown that the relationship between specific gravity of potatoes and their quality as judged by mealiness is very close. Coudon and Bussard in 1897 discovered that tubers of good cooking quality showed a higher dry matter content than those of inferior quality. The association of high specific gravity (or high starch content) with mealiness of tubers has been noted by Cobb (1935), Sweetman (1936), Wright et al. (1936), Bewell (1937), Haddock and Blood (1939), Clark et al. (1940), Smith and Nash (1940), Prince et al. (1940), and Bonde and Covell (1955) and others.

Comprehensive studies by Kirkpatrick (1953) showed that dry matter, starch and alcohol insoluble solids content were also highly correlated with dryness and mealiness in boiled, mashed and baked potatoes. Bettelheim and Sterling (1955a) pointed out that specific gravity and starch content of raw tubers were significantly correlated with texture scores and a high degree of correlation was found between the starch content of cooked potatoes and organoleptic tests. Heinze et al. (1955) noted considerable variation in cooking quality between tubers of a single variety grown at different locations. In many varieties, differences between scores of samples grown at different localities were as great as differences among varieties at a single location. Chemical composition varied as much with locality as with variety.

These investigations indicate that at present, measurement of specific gravity is the best means of predicting the mealiness of cooked potatoes. However, it can not be concluded that specific gravity may be used safely as the sole criterion in assuring mealiness. Sweetman (1936) pointed out some exceptions to a positive correlation between specific gravity and mealiness. Kirkpatrick et al. (1951) working with four early varieties of potatoes, ranging in specific gravity from 1.06 to 1.08 found no significant correlation between specific gravity and mealiness in boiled, mashed and baked potatoes. Haddock and Blood (1939) indicated that potatoes of identical specific gravities grown at different locations differed in mealiness. Greenwood et al. (1952) showed that tubers with similar specific gravity may not always exhibit the same degree of mealiness. They demonstrated that association between specific gravity and mealiness varied depending on the location where the potatoes were grown. Whittenberger (1951) demonstrated that specific gravity did not indicate correctly the starch content nor by inference the mealiness of potatoes which had been stored either at very high or very low temperature. Nylund and Poivan (1953), working with Irish Cobbler, Waseca and Pontiac potatoes, concluded that two varieties even though identical in specific gravity may be quite different in components of quality. Similarly, tubers of a single variety having the same specific gravity but produced under different environmental conditions may be quite different in cooking quality as indicated by the difference between tubers from different dates of planting in this study. Unrau and Nylund (1957) conducted organoleptic tests on three varieties of potatoes and found that potatoes of different varieties which were identical in specific gravity differed in mealiness depending on the varieties being compared.

Although numerous investigators have studied the factors affecting the cooking quality of potatoes, many contradictory conclusions have been drawn and still persist. Some workers are of the opinion that there is a definite positive correlation between starch content and mealiness, whereas some have found evidence to the contrary. Shewfelt et al. (1955)

examined five varieties of potatoes and found that decreasing mealiness of cooked potatoes was associated with decreasing size of raw starch granules, increasing thickness of cell walls after cooking, increased fragmentation of cells after swelling, and increased gelatinization of starch. Tubers of the same variety grown at different places varied in mealiness and in thickness of cell walls after cooking. This led to the belief that starch, or dry matter, alone is not the only factor influencing texture.

Variation in cooking of different tuber areas. The several zones within a potato tuber have been reported to cook differently. Sweetman and Lancaster (1931) indicated that the texture (firmness) of cooked potatoes varied between different points on the same slice but that significant differences between slices were denoted by averages of ten penetrometer readings. Bud ends cooked to a much softer stage than stem ends as indicated by depth of penetration. Barmore (1937) on plotting penetration after cooking against starch content of the whole tuber, found marked inverse relationship between ease in penetration and starch content. Thus in tubers of high starch content penetration was low and softening on cooking less pronounced than in tubers of lower starch content. Since such a definite relationship between texture (firmness) and starch and between penetration and starch was found, a high correlation between texture (mealiness) and penetration was expected, but was not found. Thiessen (1935) working with potatoes grown upon dry and irrigated land discovered that dry land tubers showed greater resistance to softening at the cortex than in the medullary region, whereas these different regions of tubers from irrigated fields cooked uniformly. Cells of dry land potatoes were much larger than those of irrigated tubers of the same variety, particularly in the medullary area. The fact that greatest resistance to softening was found in the area of smallest cells and least in the area of largest cells afforded a plausible explanation for the rapid cooking of dry land as compared to irrigated potatoes of the same variety.

Thiessen (1947) studied the penetrometer readings of cooked Bliss Triumph and Cobbler potatoes after they had been stored three, six and nine months. The penetrometer reaoings were taken in the outer medullary area. The Bliss Triumph potatoes usually softened readily after cooking late in February and March. This change was more evident in the bud than in the stem half of the tuber. As the storage period continued until June, old potatoes from both varieties could be penetrated more readily than those from the same lot earlier in the year. Thiessen (1947) also found differences in penetration in a single tuber when two centimeter thick sections had been cooked for various periods. In most of the tubers the cortex was penetrated less easily than the other areas, and stem end also cooked harder than the bud end. There were also some tubers which reacted abnormally in each of the lots tested. In some, the pith or inner medullary area resisted penetration to a greater degree and for a longer period than the remainder of the tuber. As cooking progressed, however, easier penetration was usually obtained in the pith than in the cortex area. Although the pith or inner medullary area was usually penetrated more easily than the cortex, it frequently was rawer to the taste with similar cooking.

Hilton and Evans (1950) could not find any correlation between specific gravity of raw potatoes and either the force required to penetrate the raw tubers by a fruit maturity gauge or electrical resistence of tuber tissue. The penetration force as determined by their experiment had no close relationship with tuber density. They did not state at what time during the storage season their observations were made.

In general, there seems to be an inverse relationship between starch content and softness after complete cooking. The portions of a single tuber having much starch are harder after cooking than those having less starch.

Variation in composition of different tuber areas. If a potato is cut in two, several zones can be distinguished, each slightly different in composition. Coudon and Bussard (1897) reported that percentage of water increased, percentage of starch decreased and the percentage of total nitrogen increased from cortex to core (inner medullary area). They found that the cortex was richer in protein nitrogen than the core. East (1908) also separated potatoes into three parts. His results confirmed these findings. Frisbie and Bryant (1897) separated the cortex from the medullary area and analyzed the two parts separately. Their results directly opposed those of Coudon and Bussard, except that they also found more protein nitrogen in the cortex than in the medullary area.

Johnson and Boyle (1919) noted that the percentage of dry matter in tubers of a single variety varied from 21.07 to 27.18 and the starch percentage varied from 14.65 to 20.16. Glynne and Jackson (1919) reported that the percentage dry matter in tubers was lowest in the skin, increased to the inner cortical layer and decreased towards the centre of the tuber. Goldthwaite (1925) determined the chemical composition of cortex and medullary area of individual tubers and found that the percentages of dry matter, starch, total carbohydrate and ash were greater in the cortex than in the corresponding medullary area. No two potatoes of identical composition were found in the same variety, in the same group or in the same hill.

Thiessen (1947) showed distinct differences in composition of different areas of the same potato tuber. The stem end of the tuber contained more starch, less water and less crude fiber than the bud half. The cortex was higher in starch and lower in water than the other zones of the tuber. The outer medullary area had a slightly lower percentage of starch and higher percentage of water than the cortex. The inner medullary area had a higher proportion of crude fiber, pectin, and nitrogen than the rest of the tuber. She also found that no two tubers taken from the same lot had the same identical chemical composition. Whittenberger and Nutting (1950) noticed that generally, tissues of highest specific gravity occurred on both sides of the vascular ring, and tissues of lowest specific gravity were in the central pith or medulla. The starch content ranged from 10 percent in the central pith to about 25 percent in peripheral zone.

There is general agreement that the distribution of dry matter increases from the periphery inwards to the inner cortical tissue, thence decreasing to the centre. Thus much of the dry matter is contained in the storage parenchyma associated with the phloem, less in the cortex and still less in the pith.

<u>Pectic constituents as related to potato texture</u>. The relation of pectic materials to texture in plant tissue has received both theoretical and practical investigation. Some investigators have looked for a relationship between pectins and potato tissue texture.

Coudon and Bussard (1897), Sweetman (1936) and Barmore (1937) found no significant relation between pectic content and mealiness of tubers. Freeman and Ritchie (1940) offered additional evidence that the solution and disintegration of pectic material did not determine mealiness in potatoes. Bettelheim and Sterling (1955b) observed no direct relationship between various pectic fractions and texture of different varieties of potatoes. Recently Potter and McComb (1957) determined total pectin in individual potatoes of different specific gravities from a single variety and in potatoes of different varieties from different lots. Results showed very little difference in the pectin content of different varieties. Pectin content was independent of the specific gravity of the tubers and varied with different growing locations and cultural conditions. There was no correlation between subjective appraisal for texture and the pectin content of the potatoes. These results appear to discount the hypothesis that low pectic content is casually related to mealiness.

Personius and Sharp (1939a) explained the decrease in cell adhesion after cooking by weakening of intercellular cementing material of potato tissue. Pyke and Johnson (1940) demonstrated that soluble pectin readily dissolves in cold water and protopectin becomes rapidly soluble in water at 85° C. (185° F.). The calcium pectate content of potato decreased continuously during boiling in pure water or more rapidly in salt water indicating that these cementing materials were rapidly dissolved, permitting segments of potato tissue to break away.

In an attempt to explain the shrinkage which occurred in storage, pectic changes in seed potatoes were examined by Dastur and Agnihotri (1934). Tubers were stored according to size and size was assumed to represent advancing age of the tubers. The results indicated a progressive increase in the soluble pectic fraction while the total pectic substance also increased indicating continuous formation of pectic substances during growth. During storage the free soluble pectin, which previously was present in small amount, was formed at the expense of protopectin and middle lamella pectin.

There have been many attempts to relate potato texture with pectic content. On the whole, no obvious relationship has been found. The observed changes in texture can not be adequately explained in terms of the changes in pectin alone.

Changes of pectic substances in fruits during ripening and storage. Several investigators have found softening of fruit to be associated with changes in pectic substances in cell walls and middle lamella.

In the literature dealing with pectic materials in fruits and vegetables, the following pectic substances have been recognized. Pectin, which is water soluble and probably is derived from protopectin by enzyme action; protopectin or pectose, which is water insoluble; and the pectic substance of middle lamella which is also water insoluble. The total pectic substance includes all three of these.

The development, maturation and senescence of fruit involves striking changes in the amount and nature of pectic materials contained in the fruit cell walls, a fact first appreciated by Fremy in 1840. He observed that the softening of the flesh of apple was at times closely associated with changes in pectic constituents. Carre (1922, 1925) made extensive studies of pectic materials of apples during storage. She associated ripening in storage with an increase in pectin and corresponding decrease in protopectin (pectose). The protopectin also decreased. These changes were accelerated by increasing temperature. The protopectin decreased in the apples during storage, first rapidly and later slowly. Similarly good correlation between changes in firmness and increase in soluble pectin substances in apple was found by Haller (1929, 1941), Smock and Allen (1938), Fisher (1943), Phillips and Poapst (1950) and others.

In studies of pectic changes in peaches, Appleman and Conard (1926), Conard (1930) and Fisher, Britton and O'Reilly (1943) found decrease in the protopectin and a corresponding increase in pectin with ripening in storage. The rate of these changes increased with increasing temperature. Working with pears, Emmett (1926, 1929), Gerhard and Ezell (1938), Smock and Allen (1938) and Hansen (1939) observed similar changes in pectic constituents. The transformation of insoluble pectic substances into soluble forms during storage and ripening was observed in banana by Conard (1930). Barnell (1943), and Von Loesecke (1950); in plums by Bondet (1952); in citrus by Gaddum (1934) and in grapes by Hopkins and Gourley (1930).

These investigations suggest that the cell walls are thickened and cemented together by insoluble pectic materials. As these insoluble pectic fractions change to a soluble form softening takes place, thus permitting the cells to separate readily and decreasing the thickness of the cell walls. These changes are accelerated by an increase in temperature.

EXPERIMENTAL PROCEDURE

Specific Gravity Separation, Storage, Cooking and Pressure Testing of Katahdin Potatoes

For the study of the effect of specific gravity and two storage temperatures, 40° and 70° F., on the cooking time of potatoes, Katahdin tubers were taken from cold storage in December and separated into three specific gravity groups (1) 1.065 - 1.070, (2) 1.074 - 1.076, and (3) 1.080 - 1.085 by immersing in brine solutions of known specific gravity. About 250 medium sized tubers in each group were obtained in this way. They were washed with water and half of the tubers of each specific gravity group were stored in cold storage at 40°. The other halves were stored at 70° F. under conditions simulating kitchen storage. At weekly intervals for eight weeks three potatoes of each specific gravity group and from each storage were cooked in boiling water for 15, 20, 25 and 30 minutes. After cooking they were peeled and tested for done-ness by the pressure resistance tester.

One time-tested method of determining whether or not potatoes are thoroughly cooked is to pierce them with some pointed instrument to gauge the softness or hardness of the tuber tissue. From this grew the use of a penetrometer to test the degree of done-ness of potatoes, introduced and used by Landreth (1929) followed by Sweetman and Lancaster (1931), Thiessen (1935) and Barmore (1937). Since in this experiment it was desired to measure the characteristics of the tuber as a unit, and since several investigations have found differences in the rates of cooking of the different parts within a tuber, it was decided to make penetration measurements on the surface (cortex) and internal area (inner medulla) of each tuber. Five pressure resistance measurements were made on both surface and internal areas. The tester recorded the pressure in grams necessary to force a plunger 0.1596 cm. in diameter (0.02 $cm.^2$) into the potato tissue to a distance of 1.2 cm. (Figure 1.) All pressure readings in this study refer to resistance of tuber tissue after cooking.

Specific Gravity Determination of Three Tuber Zones and Cooking Test

In the 1956 study of the differences in cooking characteristics between tuber areas, the specific gravity of ten individual tubers of 14 varieties was calculated from the weight of the tubers in air and in water. The specific gravity was calculated by the following formula:

$$\text{Specific gravity} \doteq \frac{\text{weight in air}}{\text{weight in air} - \text{weight in water}}$$

The specific gravity of three different zones of each tuber was also determined. An outer layer of each tuber about one centimeter thick from skin to vascular ring (cortex) was removed and the weight of the remaining tuber in air and in water was determined; again a layer was removed up to the inner medullary area and the remaining portion (pith) of the tuber weighed in air and in water. All the weighing was done on a triple beam balance, with accuracy of 0.01 gram.

In 1957, 25 varieties were planted to provide material for examination of the specific gravity of entire tubers, and of the different zones; and the differences in cooking both within and between varieties. Varieties of different characteristics, early and late maturing varieties,

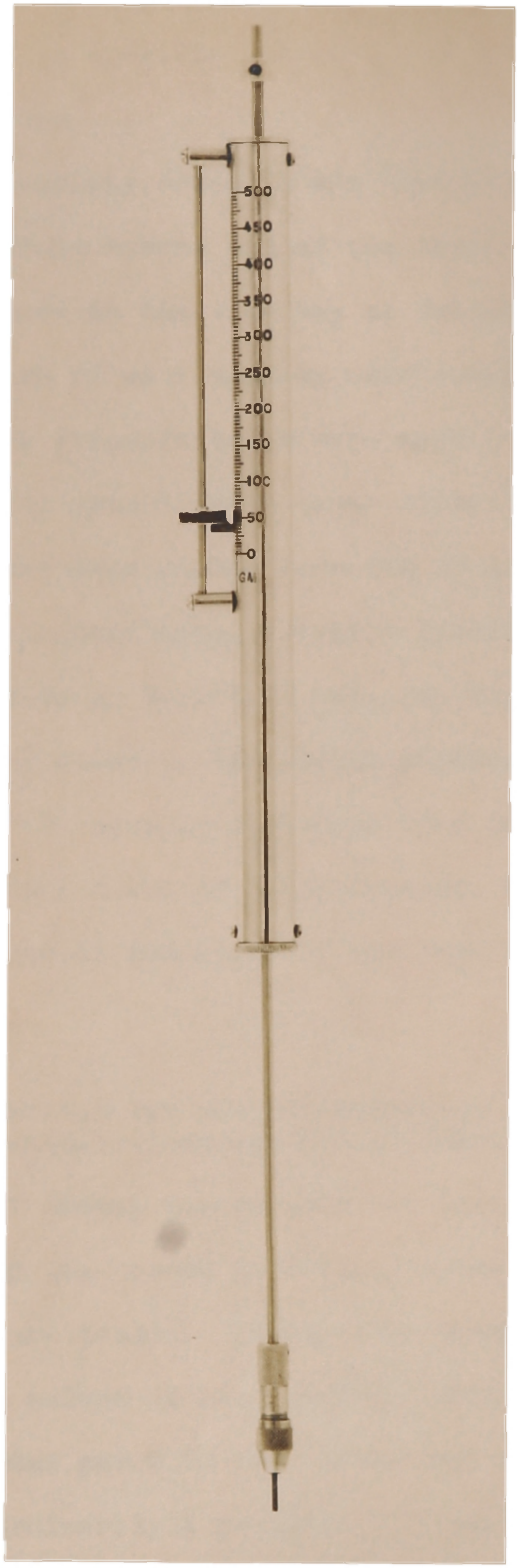

Figure 1. Penetrometer used to test the resistance to pressure of the tuber tissue after cooking.

varieties high and low in specific gravity, and of varied cooking characteristics were included.

As the tops of a variety dried it was harvested and the specific gravity of ten large whole tubers and of the three different zones of each tuber was determined in the same way as described previously. Fifteen medium sized tubers of each variety were cooked in boiling water for 25 minutes and five pressure tests were made on the surface area and five on the internal area of each tuber after cutting the tubers in half. Fifteen varieties were chosen from the 25 as representative of the greatest extremes in earliness, specific gravity and cooking characteristics. Among these 15 varieties only one variety, Onaway, was found to be a very hard cooker. The inside portion of about 80% of all Onaway tubers did not cook to done-ness when boiled in water for 25 minutes. To study the cause of this hardness, cellulose, hemicelluloses, and different pectic fractions of the hard and soft cookers were analyzed.

Sample Preparation for the Determination of Cellulose, Hemicelluloses and Pectic Fractions

A large number of Onaway tubers were cut into halves and numbered. One half of each tuber was cooked in boiling water for 25 minutes and tested with the pressure tester. Twenty-five uncooked halves of soft cooking tubers and 25 halves of hard cookers (indicated by pressure resistance of about 300 grams per 0.02 $cm.^2$ after cooking) were used for chemical analysis. Ordinarily a pressure reading of about 80 or below indicated done-ness. The centermost portion of each raw tuber was removed, cut into very small pieces and the pieces composited. Twelve samples weighing 20 grams each were drawn from the composite. Twelve similar samples from soft cookers were prepared. Six samples from each group were used for the analysis of cellulose and hemicelluloses and the remaining six from each group were used for estimation of water soluble pectin, ammonium oxalate soluble pectin (middle lamella pectin) and acid soluble pectin (protopectin).

It had been observed that hard cookers would cook easily after storage at room temperature for some time. A number of large Onaway tubers were cut into pieces and each piece was numbered. One piece from each tuber was cooked in boiling water for 25 minutes and was tested for pressure resistance. The remaining pieces from tubers which cooked very hard were stored at 70° F. in cellophane bags for further cooking tests. Every week for six weeks 20 pieces were cooked for 25 minutes in boiling water and tested for pressure resistance. When these pieces cooked soft, samples of raw tuber tissue were analyzed for three pectic fractions, cellulose and hemicelluloses. The samples for analysis were prepared the same way as described above.

Analytical Procedure

Determination of cellulose and hemicelluloses. The work of Norris and Preece (1930) was the basis on which the folowing method was developed. Samples for determination of cellulose and hemicelluloses were blended in a Waring blender with distilled water for one minute, transferred to a 250 ml. beaker. Water was added to make the final volume approximately 100 ml. They were heated at about 80° C. for three minutes (with constant stirring to prevent scorching the starch) to gelatinize the starch. To avoid erroneously high values due to presence of starch, the starch was hydrolyzed by enzymatic hydrolysis with a solution of equal amounts of alpha-and beta-amylase. The amylases attack raw starch very slowly in vitro. Rapid digestion under these conditions occurs only after the starch has been heated in the presence of water or the starch granule structure has been destroyed by heating.

After gelatinization and cooling the starch solution to room temperature, the pH was adjusted to 5.7 and enzyme solution composed of equal amounts of alpha-and beta-amylase were added to bring the concentration of the total enzyme to 0.05% in the final solution (1 ml. of 1% alpha-and beta-amylase mixture in water was added for 20 ml. of liquid). The surface of the mixture was covered with toluene to prevent spilage and the enzyme was permitted to act for 12 hours at 37.5° C. After 12 hours, the samples were again heated at 80°-85° C. for three minutes, cooled to room temperature and fresh enzyme solution added as before. After the second 12 hours of digestion an iodine test was made to verify completeness of hydrolysis.[1/]

After the starch was completely hydrolyzed, steps were taken to remove sugars and water soluble pectins from the samples. The samples were centrifuged for 25 minutes (2400 x gravity). The tubers were allowed to stand for about five minutes after removal from the centrifuge and the supernatent liquid was removed by pipette. The residue was washed with distilled water in an Erlenmeyer flask, shaken on a mechanical

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[1/] Two ml. of the hydrolyzed solution was placed in a 3 ml. tube. Five drops of 0.1 N iodine solution (1.26 grams of iodine and 2.5 grams of potassium iodide in 100 ml. water) were added. Absence of blue color indicated complete conversion of starch.

The starch test was also performed by putting a small amount of hydrolyzed solution on a porcelain spot plate and adding two drops of iodine-potassium iodide solution. Absence of blue color indicated complete conversion of starch.

shaker for two hours, and centrifuged as before. The supernatant liquid was discarded. The residue was extracted once more by the same procedure for the final removal of sugars and water soluble pectin.

To remove ammonium oxalate soluble pectin, the residue was again washed and transferred to an Erlenmeyer flask with 0.5% ammonium oxalate solution, and was extracted for two hours on the mechanical shaker. It was centrifuged and the supernatant liquid discarded. Again the residue was extracted with 0.5% ammonium oxalate solution for two hours, centrifuged, and the supernatant liquid discarded. The residue was then washed in hot distilled water to remove all the ammonium oxalate. It was centrifuged and wash water was discarded. The residue now contained cellulose and hemicellulose, which was dried to constant weight at 90° C. in the centrifuge tubes which had been previously weighed. Thus the combined weight of cellulose and hemicelluloses was determined.

To remove hemicelluloses the dried residue (cellulose and hemicelluloses) was treated with hot 4% sodium hydroxide, transferred to an Erlenmeyer flask, and extracted on the mechanical shaker for two hours. It was centrifuged and the supernatant liquid discarded. The residue was extracted and centrifuged three or four times in this manner, until a portion of the extract no longer gave a precipitate when neutralized with acetic acid and diluted with an equal volume of acetone.

The final residue was washed with hot distilled water to remove all the sodium hydroxide. It was centrifuged and wash water discarded. The residue was washed thrice in this way. The residue now contained cellulose, which was dried in the weighed tubes to constant weight at 90° C. The percent of cellulose was calculated. Dry weight of hemicelluloses was found by difference, and percentage of hemicelluloses calculated.

Determination of pectic substances. Methods used to isolate the pectins and separate them into water-soluble, 0.5% ammonium oxalate-soluble, and hot 0.05 N. HCl soluble-fractions were essentially the same as those described by McColloch (1952).

The samples of finely-cut tissue were boiled in 50 ml. 95% ethanol for ten minutes to inactivate the pectic enzymes and extract the sugars. They were blended for one minute and transferred into a beaker using 95% ethanol to a final volume of about 125 ml. The samples were allowed to stand overnight. After extraction with ethanol the residue was removed from the extract by filtration. In the first extract, the pulp was added to twice its weight of distilled water, extracted on the mechanical shaker for two hours, centrifuged, and the supernatant liquid collected. The residue was again extracted in the same way, and both the extracts were combined and called "water-soluble fraction". In the second extraction the pulp was extracted twice as above with 0.5% ammonium oxalate and both the extracts were combined and called "calcium pectate filtrate". The last extraction was performed with 0.05 N. HCl at 85° C. for two hours. Then the material was centrifuged and the supernatant liquid collected. It was again extracted and both extracts combined and designated as "HCl-soluble fraction".

In the process of filtrating small amounts of starch often contaminates the pectic fractions hence they must be freed from starch before precipitation by ethanol. The starch was hydrolyzed by alpha-and beta-amylase as described for the determination of cellulose and hemicelluloses except that the enzymes were permitted to act for 12 hours only once. The pectic substances in each fraction were precipitated by adding two volumes of 95% ethanol and enough concentrated HCl to make the solution 0.05 N. in HCl. The precipitated pectins were removed on weighed and dried filter paper. After the filtration the filter papers were dried to constant weight and the percentage fresh weight of each pectic fraction was calculated.

EXPERIMENTAL RESULTS

Effect of Storage at Two Temperatures, 40° and 70° F., on the Cooking of Katahdin Potatoes of Three Specific Gravity Groups

This experiment was performed to assess the changes in cooking of Katahdin potatoes of different specific gravities, stored at 40° and 70° F. Three tubers from each of the three specific gravity groups (1.065 - 1.070, 1074 - 1.076 and 1.080 - 1.085) and both storages were cooked for 15, 20, 25 and 30 minutes at weekly intervals and pressure tested on surface and internal areas. The data from the potatoes cooked for 25 minutes is presented because the differences between penetrometer readings were most obvious when the tubers were boiled until not quite cooked to done-ness. If the potatoes were completely cooked, differential measurements could not be obtained. A similar technique was employed by Thiessen (1947).

Tables I, II and III indicate the resistance to pressure of surface and internal regions of these potatoes after cooking. The data show that as the weeks in storage at either temperature increased, the resistance to pressure of surface and internal areas fell in each of the three specific gravity groups. The results from potatoes stored at 70° F. are illustrated in Figures 2, 3, and 4. It is evident from these figures that resistance to pressure of internal area was greater than that of surface area at 0 weeks of storage in all the specific gravity groups. As the storage period increased, resistance to pressure after cooking of both

Table I. Penetration resistance in grams per 0.02 $cm.^2$ of Katahdin potato tubers (specific gravity 1.065 - 1.070) from 40° and 70° F. storage, after cooking at weekly intervals.*

Weeks in Storage	Stored at 40° F.		Stored at 70° F.	
	Surface Area	Internal Area	Surface Area	Internal Area
0	72.6	90.3	72.6	90.3
1	76.8	95.2	61.3	74.5
2	74.3	87.4	63.2	71.5
3	78.5	90.2	55.3	65.0
4	80.1	89.1	57.6	63.3
5	70.4	89.1	53.2	60.4
6	55.3	68.3	42.1	46.6
7	52.2	58.7	39.4	40.6
8	49.3	53.4	32.4	34.3

* Means of 15 penetrometer measurements, five from surface and five from internal areas of each of three tubers.

Table II. Penetration resistance in grams per 0.02 $cm.^2$ of Katahdin potato tubers (specific gravity 1.074 - 1.076) from 40° and 70° F. storage, after cooking at weekly intervals.*

Weeks in Storage	Stored at 40° F.		Stored at 70° F.	
	Surface Area	Internal Area	Surface Area	Internal Area
0	82.8	106.4	82.8	106.4
1	85.2	108.7	74.4	83.2
2	88.2	111.3	66.8	79.4
3	85.4	106.1	58.4	78.7
4	85.4	110.1	60.4	74.8
5	78.4	95.4	61.3	66.3
6	64.2	79.6	55.0	58.7
7	60.3	70.8	45.2	43.1
8	58.2	67.3	38.7	21.2

* Means of 15 penetrometer measurements, five from surface and five from internal areas of each of three tubers.

Table III. Penetration resistance in grams per 0.02 $cm.^2$ of Katahdin potato tubers (specific gravity 1.080 - 1.085) from 40° and 70° F. storage, after cooking at weekly intervals.*

Weeks in Storage	Stored at 40° F.		Stored at 70° F.	
	Surface Area	Internal Area	Surface Area	Internal Area
0	83.2	106.9	83.2	106.9
1	80.4	110.0	64.8	87.4
2	89.1	109.1	68.6	81.4
3	81.6	110.4	57.0	82.8
4	77.6	112.0	62.8	77.4
5	72.6	98.3	59.3	55.8
6	52.1	70.0	52.6	39.5
7	51.8	64.3	50.1	25.5
8	46.1	63.2	47.3	17.0

* Means of 15 penetrometer measurements, five from surface and five from internal areas of each of three tubers.

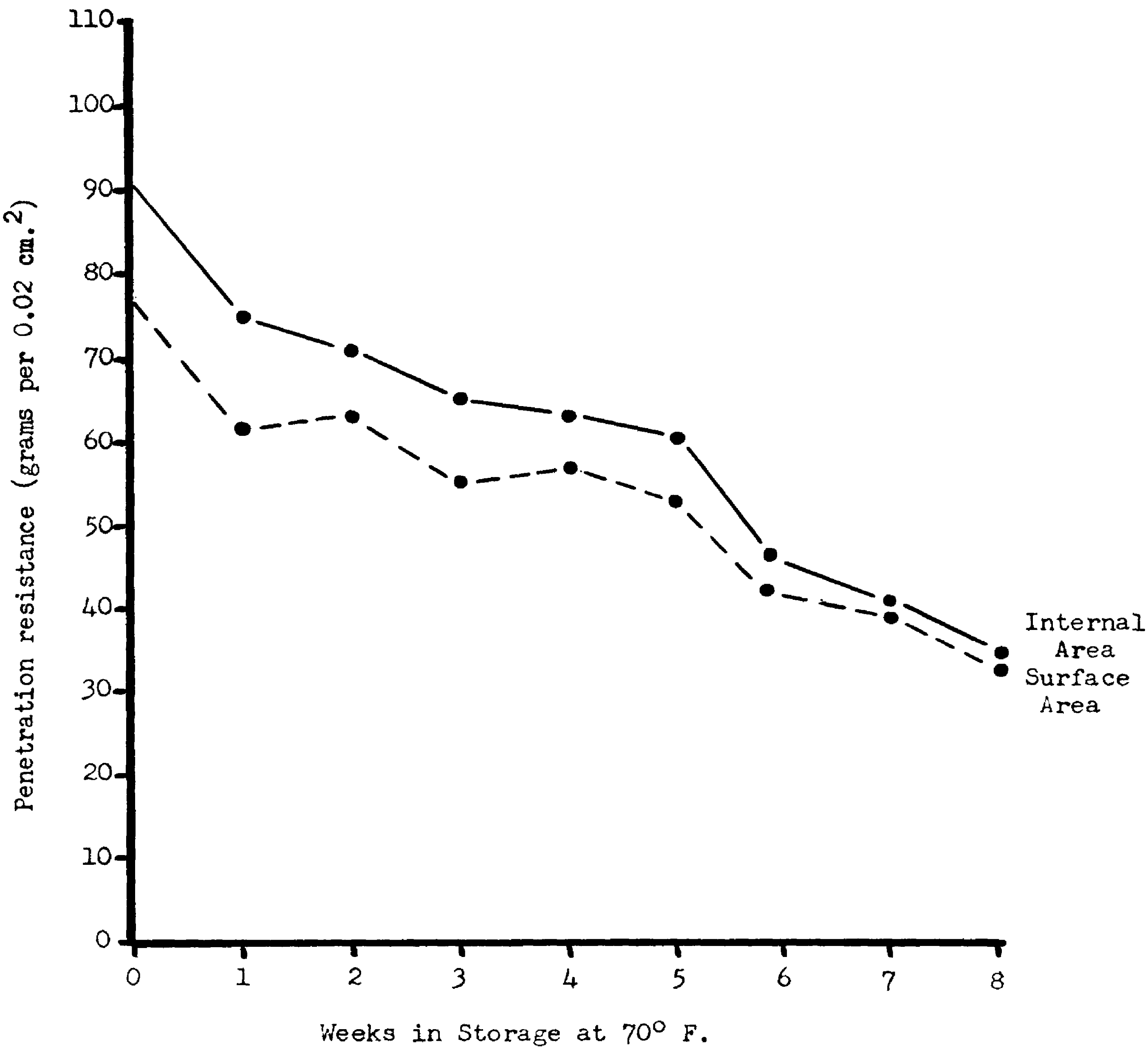

Figure 2. Effect of pre-cooking storage at 70° F. on post-cooking penetration resistance of surface and internal areas of Katahdin potato tubers (specific gravity 1.065 - 1.070) boiled 25 minutes.

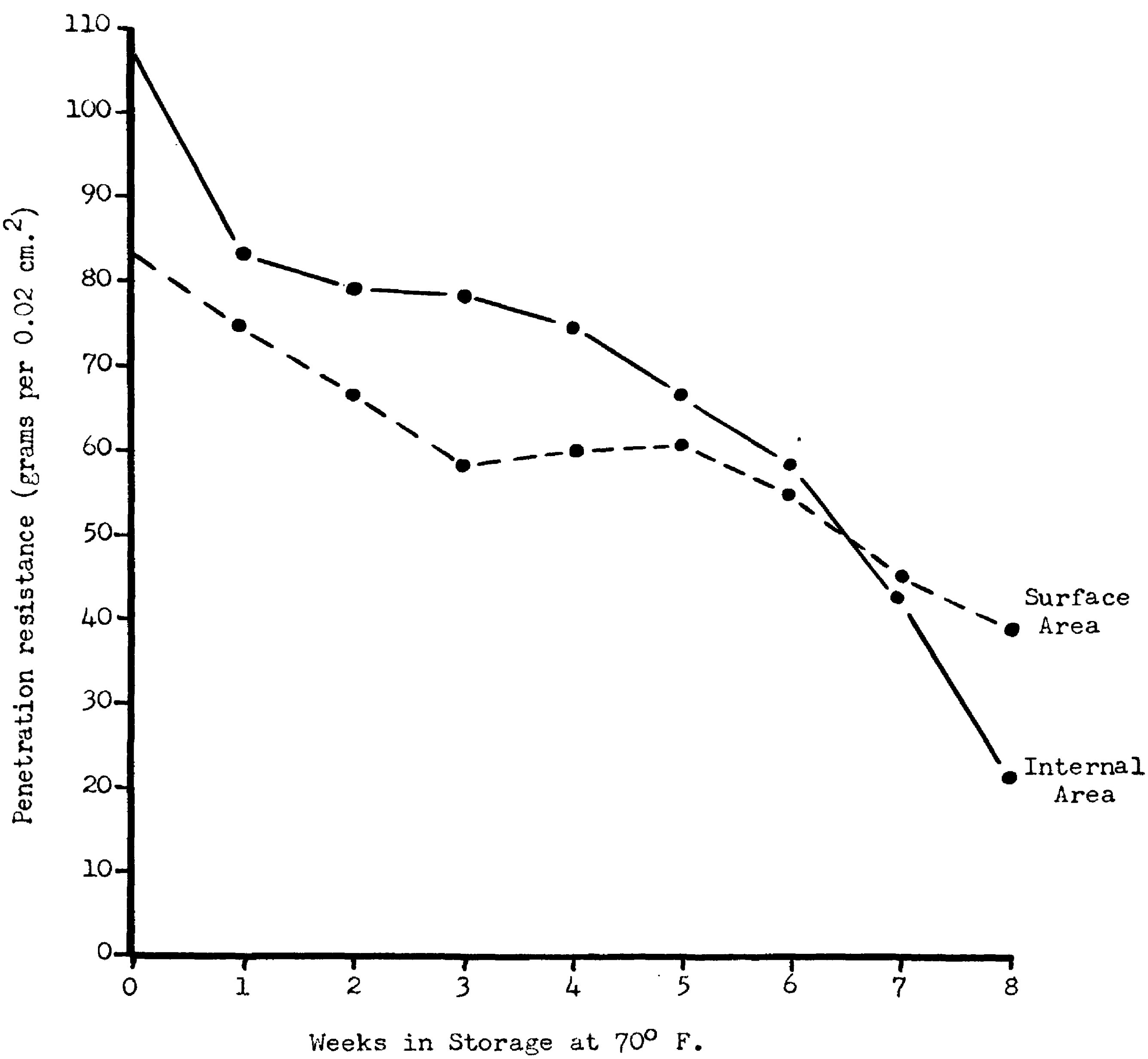

Figure 3. Effect of pre-cooking storage at 70° F. on post-cooking penetration resistance of surface and internal areas of Katahdin potato tubers (specific gravity 1.074 - 1.076) boiled 25 minutes.

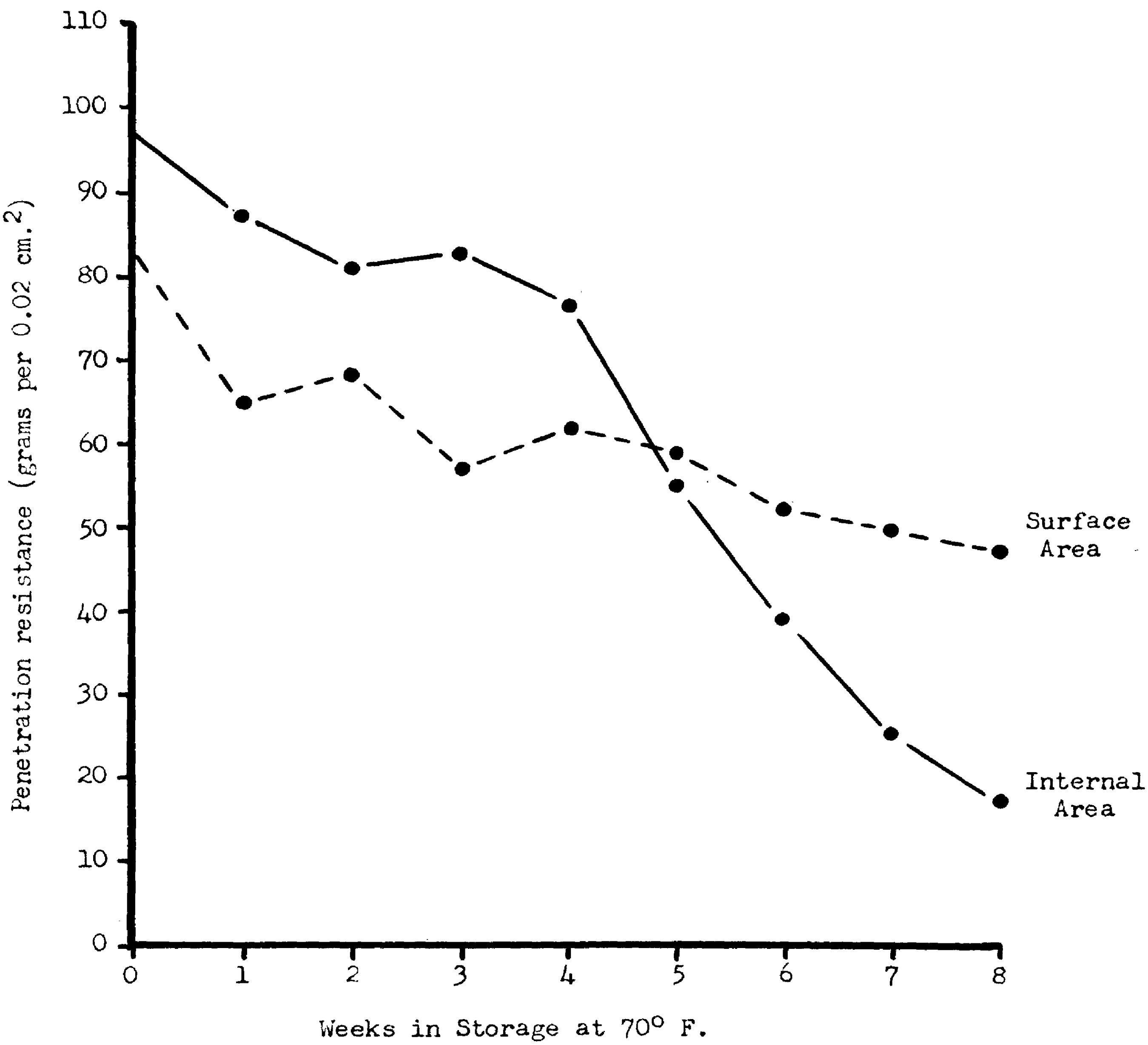

Figure 4. Effect of pre-cooking storage at 70° F. on post-cooking penetration resistance of surface and internal areas of Katahdin potato tubers (specific gravity 1.080 - 1.085) boiled 25 minutes.

surface and internal areas went down. In every case the change in resistance to pressure of the internal area was more rapid than that of the surface area.

After seven weeks of storage the resistance of surface and internal area to pressure after cooking was almost the same in potatoes of specific gravity 1.065 - 1.070 (Figure 2.) While the pressure resistance of surface and internal area of tubers of 1.074 - 1.076 was approximately equal at five, six and seven weeks of storage, at eight weeks of storage pressure resistance of internal area was much lower than that of surface area (Figure 3.) Thus after eight weeks of storage the inside cooked softer than the outside. Resistance to pressure of internal area fell rapidly in potatoes of specific gravity 1.080 - 1.085 after four weeks of storage, and at five weeks of storage, both surface and internal area were equally hard. At six weeks the internal area cooked softer than the surface area and at the end of eight weeks the penetration resistance of internal area was much lower than that of surface area (Figure 4.).

Table IV indicates the change in resistance to pressure of the internal and surface areas (means of all tubers from the three specific gravity groups) stored at 70° and 40° F. These data show that resistance of the surface and internal area to pressure decreased in potatoes stored at 70° F. Figure 5 illustrates the results from potatoes stored at 70° F. and indicates that the resistance to pressure of the internal area was more than that of surface area at 0 weeks but that it fell more rapidly than the resistance of surface area. After five and six weeks of storage both surface and internal areas were equally hard, and after seven weeks of storage, the internal area cooked softer than surface area.

Table IV. Penetration resistance in grams per 0.02 cm.^{2} of Katahdin potato tubers (means of three specific gravity groups) from 40° and 70° F. storage, after cooking at weekly intervals.*

Weeks in Storage	Stored at 40° F.		Stored at 70° F.	
	Surface Area	Internal Area	Surface Area	Internal Area
0	79.5	101.2	79.5	101.2
1	80.8	104.6	66.8	81.7
2	83.9	102.6	66.2	77.4
3	81.8	102.2	56.9	75.5
4	81.0	103.7	60.3	71.8
5	73.8	94.3	57.9	60.8
6	57.2	72.6	49.9	48.3
7	54.8	64.6	44.9	36.4
8	51.2	61.3	39.5	24.2

* Means of 45 penetration measurements, five from surface and five from internal area of nine tubers.

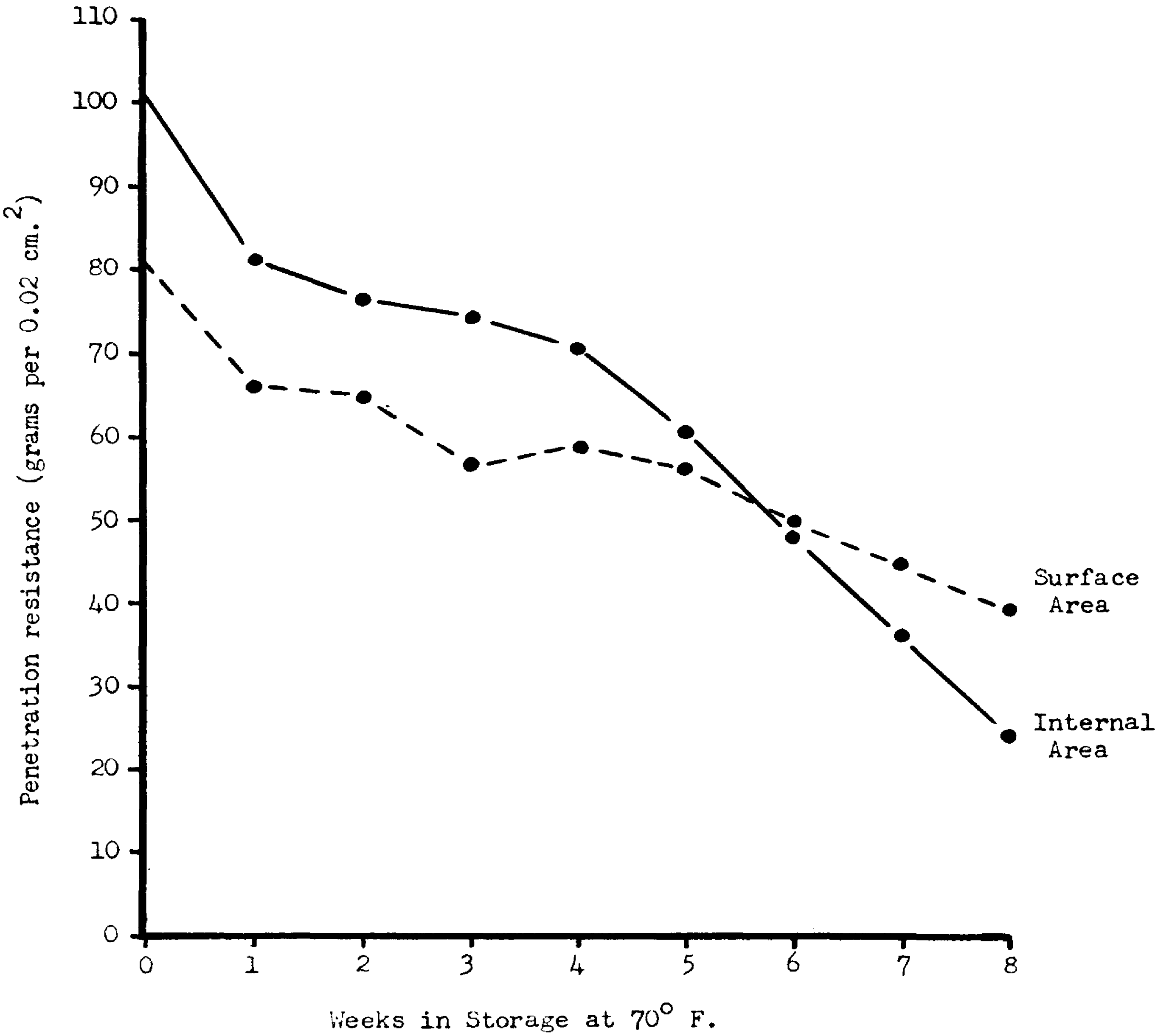

Figure 5. Effect of pre-cooking storage at 70° F. on post-cooking penetration resistance of surface and internal areas of Katahdin potato tubers boiled 25 minutes (means of three specific gravity groups).

The changes in resistance to pressure of the internal and surface areas of the potatoes stored at 40° F. in three specific gravity groups, 1.065 - 1.070, 1.074 - 1.076 and 1.080 - 1.085, are shown in Figures 6, 7 and 8, respectively. The tendencies in the changes are similar in all the three groups, unlike the potatoes stored at 70° F. The results of all three specific gravity groups have been combined and are shown in Table IV and in Figure 9. The difference in resistance to pressure of surface and internal areas of potatoes stored at 40° F. was great at 0 weeks of storage (Figure 9.). There was practically no change in resistance of either area up to four weeks but after this period as the storage period increased the resistance to pressure went down. In the internal area it fell more rapidly than in surface area. At seven or eight weeks of storage the differences were not very great, whereas in potatoes stored at 70° F. the inside cooked softer after the same period of storage (Figure 5.).

Penetration resistance of the surface and internal areas are shown in Figures 10 and 11 respectively, comparing the potatoes stored at 40° and 70° F. The change in resistance to pressure of the surface was greater in potatoes stored at 70° F. than in those stored at 40° F. (Figure 10). The changes in resistance to pressure of internal area were also greater in potatoes at 70° F. than at 40° F. (Figure 11) and were more marked in the internal area than in surface area.

Specific Gravity of Different Parts of the Tubers and Cooking Tests of Different Varieties Before Storage

<u>1956</u>.

In 1956 the specific gravity of three different portions, cortex, outer medulla and pith, of the tubers of 14 varieties was determined as

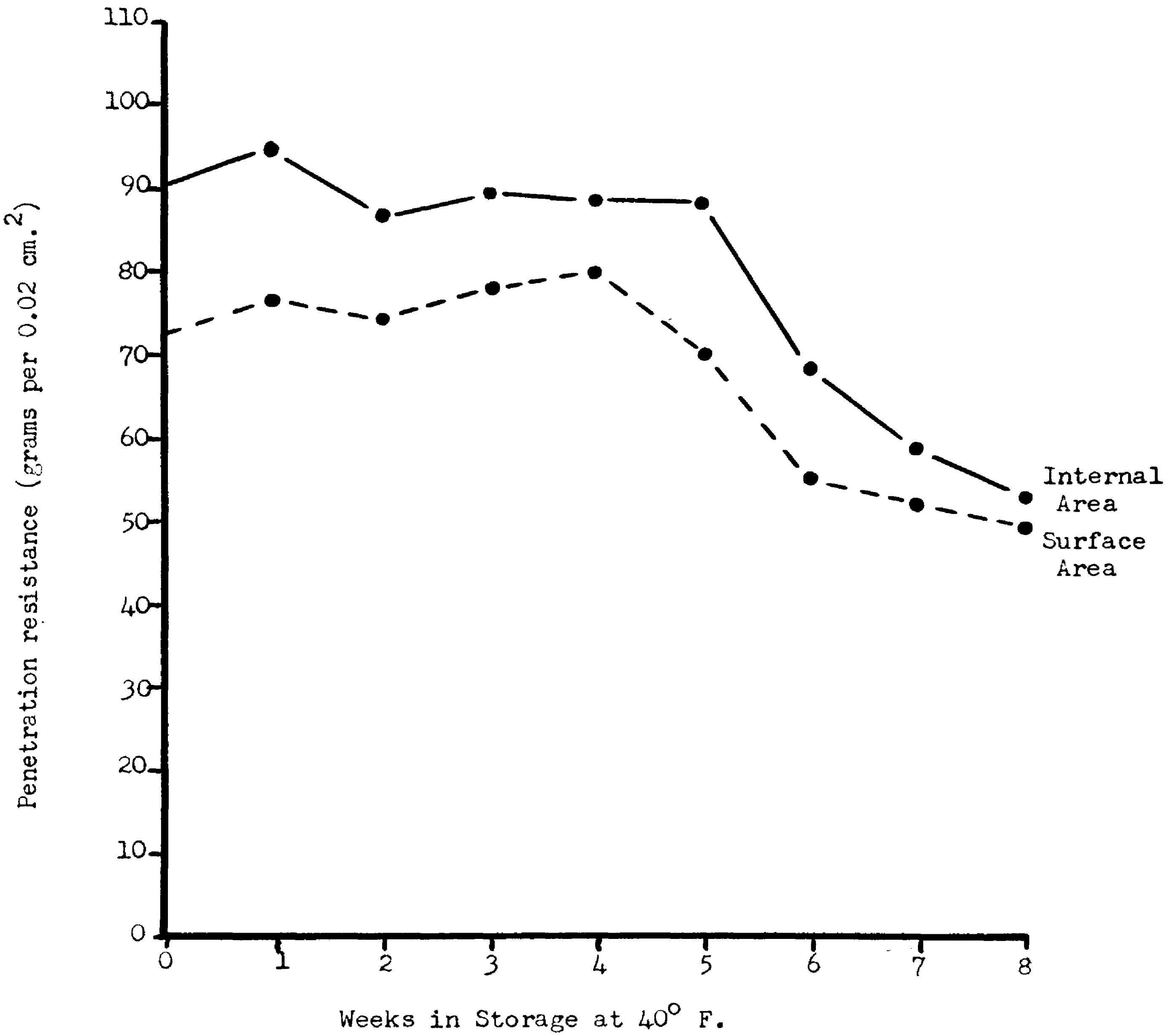

Figure 6. Effect of pre-cooking storage at 40° F. on post-cooking penetration resistance of surface and internal areas of Katahdin potato tubers (specific gravity 1.065 - 1.070) boiled 25 minutes.

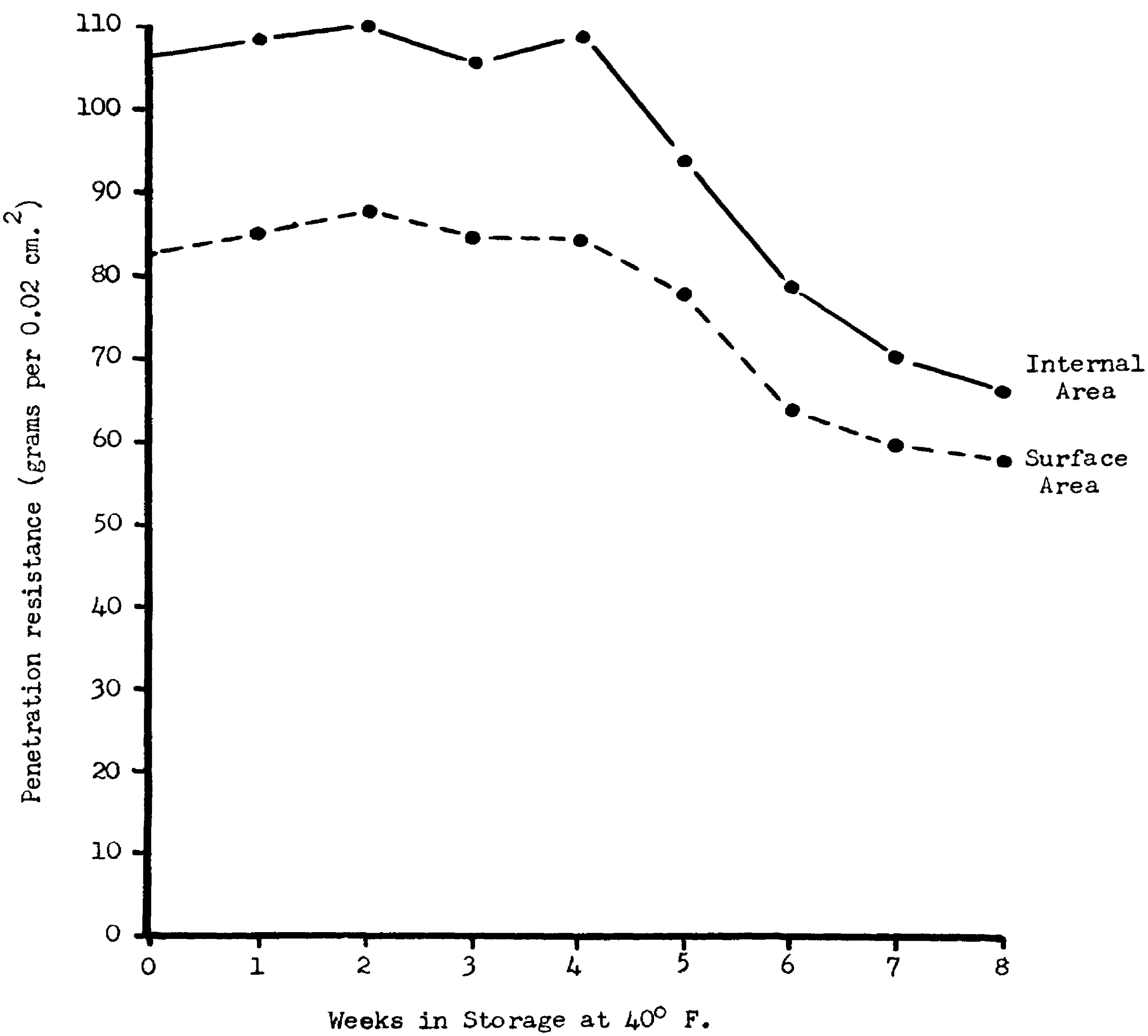

Figure 7. Effect of pre-cooking storage at 40° F. on post-cooking penetration resistance of surface and internal areas of Katahdin potato tubers (specific gravity 1.074 - 1.076) boiled 25 minutes.

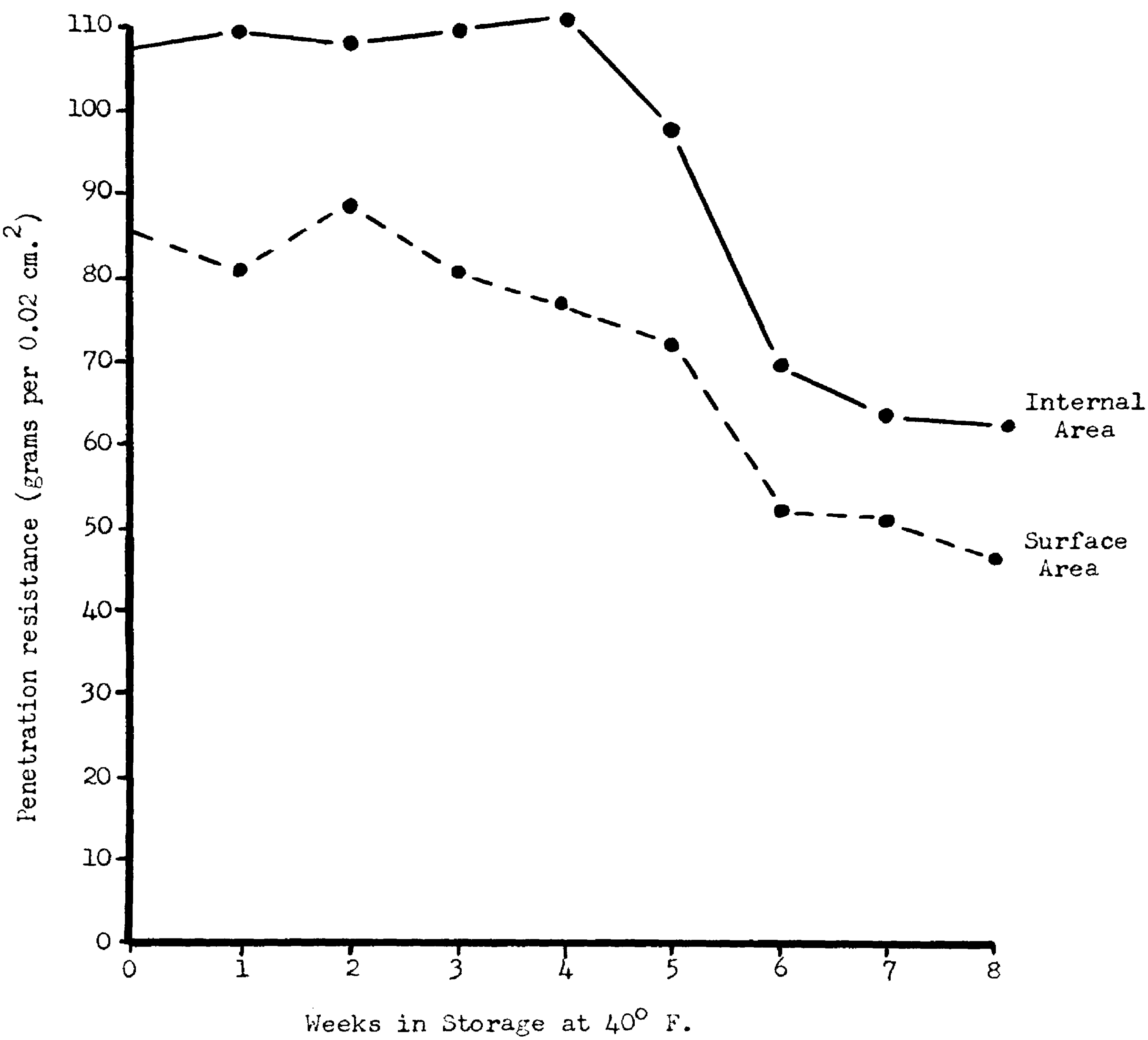

Figure 8. Effect of pre-cooking storage at 40° F. on post-cooking penetration resistance of surface and internal areas of Katahdin potato tubers (specific gravity 1.080 - 1.085) boiled 25 minutes.

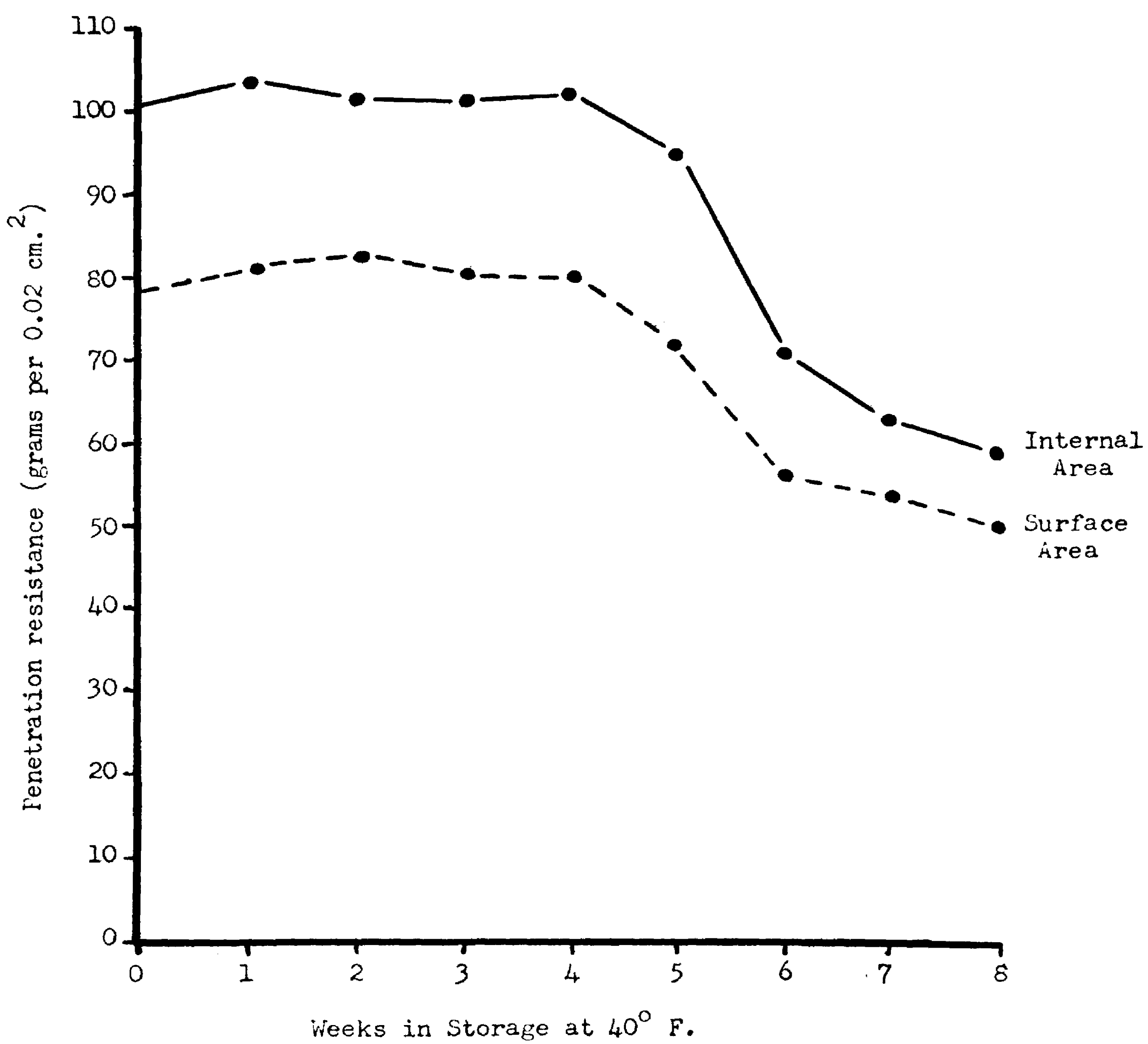

Figure 9. Effect of pre-cooking storage at 40° F. on post-cooking penetration resistance of surface and internal areas of Katahdin potato tubers boiled 25 minutes (means of three specific gravity groups).

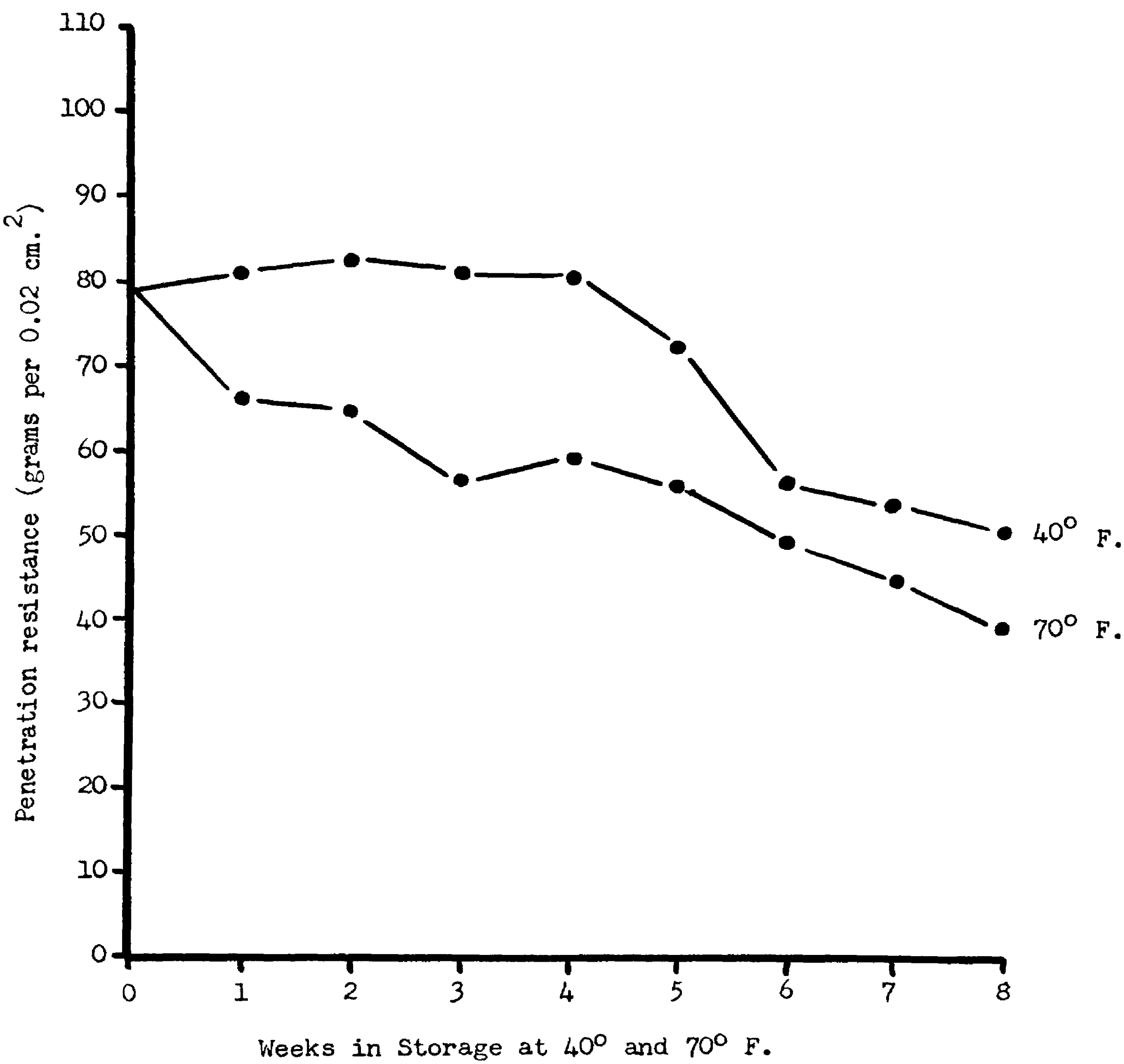

Figure 10. Effect of pre-cooking storage at 40° and 70° F. on post-cooking penetration resistance of surface area of Katahdin potato tubers boiled 25 minutes (means of three specific gravity groups).

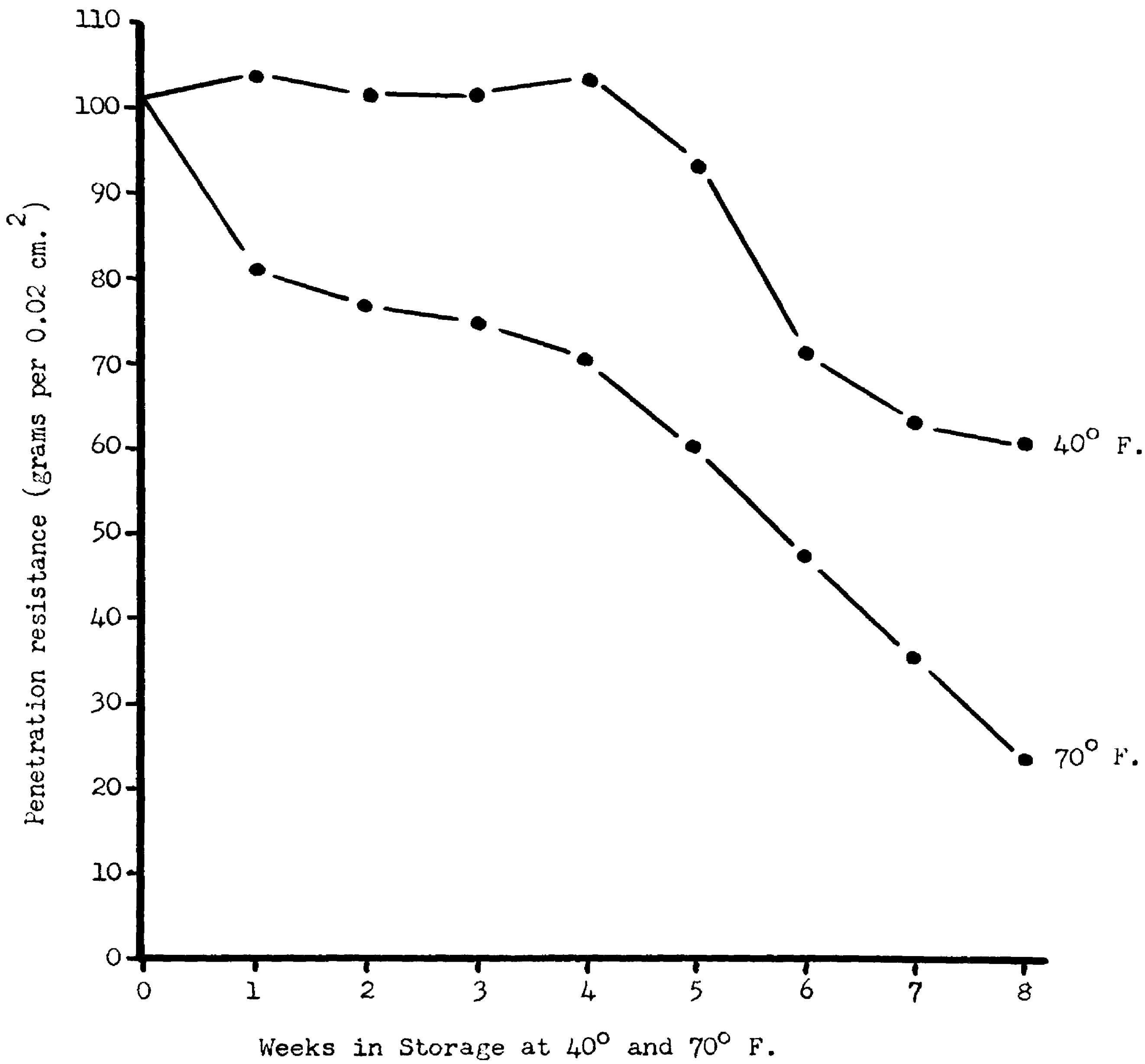

Figure 11. Effect of pre-cooking storage at 40° and 70° F. on post-cooking penetration resistance of internal area of Katahdin potato tubers boiled 25 minutes (means of the specific gravity groups)

shown in Table V. Table VI indicates the same data, calculated as percent after deleting the constant 1.000 from each determination and taking the entire tuber as 100. Ten tubers of each variety were used. In most cases the outer medullary area had the highest specific gravity. In general the tubers of varieties high in specific gravity showed wide differences in specific gravity between cortex and pith. The varieties whose tubers were low in specific gravity showed little difference in specific gravity between these two zones. Means of the varieties revealed a great difference between cortex and pith area. There was almost no difference between cortex and outer medullary area.

In December 15 tubers of each variety were cooked in boiling water for 25 minutes and resistance to pressure of the surface and internal area was noted. These results are shown in Table VII. From these results it is evident that there was very little difference between varieties in softening after cooking. However, there were some differences in penetration between cortex and pith area within tubers of a single variety. The pith cooked slightly harder than the cortex although these differences were not great.

1957.

Table VIII shows the specific gravity of three different portions of the tubers of 15 potato varieties grown in 1957. Each of these figures represents the mean of ten tubers of each variety. The same data calculated as percentage after deleting the constant 1.000 from each determination, and taking the entire tuber as 100, is shown in Table IX. These results are almost identical to those of 1957. In most cases the outer medulla had highest specific gravity of the three tuber

Table V. Specific gravity of whole and different portions of potato tubers of 14 varieties grown during 1956 (means of ten tubers).

No.	Variety	Whole Tuber	Cortex	Outer Medulla	Pith
1.	Red LaSoda	1.0731	1.0727	1.0836	1.0623
2.	Waseca	1.0734	1.0723	1.0813	1.0616
3.	Onaway	1.0745	1.0713	1.0805	1.0628
4.	Chippewa	1.0795	1.0807	1.0771	1.0726
5.	Sebago	1.0807	1.0855	1.0847	1.0654
6.	Pontiac	1.0815	1.0814	1.0878	1.0675
7.	Katahdin	1.0826	1.0845	1.0910	1.0689
8.	Osage	1.0860	1.0894	1.0909	1.0697
9.	Russet Rural	1.0870	1.0862	1.0901	1.0674
10.	Tawa	1.0891	1.0946	1.0952	1.0678
11.	Delus	1.0948	1.1001	1.0949	1.0631
12.	Saco	1.0954	1.1014	1.0939	1.0677
13.	Green Mountain	1.0970	1.1032	1.0950	1.0751
14.	Merrimack	1.1029	1.1089	1.0982	1.0717
	Mean	1.0855	1.0880	1.0889	1.0674

Table VI. Specific gravity of different tuber portions from 14 varieties grown in 1956, expressed as percentage of entire tuber specific gravity.*

No.	Variety	Whole Tuber	Cortex	Outer Medulla	Pith
1.	Red LaSoda	100	99.45	114.36	85.22
2.	Waseca	100	98.50	110.76	83.92
3.	Onaway	100	95.70	108.05	84.29
4.	Chippewa	100	101.50	96.98	91.32
5.	Sebago	100	105.94	104.95	81.04
6.	Pontiac	100	99.87	107.73	82.82
7.	Katahdin	100	102.30	110.16	83.41
8.	Osage	100	103.95	105.69	81.04
9.	Russet Rural	100	99.08	103.56	77.47
10.	Tawa	100	106.17	106.84	76.09
11.	Delus	100	105.59	110.10	66.56
12.	Saco	100	106.28	98.42	70.96
13.	Green Mountain	100	106.39	97.93	77.42
14.	Merrimack	100	105.83	95.43	69.67
	Mean	100	102.61	104.35	79.37

* Percentage calculated after deleting the constant 1.000 from each determination.

Table VII. Resistance to pressure in grams per 0.02 $cm.^2$ of surface and internal areas of cooked potato tubers from 14 varieties grown in 1956 (means of 15 tubers).

No.	Variety	Surface Area	Internal Area
1.	Red LaSoda	77.6	94.6
2.	Waseca	71.6	87.5
3.	Onaway	84.3	96.6
4.	Chippewa	64.5	78.9
5.	Sebago	82.3	100.2
6.	Pontiac	69.3	81.4
7.	Katahdin	78.6	97.4
8.	Osage	74.3	93.2
9.	Russet Rural	70.2	88.9
10.	Tawa	88.0	99.7
11.	Delus	68.5	86.4
12.	Saco	77.9	96.3
13.	Green Mountain	77.6	92.8
14.	Merrimack	78.8	96.3
	Mean	75.9	91.4

Table VIII. Specific gravity of whole and different portions of potato tubers of 15 varieties grown during 1957 (means of ten tubers).

No.	Variety	Whole Tuber	Cortex	Outer Medulla	Pith
1.	Sebago	1.0611	1.0608	1.0663	1.0508
2.	Pontiac	1.0615	1.0584	1.0688	1.0587
3.	Onaway	1.0627	1.0636	1.0614	1.0626
4.	Chippewa	1.0654	1.0675	1.0686	1.0634
5.	Ontario	1.0668	1.0710	1.0676	1.0503
6.	Tawa	1.0672	1.0632	1.0760	1.0597
7.	Osage	1.0712	1.0650	1.0842	1.0685
8.	Katahdin	1.0723	1.0750	1.0752	1.0565
9.	Irish Cobbler	1.0732	1.0705	1.0795	1.0678
10.	Cherokee	1.0758	1.0789	1.0756	1.0593
11.	Menominee	1.0767	1.0807	1.0782	1.0543
12.	Russet Rural	1.0775	1.0791	1.0831	1.0670
13.	Delus	1.0808	1.0869	1.0810	1.0593
14.	Merrimack	1.0822	1.0804	1.0891	1.0710
15.	Green Mountain	1.0930	1.0957	1.0916	1.0713
	Mean	1.0725	1.0731	1.0764	1.0614

Table IX. Specific gravity of different tuber portions from 15 varieties grown in 1957, expressed as percentage of entire tuber specific gravity.*

No.	Variety	Whole Tuber	Cortex	Outer Medulla	Pith
1.	Sebago	100	99.51	108.51	83.14
2.	Pontiac	100	94.96	111.87	95.77
3.	Onaway	100	101.43	97.92	99.82
4.	Chippewa	100	103.21	104.89	96.94
5.	Ontario	100	106.29	101.19	75.30
6.	Tawa	100	94.05	113.09	88.84
7.	Osage	100	91.29	118.26	96.21
8.	Katahdin	100	103.71	104.01	78.14
9.	Irish Cobbler	100	96.31	108.61	92.62
10.	Cherokee	100	104.09	99.73	78.23
11.	Menominee	100	105.21	101.95	70.79
12.	Russet Rural	100	100.13	107.23	86.45
13.	Delus	100	107.55	100.25	73.39
14.	Merrimack	100	97.81	108.39	86.37
15.	Green Mountain	100	102.90	98.49	76.67
	Mean	100	100.56	105.63	85.24

* Percentage calculated after deleting the constant 1.000 from each determination.

areas. Here again varieties of high specific gravity had greater differences between cortex and pith than varieties which were low in specific gravity.

Means of varieties indicated very little difference between specific gravity of cortex and outer medulla. The difference between cortex and pith area were greater, but this difference was more marked in 1956 than in 1957.

Fifteen tubers of each variety were cooked just after harvest in boiling water for 25 minutes and resistance to pressure of the surface and internal areas was noted. These data are shown in Table X, which indicates very little difference in penetration resistance except for Onaway tubers. Eighty percent of these were hard in the inside after being cooked in boiling water for 25 minutes. There were various degrees of hardness in different tubers, but the average resistance to pressure of all the cooked Onaway tubers (including tubers which cooked soft) was 136.7, while the resistance to pressure of a cooked potato should be approximately 80 grams per 0.02 $cm.^2$ or below. Onaway tubers from this lot were used for the determination of three different pectic fractions, cellulose and hemicelluloses, both before and after extended storage.

Determination of Three Pectic Fractions, Cellulose and Hemicelluloses

Twelve composite samples of the inner portion of the 25 hard cooking tubers and 12 composite samples of the inner part of 25 soft cooking tubers of Onaway potatoes were made and analyzed as previously described. Results of these analysis are shown in Table XI. It may be seen from the

Table X. Resistance to pressure in grams per 0.02 $cm.^2$ of surface and internal areas of cooked potato tubers from 14 varieties grown in 1957 (means of 15 tubers).

No.	Variety	Surface Area	Internal Area
1.	Sebago	72.4	91.0
2.	Pontiac	78.6	90.3
3.	Onaway	64.1	136.7
4.	Chippewa	60.1	71.4
5.	Ontario	75.8	86.3
6.	Tawa	69.5	88.3
7.	Osage	82.8	105.5
8.	Katahdin	78.0	94.6
9.	Irish Cobbler	81.3	101.6
10.	Cherokee	72.0	88.3
11.	Menominee	69.0	86.6
12.	Russet Rural	74.3	96.7
13.	Delus	65.6	80.3
14.	Merrimack	87.2	101.4
15.	Green Mountain	70.6	90.3
	Mean	73.42	93.95

Table XI. Three pectic fractions, cellulose and hemicelluloses of hard and soft cooking Onaway potato tubers, expressed as percentage fresh weight.*

Sample No.	Water Soluble Pectin	Ammonium Oxalate Soluble Pectin (middle lamella pectin)	Acid Soluble Pectin (proto-pectin	Cellulose	Hemicelluloses (includes Acid Soluble Pectin)	Hemicelluloses Minus Acid Soluble Pectin
Hard						
1.	0	0.6102	0.7954	0.4000	2.6920	1.8948
2.	0	0.5949	0.8556	0.4321	2.5142	1.6586
3.	0	0.5079	0.9001	0.3921	2.4069	1.5068
4.	0	0.6200	0.8356	0.3887	2.7200	1.8844
5.	0	0.5947	0.8124	0.4589	2.9013	2.0889
6.	0	0.5411	0.8317	0.4399	3.0012	2.1695
Soft						
1.	0.0589	0.2986	0.3891	0.4902	1.5789	1.1898
2.	0.0484	0.3001	0.3902	0.4833	1.3245	0.9343
3.	0.0570	0.2876	0.4117	0.5210	1.5242	1.1125
4.	0.0678	0.3233	0.4254	0.5004	1.4788	1.0534
5.	0.0524	0.3838	0.3758	0.4463	1.4524	1.0766
6.	0.0624	0.2732	0.4101	0.4536	1.3024	0.8933
Means						
Hard	0	0.5781	0.8384	0.4186	2.7056	1.8671
Soft	0.0578	0.3111	0.4003	0.4824	1.4435	1.0431

* Each of the six samples drawn from a composite sample of 25 tubers.

means that in hard cooking tubers there was no water soluble pectin, while in soft cookers there was 0.0578 percent of fresh weight. There was almost twice as much ammonium oxalate soluble pectin and acid soluble pectin in hard cookers as in soft cookers. Again the percentage of hemicelluloses was much higher in hard cookers than in soft cookers. The cellulose percentage was almost the same in both kinds of tubers. Thus hard cooking inside was associated with the presence of a high percentage of water insoluble pectins (ammonium oxalate and acid soluble pectins) and hemicelluloses.

The hard cooking tubers cooked soft after being stored at 70° F. Table XII indicates the penetration resistance of the twenty halves taken from the lot of very hard cooking Onaway tubers stored at 70° F. and pressure tested after cooking at weekly intervals. Figure 12 shows this data graphically. At 0 days of storage the resistance to pressure was over 300 grams per 0.02 $cm.^2$ As the storage period increased the resistance to pressure declined rapidly and after five weeks storage these tubers cooked soft.

Twenty-five halves of the tubers which were stored at 70° F. for six weeks were analyzed for three different pectic fractions, cellulose and hemicelluloses to determine the changes which made these hard cookers cook soft. These data as percentage fresh weight are shown in Table XIII. Table XIV compares the percentage fresh weight of the three pectic fractions, cellulose and hemicelluloses of hard cookers initially and after six weeks storage, when they cooked soft. It is evident from Table XIV that at the beginning in the hard cookers no water soluble pectin was present but when they cooked soft .1345% water soluble pectin was present.

Table XII. Penetration resistance in grams per 0.02 cm.^{2} of internal area of hard cooking Onaway tubers stored at 70° F. and cooked at weekly intervals for 25 minutes (means of five pressure tests).

Tuber No.	Weeks in Storage at 70° F. 0	1	2	3	4	5	6
1.	264.6	265.0	251.6	206.4	138.6	111.6	62.8
2.	295.3	253.8	240.9	188.3	132.6	94.2	73.0
3.	370.1	260.1	228.5	210.5	136.8	98.2	80.6
4.	327.3	278.8	258.4	196.0	118.7	82.8	86.2
5.	296.9	236.6	220.7	180.2	146.5	93.0	64.4
6.	300.5	251.1	238.8	200.5	134.0	92.9	61.3
7.	338.8	270.0	257.9	207.6	130.2	106.6	80.5
8.	310.2	244.5	239.6	214.5	140.6	88.6	79.7
9.	345.5	268.8	240.0	188.7	126.3	116.7	84.6
10.	272.0	250.0	250.5	207.3	148.2	83.4	66.2
11.	285.2	258.8	223.8	204.4	148.8	85.4	91.6
12.	326.1	281.6	220.4	186.4	124.2	99.3	74.2
13.	338.0	294.2	251.1	210.3	106.6	106.2	78.0
14.	274.4	269.5	248.5	215.2	146.2	84.4	63.4
15.	286.4	270.0	260.5	189.0	119.7	90.2	65.4
16.	241.7	281.2	218.2	188.3	122.5	81.3	79.4
17.	278.7	254.0	216.6	194.5	146.7	99.7	70.2
18.	309.3	270.0	230.5	208.4	126.0	86.2	86.6
19.	333.0	267.9	232.6	193.6	102.5	104.6	68.6
20.	356.7	270.6	251.0	198.7	140.0	100.5	96.7
Mean	307.4	264.8	239.0	199.4	131.8	95.3	75.7

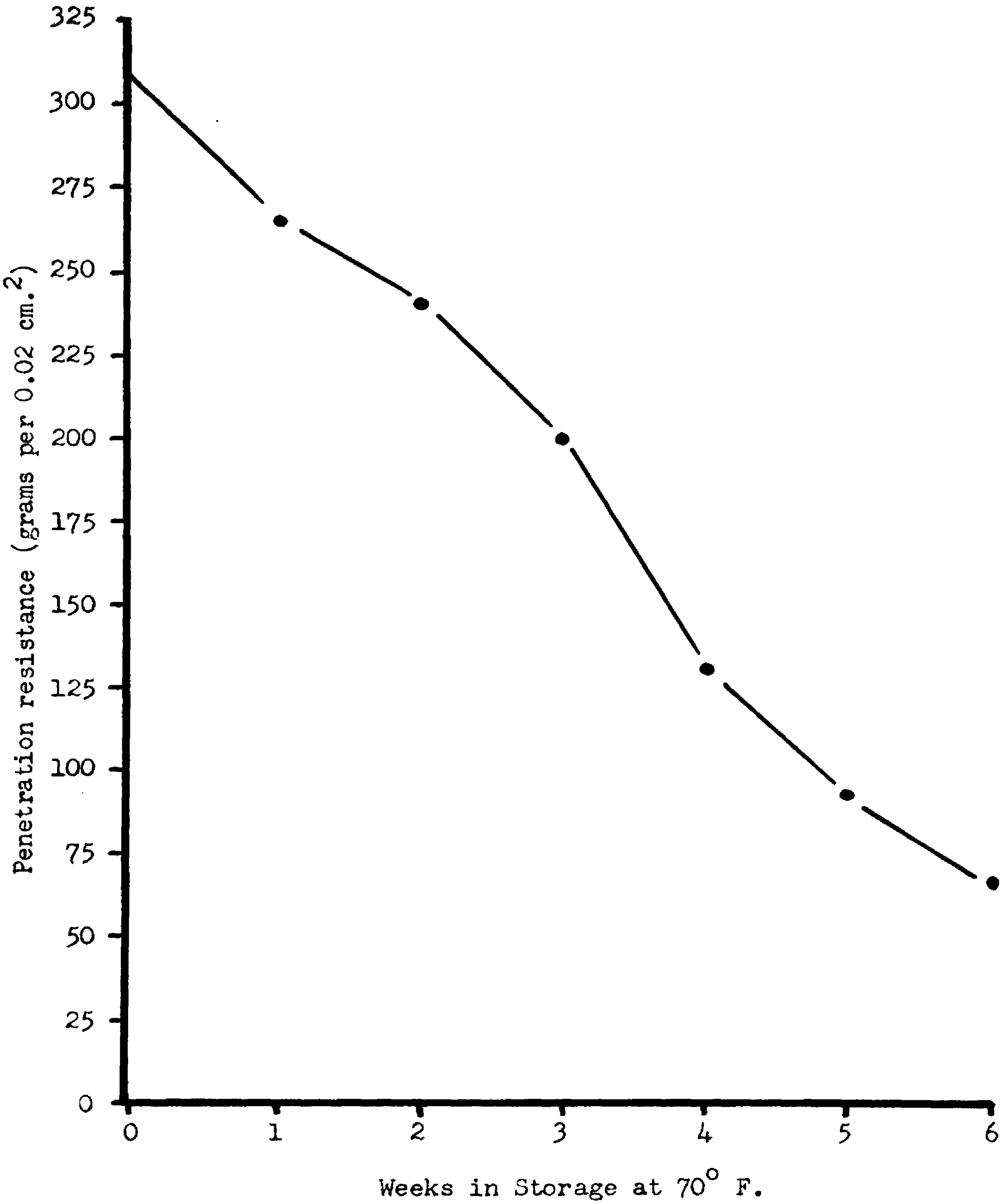

Figure 12. Effect of pre-cooking storage at 70° F. on post-cooking penetration resistance of Onaway tubers (internal area) selected for extreme internal "hardness".

Table XIII. Percentage fresh weight of three pectic fractions cellulose and hemicellulosesof hard cooking Onaway tubers analyzed after being stored until they cooked soft.

Sample No.	Water Soluble Pectin	Ammonium Oxalate Soluble Pectin (middle lamella pectin)	Acid Soluble Pectin (proto-pectin)	Cellulose	Hemicel-luloses (includes Acid Soluble Pectin)	Hemicel-luloses Minus Acid Soluble Pectin
1.	0.1266	0.3972	0.4916	0.4412	1.8112	1.3296
2.	0.1239	0.3511	0.5329	0.4400	1.7034	1.2505
3.	0.1284	0.4016	0.5009	0.4055	1.7380	1.2771
4.	0.1483	0.3624	0.4926	0.4508	2.0021	1.3195
5.	0.1357	0.3500	0.5200	0.4187	1.8222	1.3622
6.	0.1442	0.4084	0.5306	0.4272	1.7236	1.1930
Mean	0.1345	0.3784	0.5114	0.4306	1.8001	1.2887

Table XIV. Percentage fresh weight of three pectic fractions cellulose and hemicelluloses of hard cookers before and after being stored until they cooked soft (means of six samples from a composite of 25 tubers).

	Water Soluble Pectin	Ammonium Oxalate Soluble Pectin (middle lamella pectin)	Acid Soluble Pectin (proto-pectin)	Cellulose	Hemicelluloses (includes Acid Soluble Pectin)	Hemicelluloses Minus Acid Soluble Pectin
Before Storage (hard)	0	0.5781	0.8384	0.4186	2.7056	1.8671
After Storage (soft)	0.1345	0.3784	0.5114	0.4306	1.8001	1.2887

The ammonium oxalate soluble pectin and acid soluble pectin had decreased to a marked degree. The cellulose percentage remained the same, but the percentage of hemicelluloses was much reduced after storage.

These results clearly indicate that due to the presence of a high amount of ammonium oxalate and acid soluble pectins and of hemicelluloses these potatoes cooked hard. After storage at 70° F. for five to six weeks they cooked soft as the amount of these substances had been considerably reduced.

SUMMARY AND DISCUSSION

The internal portions of a fraction of the potatoes in a given lot sometimes cook much more slowly than the outer portions. This leads to considerable inconvenience and loss since the over-cooked portions slough off, and the rapid cookers are badly over-cooked and water soaked in the attempt to complete the cooking of the slow cookers. The previously described investigation attempted to clarify the causes and discover the remedy for this condition.

The firmness of a potato after cooking can readily be determined by the use of a penetrometer that measures the resistance, in grams, to penetration by a small rod. The cooked and cooled potato starch forms a relatively stiff mass, depending upon the proportions of starch and water, and thus gives a relatively low resistance to penetration when uncomplicated by other factors. However, when cooked starch is held inside cell walls that do not readily separate on the application of pressure, the resistance to penetration may be many times that of the starch gel, itself. Thus, minimum pressures for high-starch potatoes were around 40-60 grams, and for low-starch potatoes were around 20-30 grams. But resistance pressures after the same period of cooking, but before cell walls separated readily, were from 100-300 grams pressure. Any pressure more than about 80 grams would designate the potato as being somewhat raw or uncooked.

The condition of hard cooking at the start of storage of several specific gravity groups of Katahdin potatoes and the changes during storage at 40° and 70° F. (indicated by resistance to pressure after cooking) may be summarized as follows:

(1) Surface area of all potatoes cooked more rapidly than internal area at the start of storage.

(2) As the storage period increased the resistance to pressure after cooking of both surface and internal areas fell.

(3) There was more change in resistance to pressure of the internal area than surface area as the storage period increased; these changes were more rapid at 70° storage than at 40° F.

(4) At 70° F. the internal area cooked softer than surface area after seven weeks of storage. The internal area cooked much softer than surface area in high specific gravity potatoes (1.080 - 1.085) while in low specific gravity potatoes (1.065 - 1.070) the softness of the surface and internal areas after cooking was almost the same.

(5) At 40° F. the inside did not cook softer than the surface area in any of the specific gravity groups.

The condition and changes in Onaway tubers before and after storage can be summarized:

(1) At the beginning of storage the center part of about 80% of the Onaway tubers was hard to cook and calcium pectate, protopectin and hemicelluloses were present in large amounts.

(2) After 5-6 weeks of storage at 70° F. they cooked soft and the quantity of these substances was much reduced.

(3) At the beginning of storage, hard-cooking Onaway tubers were high and soft-cooking tubers low in insoluble pectic substances and hemicelluloses. After six weeks of storage the initially hard-cooking

tubers which now cooked soft had about the same quantity of these materials as tubers which had cooked soft at the beginning of storage.

Before storage. In the beginning of storage the internal area cooked harder than the surface area because of the large amount of insoluble pectic substances and hemicelluloses present in the cell walls and as cementing materials between the cells. Innermost portions of Onaway tubers cooked very hard and were high in amounts of these substances, while those which cooked softer did not have so much of these materials. This is in accordance with the findings of Thiessen (1947), who reported that in potato tubers the inner medulla had a higher proportion of crude fiber and pectin than did the rest of the tuber.

Bonner (1952) mentioned that during the development of fruit, protopectin is laid down in the primary walls and in many cases protopectin accumulates to high concentration particularly in apple, pear and citrus species. Middle lamella pectate is likewise accumulated in the fruit. Norman (1937) in his review of cellulose and related cell wall compounds, stated that middle lamella of plant tissue is believed to be insoluble calcium pectate while the cell wall substances are protopectin and soluble pectin. The protopectin is always found closely associated with other cell wall constituents. Ippolito (1928) mentioned that when predominating pectic compounds are soluble or can be hydrolyzed, the tissue easily disassociates, becoming soft. With an excess of cellulose and hemicelluloses the pectic compounds are not hydrolyzed and vegetables do not cook readily. An explanation of the observed cooking performance of hard cooking tubers incorporates these findings.

After storage. Onaway tubers which were initially very hard to cook due to the presence of large amounts of calcium pectate, protopectin and hemicelluloses cooked normally after 5 to 6 weeks of storage at 70° F. These changes may be attributed to the observed decomposition of calcium pectate, protopectin and hemicelluloses, with a consequent decrease in cell wall rigidity due to alteration in thickness and firmness of the cell walls and the cementing substances of middle lamella. These changes had a pronounced effect on the force required to push the cells apart, as measured by firmness after cooking.

At the beginning of storage hardness in cooking was due to the presence of large amount of cell wall materials. After the hydrolysis of these substances starch determined the penetration resistance after cooking. It was found in this investigation that surface (cortex) had more starch as indicated by specific gravity than the internal area (pith) and thus cooked harder after storage than internal area. There were greater differences between specific gravities of surface and internal areas of high specific gravity potatoes than in low specific gravity potatoes; this was reflected by greater difference in hardness between areas in high specific gravity tubers.

Many investigators (Sweetman and Lancaster (1931), Barmore (1937), Thiessen (1947) and others) have reported that the portions within a tuber which had high starch content were firmer after cooking than those which had less starch.

At the end of storage the potatoes stored at 40° F. cooked similarly at the surface and internal areas. Apparently the insoluble pectic substances and hemicelluloses had not yet hydrolyzed to the extent that starch content alone rather than in combination with cell-wall materials determined hardness after cooking. It seems probably that this stage would have been reached after a few more weeks of storage. There is clear indication in the literature that changes in insoluble pectic fractions are more rapid at high than at low temperature, which was confirmed by these results.

Specific gravity patterns for regions within tubers of different varieties. In 15 varieties the specific gravity of cortical, outer and inner medullary regions was determined. For the two years of this study, a rather clear pattern emerged. In varieties where specific gravity of the entire tuber was high, there was a large specific gravity difference between outer and inner regions. In varieties with a lower specific gravity, the differences between outer and inner portions was comparatively small.

When cooked, before storage, there seemed to be no relationship between rapid cooking, or resistance to the penetrometer, and specific gravity. In the cases where cooking after storage was done, varieties higher in starch, as indicated by high specific gravity, were higher in resistance to penetration than tubers low in starch.

Analogous changes in other fruits and vegetables. Several investigators have found similar changes in other fruits and vegetables during ripening and storage. This has been thoroughly studied in apples by Carre (1922, 1928), Emmett (1925, 1926), Haller (1929) and others who have found that softening of fruits takes place due to hydrolysis of insoluble pectic substances of cell wall and middle lamella. Dastur and Agnihotri (1934) noticed decomposition of protopectin and middle lamella pectin of cell walls of potatoes during storage but did not associate these changes with characteristics of cooked tubers. Several other investigators working with pears, peaches, bananas and grapes have found similar changes. The rate of such degradation increases with increasing temperature.

In the present investigation it was found that the amount of starch present in the cells, the thickness or toughness of cell walls and ease with which the cells separate as indicated by insoluble pectins and hemicelluloses play an important role in determining hardness of potatoes after cooking. In the beginning of storage the insoluble pectic fractions and hemicelluloses plus the starch determine the hardness after cooking but after storage these cell-wall materials are hydrolyzed and become soluble and the amount of starch present in the cells mainly determines the hardness after cooking. If the low resistance pressure after storage is attributed to a starch effect, the decrease during storage may be called the cell-wall effect. This cell-wall resistance decreases as cell-wall materials hydrolyze. It is thus suggested that lots of potatoes containing hard cookers be kept in storage until such time as the hardness has disappeared due to changes in the cell wall constituents.

CONCLUSIONS

1. Potatoes generally are slower to cook immediately after harvest than after a period of storage. Degree of "done-ness" can be measured with a penetrometer.
2. In some cases, extremely slow cooking shortly after harvest is encountered in a considerable fraction of the tubers in a given lot, but this does not seem to be an invariable varietal characteristic.
3. A reduction in hardness after a standard cooking procedure is accomplished more rapidly in storage at 70° F. than at 40° F.
4. Tubers from a given varietal lot may be selected for either "hard" or "soft" cooking. Those that are hard to cook are characterized by a far higher content of insoluble pectins and of hemicelluloses than those that cook soft. The cellulose contents are found to be about the same in soft and hard.
5. Storage that reduces the hardness of cooking also reduces the content of insoluble pectins and hemicelluloses to the level of the soft cookers.
6. Tubers or parts of tubers with high specific gravity, (and starch) are firmer after cooking, when cooking "soft", than are those with a low specific gravity. This is attributed largely to the relative concentration and stiffness of the potato-starch gel in either case.
7. Before storage, or when cooking hard, the effect of the high pectin and hemicelluloses in the cell walls, which prevents their easy

separation, may completely mask any starch gel effect on hardness. This cell-wall effect may easily be 10 times the starch-gel effect.

8. Varieties with a high average specific gravity strongly tended to vary greatly in the specific gravity between outer (cortex) and inner (pith) regions of the tuber, while those with a lower specific gravity had comparatively little differences between regions.

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