

FUNCTIONAL PROPERTIES OF BANANA STARCH

by

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ABSTRACT

The functional properties (ease of cooking, thickening power, paste stability, etc.) of banana starch have been deduced by comparison of the cooking and cooling curves (obtained on the Brabender Amylograph) of banana, corn, tapioca, waxy maize and cross-bonded waxy maize starches. Banana starch has functional properties generally similar to cross-bonded waxy maize, except that banana starch pastes tend to cook more slowly and are much less resistant to breakdown under acid conditions.

The three banana starch samples examined were mixtures of small and large grains, plus some agglomerates. One sample was fractionated by a simple, air classification method. The smaller grains (25% of total by weight; 22 ± 7 microns in the greatest dimension) and the larger grains (50%; 39 ± 10 microns in the greatest dimension) had functional properties almost identical to that of the whole starch. The agglomerates (15%; clumps and fragments of wide size variation) had similar functional properties, but with reduced thickening power. About 10% of the starch was lost during classification.

Banana "flour" (dried and finely ground, green banana pulp) contained 70% starch and had functional properties remarkably similar to the isolated banana starch. This "flour" could possibly be substituted for isolated starch at considerable savings.

Potential food uses for banana starch and banana "flour" are discussed, as well as the possible molecular basis for the unique properties of the banana starch.

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When I was a little girl, my grandfather often told me "you can do anything if you set your mind to it". Until I came to the Institute I didn't understand fully what he meant. The most valuable lesson that anyone ever learns is how to think for oneself. Knowledge gained, wonderful though it may be, is only a dead end if you cannot use it. I do not pretend to have mastered the art of converting knowledge into action, but I value my years at M.I.T. because they have taught me to approach a problem by "setting my mind to it".

I wish to thank Dr. James K. Palmer for his help and advice and his confidence in me. I wish to thank my professors and friends in the lab, especially Sonia Quast for her help with the starch content determinations. I wish to thank Linda Boyar for her invaluable emergency assistance in typing and my sister, Susan, for her company on occasional Saturdays. I especially appreciate the endless support and encouragement of my parents, the loving pride of my grandparents, Leonard and Eunice Coleman, and the patience of my husband Bill.

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I. LITERATURE SURVEY

Starch is one of the most abundant naturally occurring organic compounds. It is found in almost all plant tissues, where it functions as a source of reserve energy, which can be utilized gradually through enzyme action. Starch accumulates to high concentrations (20-70%) in the roots, tubers, fruits and seeds of many plants.

Starch is used in the food industry as a nutrient source, an extender, processing aid, thickener, stabilizer and texture modifier (Hahn, 1969; Wurzburg, 1968). The availability and cost of the starch are major factors in determining its use in foods. Some starches (or chemically modified versions of them) display, in addition to their nutritive value, unique properties which make them especially valuable to the industry (Wurzburg, 1968). Corn is the most widely used starch in the United States (Hahn, 1969). Other food starches readily available on the market are potato, tapioca, wheat, and rice starches (naturally occurring); the so-called waxy starches (from genetically selected plants; low amylose content); and cross-bonded, acid treated or oxidized starches (chemically modified).

Regardless of their origin, all pure starches are fine, white powders. Microscopic investigation shows the powder to be made up of tiny granules whose size and shape

are characteristic of the plant from which it was extracted. Another identifying characteristic of the starch granules is the hilum, the so-called nucleus of the granule, which displays birefringence with polarized light. The characteristic features of starches from various origins are nicely illustrated in the photographs by Wivinis and Maywald (1967).

Chemically, starches from all sources are carbohydrates, polymers of α -D-glucopyranose units linked primarily by 1,4 and 1,6 glucosidic bonds. Each glucose unit contains one primary and two secondary hydroxyl groups which are responsible for the hydrophilic properties of the starch. Starch is made up of two types of polymer chains, amylose, the linear fraction (1,4 bonds) and amylopectin, the branched chain fraction (1,4 and 1,6 bonds). The ratio of amylose and amylopectin in starches also provides some indication of their origin. The exact structural relationship between the two components in the starch grain is not known, but the molecules are linked together to form the starch granule by hydrogen bonds (Hahn, 1969; Wurzburg, 1968).

Starch granules are insoluble in cold water. In a humid environment, starches will absorb moisture, but the swelling which occurs is reversible. When starch granules in water are heated past a critical temperature, in the range 60-75°C (gelatinization temperature, characteristic of a specific starch), the hydrogen bonds which

hold the granule together begin to weaken, allowing the granule to swell. Since gelatinization begins at the hilum, the first indication of swelling is loss of birefringence. Then, as the amylose fraction is dissolved and leached out, the granules begin to take in water and the clarity and the viscosity of the slurry begin to increase. Eventually, the granules, having become completely hydrated, may collapse and break down. The resulting starch "paste" is composed of granule fragments and molecules in solution. The viscosity of the paste decreases as a result of this granule breakdown. On cooling, the paste usually increases in viscosity and decreases in clarity. This results from retrogradation of the linear (amylose) molecules, a process whereby the amylose molecules tend to form rigid gels by hydrogen bonding.

Starch granules from different sources may vary considerably in these so-called pasting properties. Some are fragile and show a sharp increase in viscosity and a severe subsequent drop in viscosity due to solubilization. Others, having a more stable granule structure, show only moderate increases in viscosity and little tendency to break down. The degree of retrogradation is dependent on amylose content and on the degree to which the amylose has been solubilized during the heating cycles. Cross-bonded

starches have their granule structure reinforced by covalent bonds and the granule shows less tendency to swell and retrogradation is minimized (Wurzburg, 1969; Leach, 1965; Smith, 1964b; Collison, 1968; Mazurs et al., 1957).

The suitability of any starch, natural or modified, for a specific use in the food industry depends on the functional properties, which are really a reflection or derivation of the pasting properties described above. The functional properties would include, for example, ease of cooking (temperature, time, and stirring energy required to cook through the initial swelling region), thickening power (final viscosity of the paste after cooking and cooling, as a function of concentration) and stability (resistance to thinning resulting from stirring, pH or temperature change).

Because of the variety of changes which may occur in a starch paste during processing, many different methods have been developed for following these changes in the paste and estimating the functional properties of the starch from them. These methods fall into two categories, those involving direct microscopic observation such as monitoring granule swelling, loss of birefringence or staining reactions (Collison, 1968; Mac Masters, 1964), and those involving measurement of physical properties such as swelling power, solubilization, sedimentation rate

or viscosity (Collison, 1968; Schoch, 1964; Smith, 1964b). The most useful methods measure the viscosity of the paste continuously during a standardized cooking and cooling cycle which simulates a wide variety of processing conditions (Smith, 1964b). The most common instrument used for this purpose is the Brabender Amylograph (Hahn, 1969). This machine continuously measures the viscosity of starch pastes while they are stirred and heated at a constant rate, held at 95°C for 30-60 minutes, cooled at the same rate from 95 to 50°C and then held at 50°C for 30-60 minutes (see Methods for details of sequence used in this study). Methods have also been developed for relating the viscosity data, to the functional properties of the starch (Mazurs et al., 1957) (see Methods for details). These kind of data are available for most food starches (Mazurs et al., 1957; Kite et al., 1957; Hahn, 1969), but not for banana starch.

Earlier microscopic investigations showed that green banana starch granules are not uniform in size (Von Loesecke, 1949). More recently, it has been observed that banana starch exists as multi-size particles which can be said to fall into two major size categories depending on their localization in the fruit tissue (J.K. Palmer, Personal Communication). Air classification is a simple and effective method of separating these

starch grains by size (Yamazaki and Wilson, 1964). These two grain size fractions from the same source offer the possibility of relating functional properties to gross morphology. There have been reports of such correlations (Meyer et al., 1949).

Since starch makes up 70-80% of the dry weight of green banana pulp, it is possible that a dried, finely ground pulp (banana "flour") would have functional properties similar to the isolated starch. No such comparison has been made with bananas or any other starch-containing tuber.

II. INTRODUCTION

Green bananas are an excellent potential source of food grade starch. Large quantities are available as by-products or waste from the fresh fruit industry and they contain approximately 20% starch on a fresh weight basis. The price, however, will be competitive only if banana starch has some unique functional properties. Banana starch would be particularly valuable if it could be substituted for more expensive, chemically modified starches. If the Food and Drug Administration disallows chemically modified starches as a result of its ongoing review of all food additives, there would be a greatly increased demand for "natural" starches with properties equivalent to the modified starches. The primary purpose of this study was to determine the functional properties of banana starch and to compare them with those of other available food starches.

One unusual feature of banana starch is the presence of two distinct starch grain sizes (J.K. Palmer, Personal Communication). Grain size could affect the functional properties. If so, it is possible that the functional properties of banana starch could be tailored by simply separating the granules by size, producing some useful starch products.

Finally, since the dried pulp of unripe bananas is 70-80% starch, this banana "flour" might possess functional properties identical to isolated banana starch. The "flour" could then be substituted for the starch in foods, at considerable savings.

III. EXPERIMENTAL MATERIALS AND METHODS

A. Materials

1. Banana Starches, U.F.#1 and U.F.#2 - These samples were kindly provided by the United Fruit Company. They were prepared primarily for evaluation of the adhesive properties of banana starch. Waste, whole bananas (mostly green) were fed to a pre-grinder, where they were mashed and delivered to a tank for dispersion in water containing 0.5% by weight of sodium hydroxide. The slurry was then screened to separate the starch from the other solids. The starch "milk" was passed through a countercurrent, four-stage, wash train to remove the protein and any low density solid particles. The starch stream from the final wash was rotary vacuum filtered to remove most of the water. The filter cake was dried in a hot air, tunnel drier. Lumps of extracted starch were crushed to a fine powder before packaging (P.C. Butler, Personal Communication).

U.F.#1 and U.F.#2 were both light brown in color, which caused the "puddings" resulting from cooking to have a brown coloration. This pigmentation was probably due to oxidation of the phenolic constituents.

2. Banana Starch, M.I.T. #1 - This technique was devised to obtain banana starch which had been treated as gently as possible, for comparison with U.F.#1 and U.F.#2.

The procedure was adapted from a general method of starch extraction (Badenhuizen, 1964).

Approximately 200 grams of pulp slices from hard, green Valery bananas were, immediately after peeling, cut and dropped into a Waring blender with an equivalent volume of cold extracting medium containing 4% NaCl, 1% ascorbic acid (antioxidant) and 0.185% E.D.T.A. (Ethylenediamine-tetraacetic acid, a metal chelator to protect the ascorbic acid). The tissue was blended at high speed until the mixture appeared homogeneous (about 10 minutes). Ice was added intermittently to keep the temperature below 20°C and to thin out the slurry. The starch "milk" was separated from the fibrous tissue debris by filtering through cheesecloth. The cell debris was redispersed in extracting solution and blended twice more, each time recovering the starch "milk". The starch "milk" solutions were then combined and centrifuged at about 300 g for five minutes. The supernatant was discarded and the starch washed and resedimented three times in fresh 4% NaCl. Protein was denatured and removed by shaking the starch in water saturated with toluene for several hours. The toluene layer was siphoned off and the water removed by vacuum filtration. After a final wash with acetone, the filter cake was air-dried. A few lumps were crushed and the fine powder was stored at room temperature.

3. Coarse, Fine and Agglomerated Starch Grains from

U.F.#1 - Earlier microscopic examination of intact banana cells revealed the presence of two major classes of grain size in banana starch (J.K. Palmer, unpublished). Microscopic investigation of U.F.#1 confirmed the presence of large and small grains, plus some agglomerates. In order to study the effect of grain size on functional properties, samples of each of these fractions were obtained by an air classification method developed for this purpose. It was assumed that the simple and flexible air classification technique could be applied to factory scale separations, if the fractions had significantly different functional properties.

It is not practical to give a detailed description of the conditions for fractionating a particular starch, since the air classifier settings will depend on the type of classifier, the starch being separated and the granule size desired (Yamazaki and Wilson, 1964). In the present study, the air classifier consisted of a tank of compressed air which was connected through a regulator to a glass column (length, 18"; O.D., 1") by flexible tubing. About 10 grams of dry starch was placed on a fritted glass filter, located at the bottom of the column, just above the point where the air stream entered. The column was supported by a vibrator which kept the starch grains, especially the fines, from clinging to the glass walls of the column. The starch grains were collected through

another flexible, u-shaped tube which led from the top of the column into a collecting bottle. By increasing the air pressure over the range from 10-60 psi at specific time intervals, it was possible to separate the banana starch into three distinct fractions: fine, coarse and agglomerates (the residue remaining in the column after classification). The three fractions were weighed and the size range of each fraction was determined by microphotography.

4. Banana Flour - Banana flour was prepared by freeze-drying pulp of hard, green Valery bananas. Approximately 200 grams of thinly sliced pulp from the center section of several quickly peeled bananas were immersed in a Waring Blender with 100 ml cold 1% ascorbic acid containing 0.185% E.D.T.A. The tissue was blended at high speed for ten minutes. Ice was added periodically to reduce the temperature of the mixture. Aliquots (about 100 ml) of the slurry were frozen in thin layers on the walls of 500 ml round-bottom flasks by swirling in liquid nitrogen. The flasks were attached to an evacuated manifold for freeze-drying. The condensor of the freeze-dryer was held at -78°C and the vacuum was sufficient to prevent any thawing of the slurry. The vacuum was maintained for about 48 hours. The dried flour was weighed and stored in a desiccator at room temperature.

The starch content of the banana flour was determined by enzymatic analysis, using a technique developed in this laboratory (J.K. Palmer, unpublished). A 1% solution was prepared by boiling a few grams of the sample in 100 ml of distilled water. Aliquots of this solution were incubated at 55°C with and without the enzyme glucoamylase at pH 4.5. The incubated mixtures were assayed for glucose with Glucostat reagent (Worthington Biochemical Corporation). The starch content was calculated from glucose content of the samples treated with glucoamylase and corrected for the glucose content of the controls (no glucoamylase).

5. Cross-Bonded Waxy Maize Starch - This starch was kindly supplied by National Starch and Chemical Corporation, designated National 1333. It was chosen to represent a typical cross-bonded waxy maize used in the food industry.

6. Waxy Maize Starch - This starch was kindly supplied by American Maize Products. The term "waxy" refers to the fact that this naturally occurring starch contains little or no amylose.

7. Corn Starch - This was a sample of "Argo" unmodified corn starch, a product of Corn Products Company.

8. Tapioca Starch - Brazilian Superior AA Tapioca Flour, designated control no. 6-49-70, was kindly supplied by Stein Hall and Company, Inc. Although termed a flour, this product was an unmodified tapioca starch.

B. Methods

1. Determination of Moisture Content - Moisture content of the starches was determined by the vacuum oven-drying method. A one gram sample of the starch was accurately weighed into a tared aluminum weighing pan with cover. The open pan and cover were placed in a vacuum oven overnight at 60°C and about 1 mm pressure. The vacuum was broken through a trap containing a desiccant. The cover was placed on the pan and the sample weighed after cooling in a desiccator. The percent moisture was calculated from the loss in weight (Smith, 1964a).

2. Microphotography of Starch Grains - A thin suspension of starch grains was examined and photographed on a Spencer microscope with a Polaroid camera attached, using transmitted light. Exposure and lighting were varied to yield prints of the best contrast. All starch grain photographs were taken at the same magnification, 150x, and therefore can be compared directly.

3. Determination of Cooking and Cooling Curves on the Brabender Amylograph (C.W. Brabender Instruments, Inc., Model VA-1B) - The Amylograph continuously measures the viscosity of a starch slurry during a pre-determined cooking and cooling cycle. The sample container and contents are rotated continuously at constant speed. Several metal prongs extend downward into the starch

solution and serve both to stir the paste and as sensing elements. The movement of the sample exerts a force on the prongs which is balanced by a calibrated torsion spring. The tension on the spring is recorded continuously as viscosity (Brabender units) on a chart recorder. The sample cup is heated electrically by an air bath and cooled by cold water circulated through a closed cooling probe. A motor-driven thermoregulator controls the rate of increase and decrease of temperature at 1.5°C per minute and also holds the temperature constant during the stirring cycles (Smith, 1964b).

The program used in this study consisted of four cycles of thirty minutes each. The heating cycle brought the starch slurry from 50°C to 95°C. The starch paste was then held at 95°C during the second cycle. A cooling cycle then reduced the temperature of the paste from 95°C to 50°C and the final cycle held the paste at 50°C. Temperature of the paste was monitored on a thermometer, independent of the thermoregulator. In the case of banana starch, banana flour and cross-bonded waxy maize, the paste was then held without stirring until it cooled from 50°C to about 25°C to note the color and the thickness of the resulting "pudding" at room temperature.

The starch slurries for analysis were prepared by stirring an appropriate weight of starch (corrected for moisture content) with a small quantity of Belmont Distilled Spring Water to form a smooth paste, then made

up to 500 ml by weight with the distilled water. Since pH affects the viscosity and other physical properties of the cooked paste, all samples were adjusted to pH 4.5 with sodium hydroxide or citric acid (Smith, 1964b). The starch slurry was stirred and added to the sample cup just prior to starting the heating cycle, to ensure even distribution of particles at the beginning.

Preliminary runs with Belmont Distilled Spring Water and with a standard starch (supplied by the Brabender Corp.) indicated that the Amylograph was functioning properly.

4. Method of Graphic Analysis for Functional Properties -

The charts of the various starch samples from the Brabender Amylograph were redrawn to make analysis and comparisons easier. (The chart paper on the Amylograph has a curved ordinate.) Several concentrations of each starch were run to produce a family of curves. Although the characteristic shape for each starch is different, they have in common five significant points or regions (Mazurs et al., 1957; Kite et al., 1957). These are outlined below and indicated on Figure 1.

a. The Peak Viscosity or Pasting Peak - This is the highest viscosity which is reached during the gelatinization of the starch. The temperature where the viscosity begins to increase and the rate of increase are also considered. Together, these three factors indicate

the ease of cooking and the pasting peak provides an estimation of the power requirements for stirring the starch paste during gelatinization.

Some starches do not have a distinct peak. The viscosity simply increases during heating and tends to remain relatively constant during the holding cycle at 95°C.

- b. The Viscosity at the End of the Heating Cycle as the Sample Reaches 95°C - This gives an indication of the stability during cooking when related to peak viscosity. A sharp drop in viscosity from the viscosity peak indicates granule fragility and solubilization.
- c. The Viscosity at the End of the 95°C Holding Cycle - This indicates the degree of fragility or stability of the hot paste. A drop suggests additional breakdown of granules or solubilization, due to stirring.
- d. The Viscosity at the End of the Cooling Cycle, When the Paste Again Reaches 50°C - This is a measure of the thickening or "set-back" of the paste with cooling. It arises from retrogradation of the linear molecules and can be a serious obstacle during processing.
- e. The Viscosity at the End of the 50°C Holding Cycle - This indicates the stability of the paste to stirring in the form in which it will most likely

be used by the industry. It is a good indication of granule rigidity and resistance to shear. The actual viscosity at this point may also be considered a measure of thickening power or thickening efficiency of a starch.

The above five points were also plotted on a semi-log graph of viscosity versus the log of concentration (see Figures 2 and 3). Expressing concentration on a logarithmic scale eliminates it as a variable when comparing the physical properties of many different kinds of starch, without distorting the data (Mazurs et al., 1957).

Table I summarizes the relationships between the Brabender viscosity curves and the functional properties. These functional properties are the basis for determining the usefulness of a food starch. Table I also indicates the molecular events which are believed to be responsible for the observed changes.

TABLE I
Properties of Starches

Paste Properties (Experimentally Determined)	Functional Properties	Molecular Properties
Rate of Increase in Viscosity when Heated to 95°C (Region Prior to Point A)	Ease of Cooking	Rate of Granule Swelling
Viscosity Peak (Point A)	Maximum Thickness on Cooking	Extent of Granule Swelling
Viscosity Changes (after reaching maximum viscosity) during heating and 95°C holding cycles (Region of Points A to C)	Stability During Cooking	Granule Fragility and Degree of Solubilization
Increase in Viscosity During Cooling (Region of Points C to D)	Set-back on Cooling	Retrogradation of Linear Molecules
Changes in Viscosity During Holding at 50°C (Region of Points D to E)	Resistance to Shear (Stability to Mixing)	Granule Rigidity
Final Viscosity after Holding at 50°C (Point E)	Thickening Power or Thickening Efficiency	Granule Rigidity Extent of Maintained Swelling

IV. RESULTS

A. Comparison of Brabender Curves of Banana Starch and of Other Food Starches

Figure 1 shows the Brabender viscosity curves for a series of starches, all at 6% concentration. The curves for corn, tapioca, waxy maize and cross-bonded waxy maize are comparable to those in earlier publications (Hahn, 1969). The banana starch curve closely resembles the curve for cross-bonded waxy maize, having no viscosity peak (in contrast, for example, with tapioca starch), showing little or no decrease in viscosity during the period of holding at 95°C and only a moderate increase in viscosity on cooling. Also, the actual viscosities of the two starch pastes were virtually identical at all points after the temperature reached 95°C. The only real difference between banana and cross-bonded waxy maize occurred during the first heating cycle from 50°C to 95°C. The banana starch paste began to thicken (as indicated by the increasing viscosity) at about 71°C and the rate of thickening was quite slow, comparable to that of corn starch. In contrast, thickening of cross-bonded waxy maize started at 65°C and the thickening proceeded rapidly once this temperature was reached (Figure 1).

When allowed to cool to room temperature without stirring, the banana starch and cross-bonded waxy maize pastes formed "puddings" with identical properties. Both starch "puddings" were firm and creamy, but banana starch retained the brown color apparent in the dry starch as a result of phenolic oxidation.

The similarities between banana starch (U.F.#1) and cross-bonded waxy maize starch were further studied by running Brabender viscosity curves of these starches at a range of concentrations. At all concentrations, the general pattern of the curves was basically similar to those in Figure 1. Figure 2 shows plots of the log of concentration versus viscosity at the significant points shown on Figure 1. These plots provide a more sensitive measure of differences in starch behavior (Mazurs et al., 1957). The similarities between banana and cross-bonded waxy maize are again apparent, especially when contrasted with similar plots for corn and tapioca starch (Figure 3).

These remarkable similarities in the viscosity curves suggested that banana starch might actually be cross-bonded. One characteristic feature of cross-bonded starch pastes is that the Brabender viscosity curves are not affected by acid conditions (Osman, 1967). Figure 4 shows that the viscosity of banana starch is markedly reduced by acidic conditions, a strong indication that banana starch is not covalently cross-bonded.

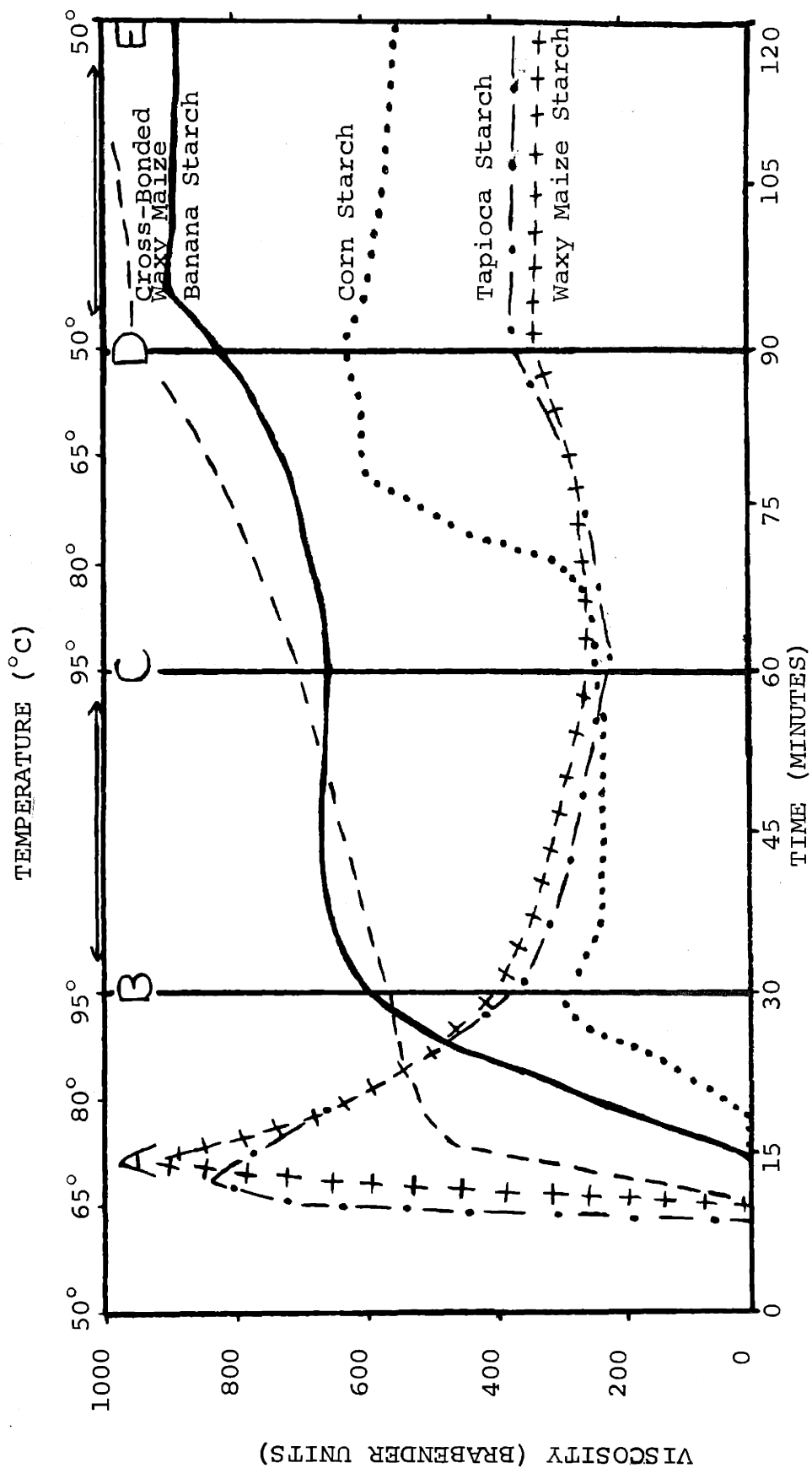
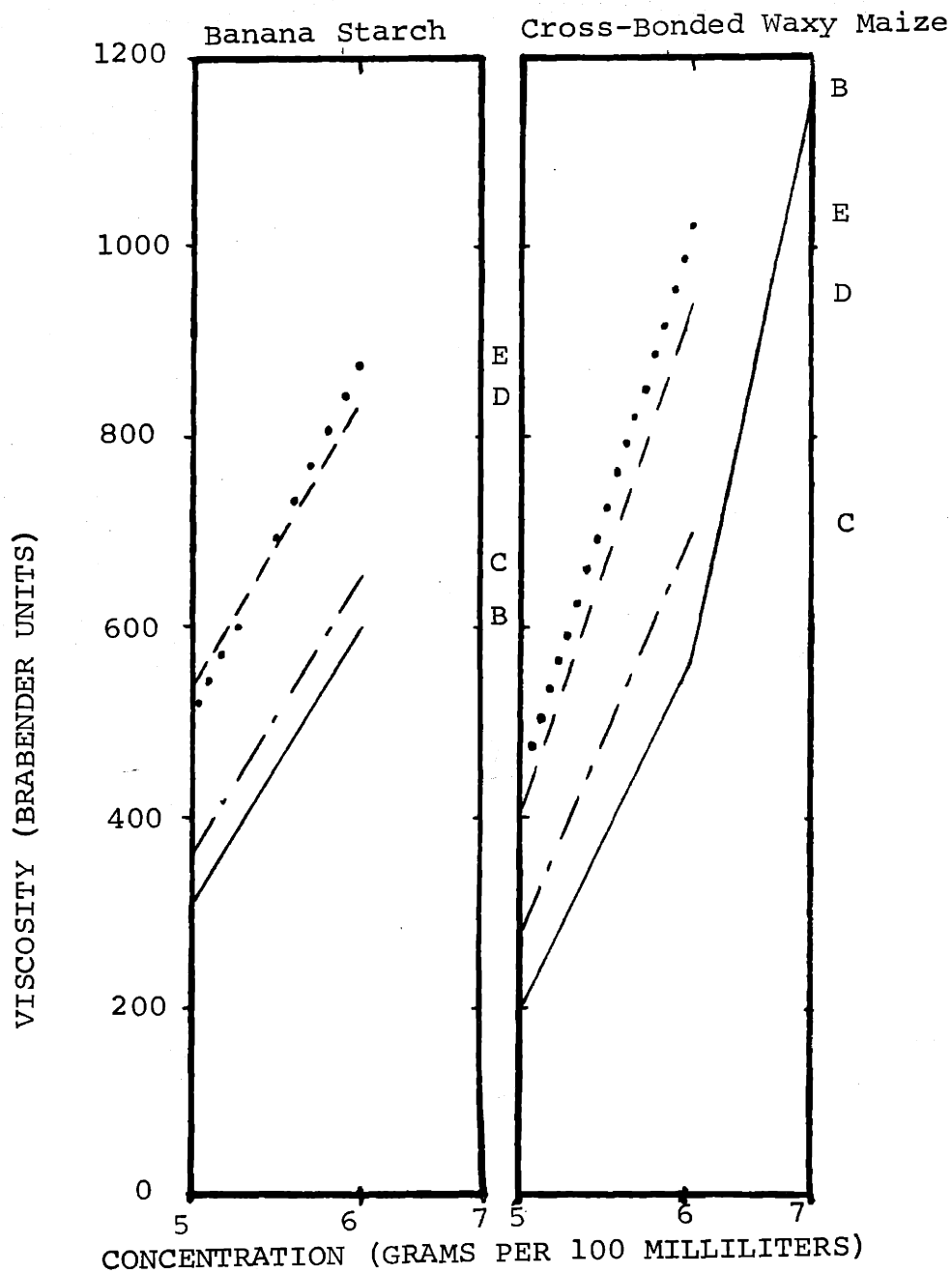


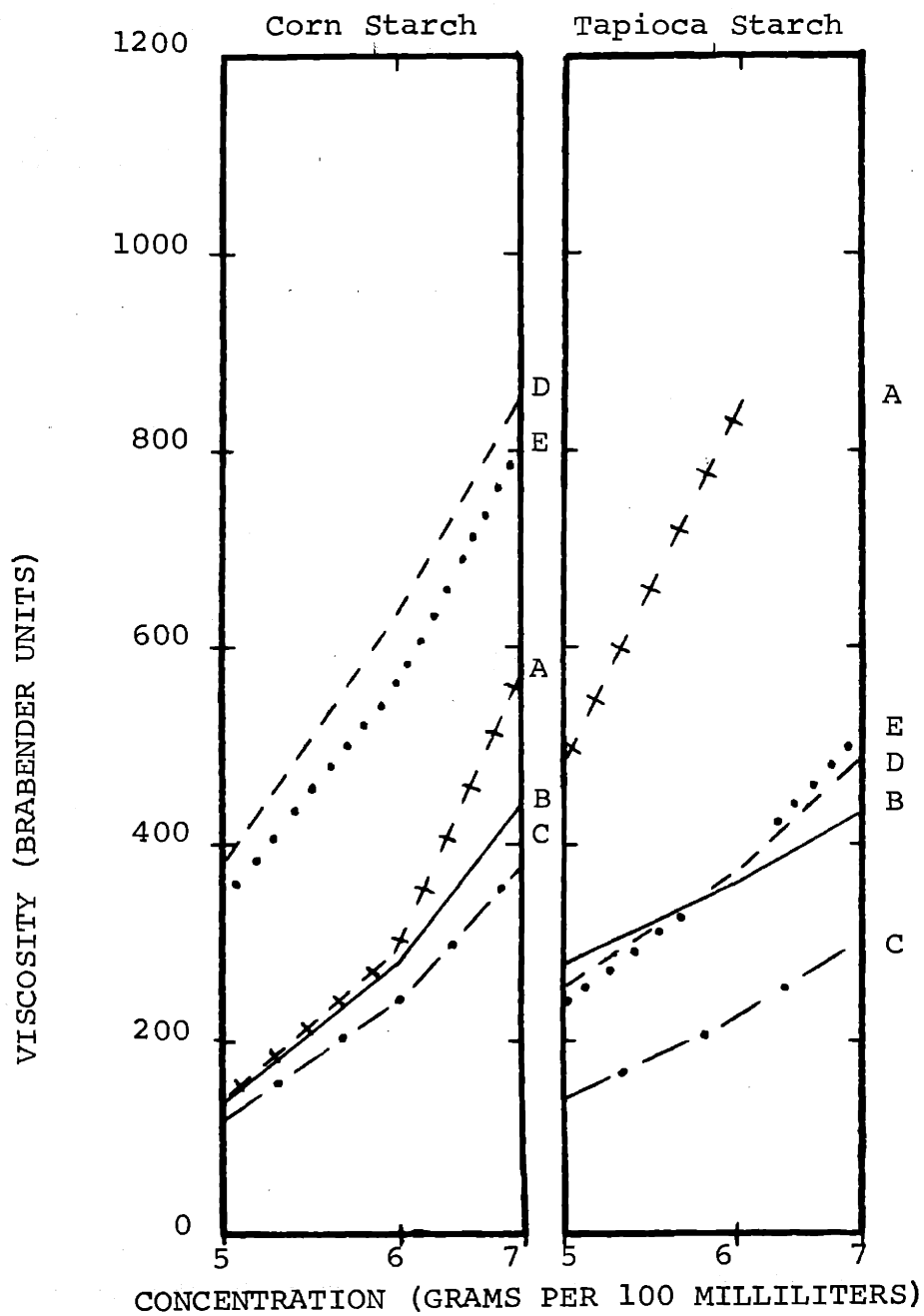
Figure 1. Brabender Curves of Banana Starch and of Other Food Starches at 6% Concentration
 Points A to E Indicate Key Points on the Viscosity Curve (See Section III, B-4, for Discussion)

Figure 2. Effect of Concentration On Viscosity



- A. - No Viscosity Peak
 B. — Viscosity After Heating 50° to 95°
 C. —. Viscosity After Holding 95°
 D. -- Viscosity After Cooling 95° to 50°
 E. ... Viscosity After Holding 50°

Figure 3. Effect of Concentration On Viscosity



- A. +++ Viscosity Peak
- B. — Viscosity After Heating 50° to 95°
- C. —• Viscosity After Holding at 95°
- D. --- Viscosity After Cooling 95° to 50°
- E. ... Viscosity After Holding at 50°

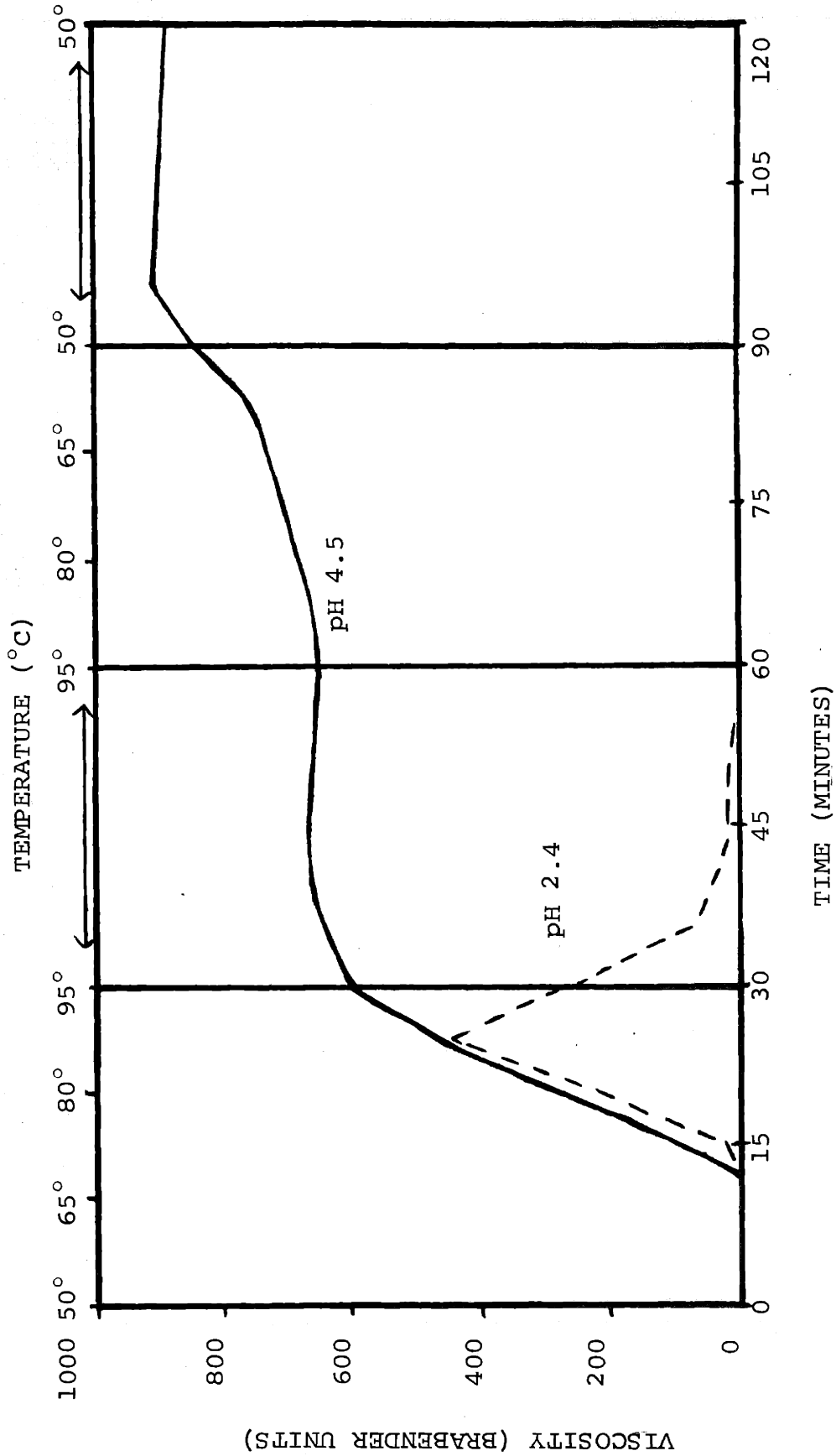


Figure 4. Effect of pH on the Viscosity of Banana Starch Paste (Concentration at 6%; pH adjusted with Citric Acid)

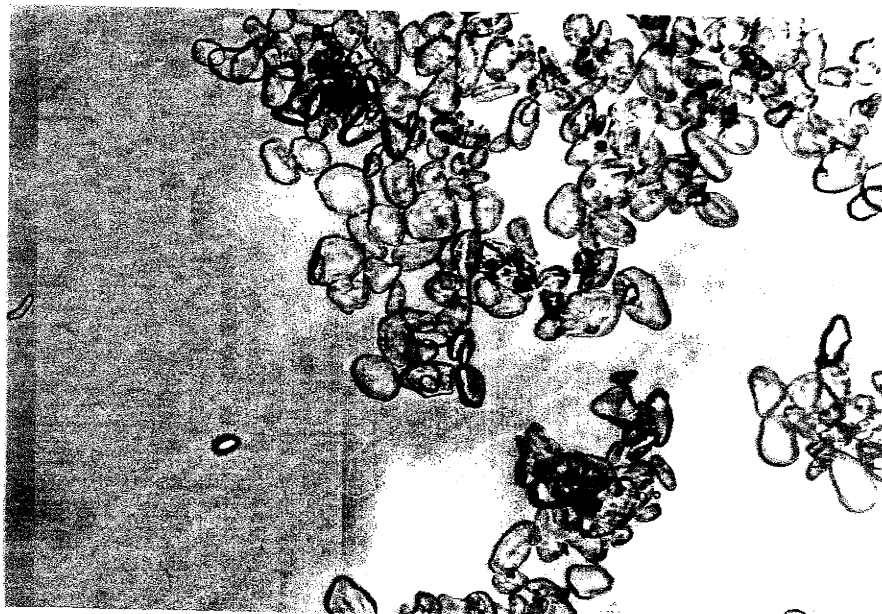


Figure 5. Banana Starch (U.F.#1)

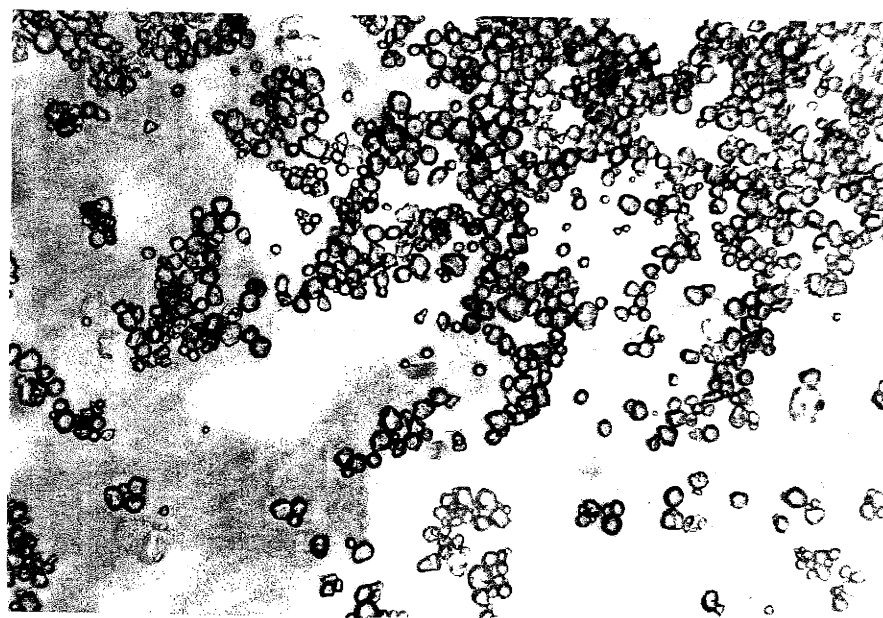


Figure 6. Cross-Bonded Waxy Maize Starch

—
100 MICRONS

There is some evidence (Meyer et al., 1949) that the size and morphological structure of the starch granule affects the formation and characteristics of the starch gel. Microphotographs (Figure 5 and 6) of banana starch ("football" shaped; 15-50 microns in the largest dimension) and cross-banded waxy maize (spherical; 10 microns in diameter) reveal that the gross morphology of the two starches is distinctly different and would provide no indication that these starches have similar functional properties.

B. Comparison of Brabender Curves of Banana Starch and of Its Three Component Fractions

Figure 7 shows the Brabender viscosity curves for banana starch (U.F.#1) and the three component fractions of this starch, all at 6% concentration. The viscosity profile for the fine granules and the coarse granules are virtually identical to the whole starch, with the following exceptions. The coarse granules have a slightly higher rate of granule swelling and the fine particles have slightly less thickening power. The curve of the residue fraction has the same general shape, but with a lower viscosity throughout. This indicates a significant depression of the thickening power resulting from the agglomerated particles in the residue.

Figures 8, 9 and 10 (taken under identical conditions) show the starch grains of the fine, coarse and residue fractions. The photographs best describe what is meant

by these designations and illustrates the presence in banana starch of two major grain sizes. The irregular shapes of the grains of banana starch make it difficult to specify their size. Therefore, only the greatest dimension has been measured. This approximates 22 ± 7 microns for the smaller grains and 39 ± 10 microns for the larger grains.

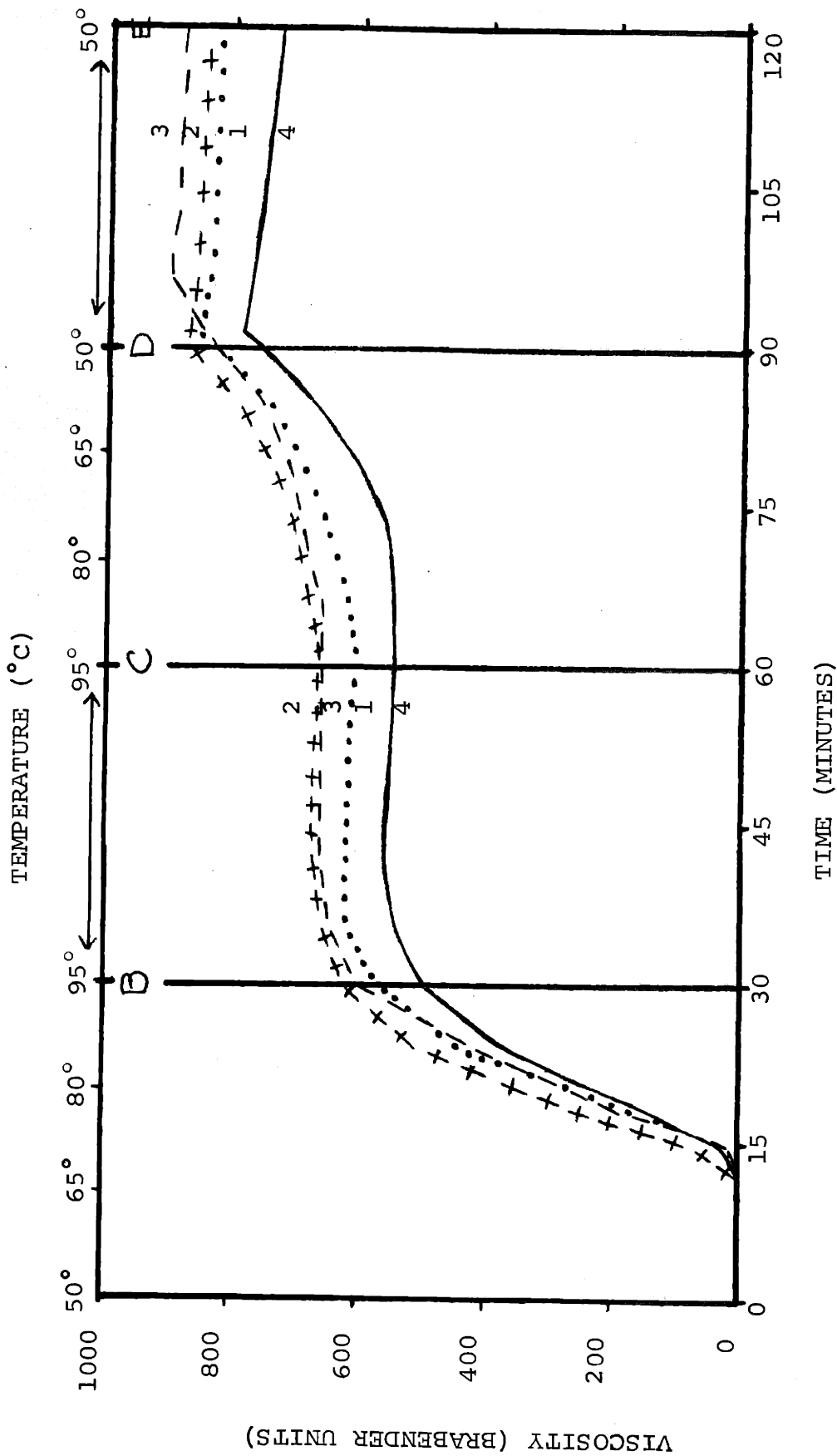


Figure 7. Brabender Curve of Whole Banana Starch and of Its Three Component Fractions (1-Fines, 2-Coarse, 3-Whole, and 4-Agglomerates)



Figure 9. Coarse Fraction of
Banana Starch

100 MICRONS

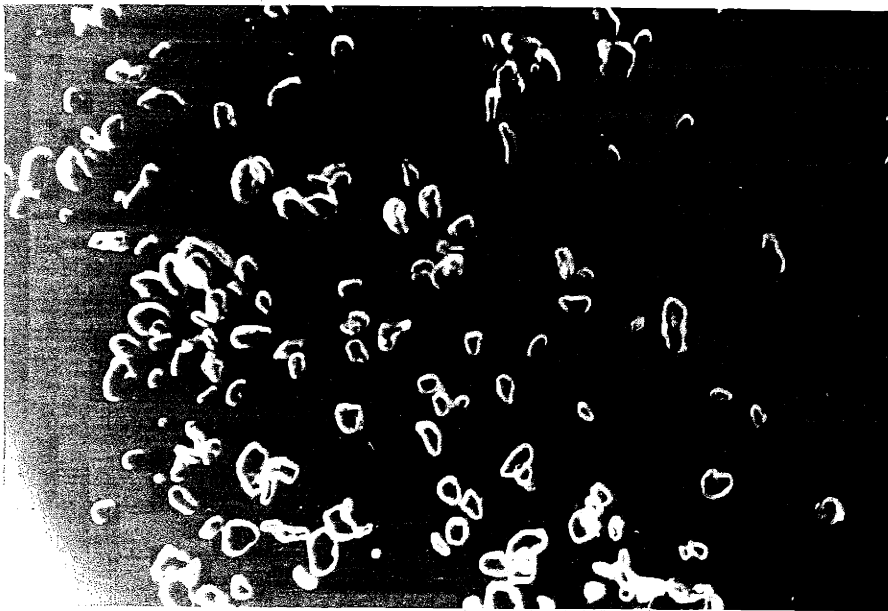
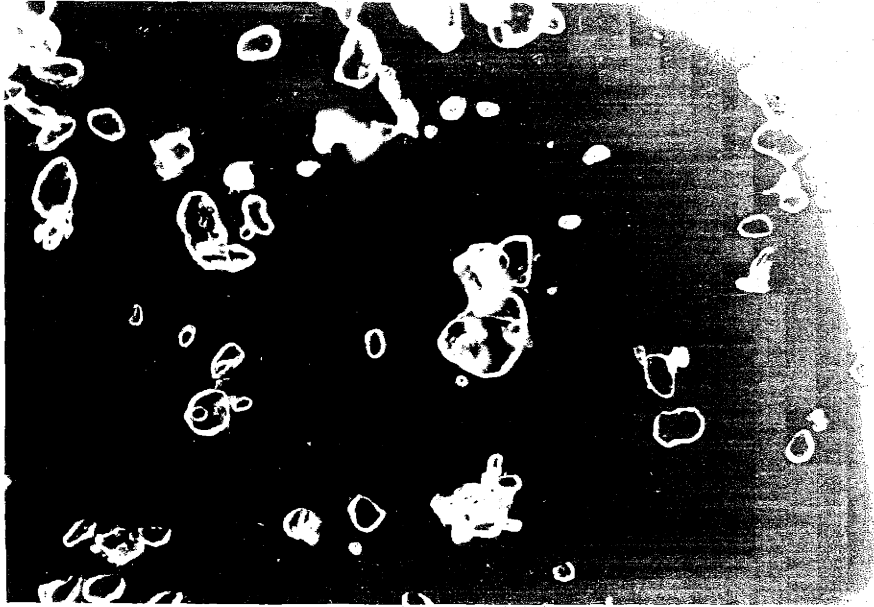


Figure 8. Fine Fraction of
Banana Starch



100 MICRONS

Figure 10. Agglomerated Fraction
of Banana Starch

C. Comparison of Brabender Curves of Banana Flour and of Banana Starch

Figure 11 shows the Brabender viscosity curves of the freeze-dried banana flour compared with U.F.#1, banana starch. All concentrations were on a dry weight basis and assay showed that 5.5% banana flour actually contained 3.9% starch. During the cooking phase (through Point C) the curve for 5.5% banana flour is virtually identical to that for 5% starch, but the subsequent portion of the viscosity curve (Point C to Point E) appears to be about that expected for 4.5% starch.

The "pudding" formed by the 5.5% banana flour when it was allowed to reach room temperature without stirring was understandably less firm than the 6% banana starch "pudding". In addition, the "pudding" retained the dark brown coloration and seeds, apparent in the flour, and an odor, reminiscent of green bananas.

Figure 12 shows banana flour to consist of a mixture of starch granules with considerably larger "debris" particles.

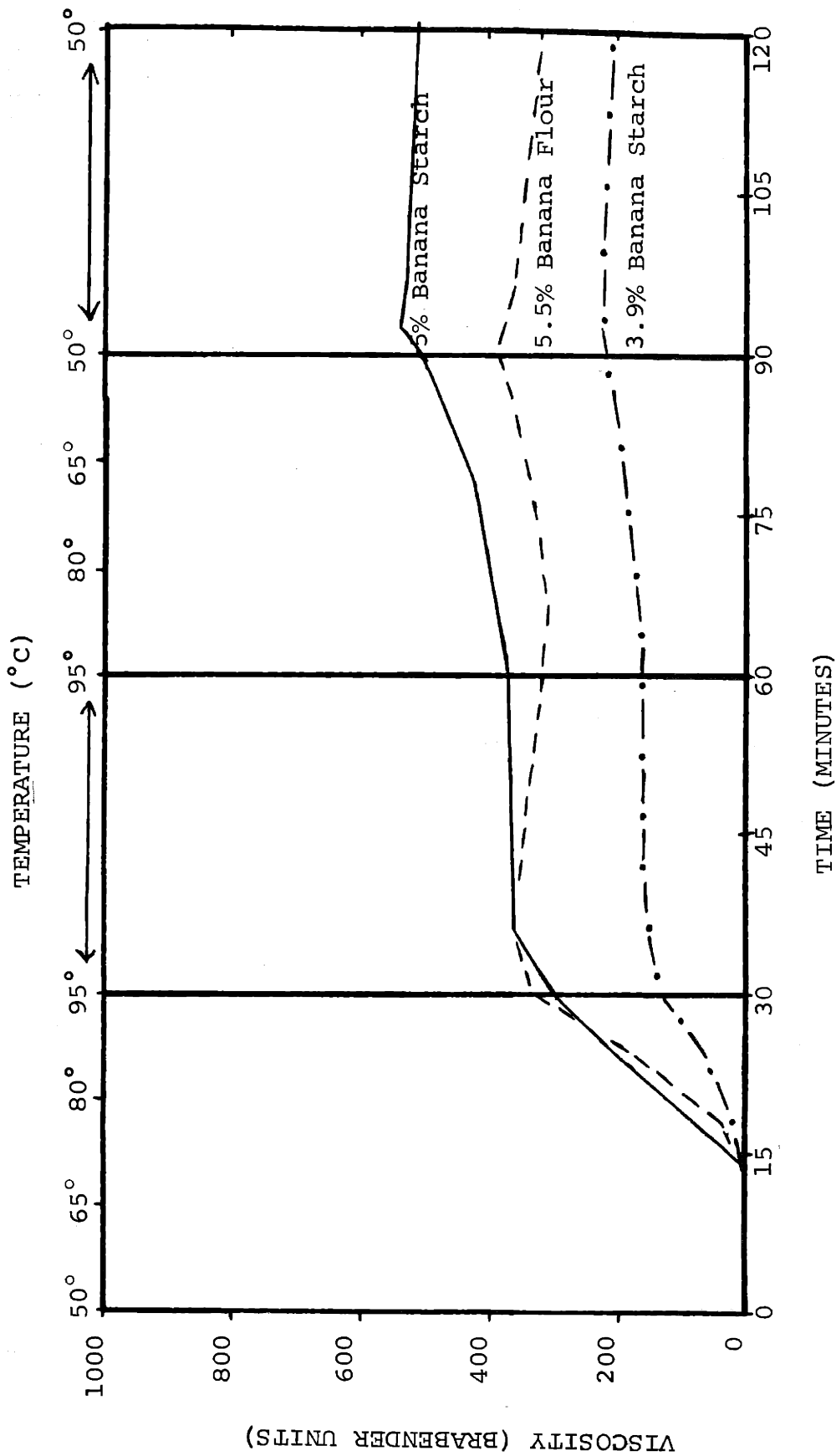


Figure 11. Brabender Curves of Banana Flour and of Banana Starch



Figure 12. Banana Flour

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100 MICRONS

V. DISCUSSION

A. Functional Properties of Banana Starch and Potential Food Uses

Table II summarizes the functional properties of banana starch and of the four food starches analyzed in this study. The functional properties were deduced from the experimental viscosity data (see Methods, especially Table I). The similarities between the functional properties of banana starch and cross-bonded waxy maize starch suggest that banana starch could be substituted for cross-bonded starches in some food products. Potential uses would include incorporation into baby food, puddings, pie fillings and canned foods such as cream-style soups, gravies, sauces, cream-style vegetables and stews to serve as a thickener and stabilizer (Wurzburg, 1968). The banana starch would presumably provide the same desirable characteristics: cuttable, but creamy body and high resistance to breakdown arising from variation in temperature (National Starch brochure, unpublished). Banana starch would also have the same thickening power as cross-bonded waxy maize, which is more than twice that of unmodified waxy maize and tapioca starches. Banana starch could not be utilized in highly acidic situations (below pH 4) such as in certain pies or other preparations containing fruits. Also, although no data are available, banana

TABLE II
Functional Properties of Banana Starch and Four Common Food Starches*

Functional Properties	Banana Starch	Cross-Bonded Waxy Maize	Waxy Maize	Corn Starch	Tapioca Starch
Ease of Cooking (Rate)	Slow	Fast	Fast	Slow	Fast
Maximum Thickness on Cooking (Viscosity Peak)	None	None	Very High	Moderate	High
Stability During Cooking	Good	Good	Poor	Good	Poor
Set-back on Cooling	Low	Low	Very Low	Very High	Very Low
Thickening Power	High	High	Low	Moderate	Low
Resistance to Shear	Good	Good	Good	Fair	Good

*Kite et al., 1957

starch is not likely to be as resistant to strong mechanical shear as a cross-bonded starch.

The retail price of the cross-bonded waxy maize used in this study is 17-20 cents per pound (Personal Communication, National Starch Corporation). Therefore, banana starch would have to be available at a lower price if it were to be competitive. If, however, cross-bonded starches were removed from the market by the Food and Drug Administration, then naturally occurring banana starch could compete even at the same or a slightly higher price.

Since all banana starch granules, regardless of size, exhibit identical functional properties, there is no reason to separate them for use in foods. The reduced thickening power of the agglomerated fraction indicates that, for full thickening efficiency, the whole starch should be relatively free of agglomerates.

The preliminary data on banana "flour" suggest that it might be substituted for banana starch in food products. The dark brown coloration and "green banana" odor of the final "pudding" are the greatest obstacles to the potential food use of banana "flour", but these could undoubtedly be overcome with some further study.

B. Molecular Properties of Banana Starch

Similarities in the functional properties of banana starch and cross-bonded waxy maize starch suggest that they have similar molecular properties as well. Cross-bonded waxy maize has been chemically treated to covalently link a small proportion of the hydroxyl groups, which reinforces the hydrogen bonds and strengthens the starch granules by retarding and restricting granule swelling (Hahn, 1969). Preliminary data suggested that banana starch might also be cross-bonded, but breakdown of the paste at pH 2.4 indicates that it actually is not. Nevertheless, the lack of a true viscosity peak suggests that banana starch granules have strong internal bonding which allows the starch to swell slowly and to resist breakdown and solubilization during the initial cooking period. A high pasting peak, followed by a rapid drop in viscosity, characteristic of many starches, is an indication of weak and fragile granules. Resistance to breakdown with stirring at 95°C (maintained thickness) is another indication of the strength and rigidity of the swollen granules.

The relatively small setback (retrogradation) on cooling indicates that the linear (amylose) molecules of banana starch show little tendency toward rebonding. Alternatively, the rebonding might occur internally, that is within the swollen, but intact and separate

granules, so retrogradation would be limited, as proposed for cross-bonded starches (Mazurs et al., 1957).

C. Properties of Starches as Related to Morphology and Origin

There are indications in the literature that the pasting properties, and hence the functional properties, of starches may be correlated with, or predicted from, the morphology (size and shape) of the starch grain and/or with the origins of the starch (Meyer et al., 1949; Hahn, 1969). These correlations are considered here in relation to banana starch.

There is certainly no correlation between morphology and functional properties for banana starch and cross-bonded waxy maize starch. They have virtually identical pasting properties and yet are markedly dissimilar in morphology (Figures 5 and 6). Perhaps this is not a fair comparison, since the cross-bonded waxy maize has been chemically altered. However, it is also clear that the two markedly different grain sizes in banana starch show little or no difference in functional properties. Thus, results obtained in this study tend to discredit the idea that functional properties can be correlated to gross grain morphology.

In considering the relationships between the origin and properties, starches are generally categorized into two classes (Hahn, 1969). The first includes starches

originating in plant organs of high water content such as tubers, where the starch represents 20-30% of the tissue weight. These starches consist of relatively large granules which exhibit rapid swelling and severe breakdown (solubilization) when a slurry is heated to 95°C. Tapioca starch (Figure 1) would be an example. The second class includes starches originating in relatively dry plant structures such as seeds of cereal grains, where the starch may represent as much as 75% by weight. These starches contain smaller granules which are more restricted in their swelling and solubilization at 95°C, but show a greater tendency to retrograde on cooling. Corn starch (Figure 1) is typical of this category.

Banana starch seems to be an exception to this generalization. It originates in the fruit pulp, an organ of high moisture content and at least some of the granules are relatively large. Nevertheless, the pasting properties are more nearly those described for starches originating in dryer structures.

It is interesting to speculate on the reasons for this apparent exception. Although the banana fruit pulp is "wet" (75% moisture content), it is also apparent that this water is tightly bound. Only a small proportion (15% or less) of this water is released when ripe (low starch) banana fruit pulp is subjected to pressures up

to fourteen atmospheres for five minutes (Czyhrinciw, 1969). In contrast, other fruits of similar moisture content yielded 28-72% of their fresh weight as juice at fourteen atmospheres. Perhaps banana starch is actually formed in an environment of low water activity resembling that of cereal grains, despite the high total moisture content of the fruit pulp.

VI. SUMMARY

The functional properties of banana starch (ease of cooking, thickening power, paste stability etc.) were deduced from the changes in viscosity which occurred when slurries, at various concentrations, were taken through a standard heating and cooling cycle on the Brabender Amylograph. The properties of several other food starches were determined under the same conditions for comparison with banana starch. Banana starch appears to have relatively unique properties, similar to those of chemically cross-bonded starches and could be valuable in a number of food applications.

Banana starch contains large and small grains. An air classification method was devised to fractionate dry banana starch by grain size. It yielded fine, coarse and agglomerated (residue) fractions. Whole starch, large grains and small grains all had similar functional properties. The agglomerated fraction had lower thickening efficiency.

A banana "flour" was prepared by freeze-drying a homogenate of green banana pulp. It contained about 70% starch and had functional properties similar to banana starch, but with a somewhat lower thickening efficiency. The final "puddings" (cooked paste cooled to 25°C) were brown in color and not as firm as with

whole starch. With further study, such a flour might be substituted for banana starch.

VII. CONCLUSIONS

- A. Unmodified banana starch has many of the characteristics of a cross-bonded starch and could potentially be used as a substitute in puddings, pie fillings, canned foods, baby foods and other food products where cross-bonded starches presently serve as thickeners and stabilizers. Banana starch would not be useful in some fruit products, since the cooked pastes are unstable below about pH 4.
- B. There is no advantage to separating banana starch by grain size since the fine and coarse grains have functional properties similar to the original whole starch.
- C. There may be some potential for a dried "flour" prepared from green bananas, since the flour has functional properties similar to the isolated starch and could presumably be produced at a much lower cost.
- D. The resistance of banana starch to swelling and breakdown during heating to 95°C suggests the presence of unusually strong holding forces which tend to keep the molecular structure intact. These are not covalent bonds, since they are readily broken by dilute acid.
- E. Banana starch, despite its origin in a tissue of high moisture content, has characteristics similar to starches originating in a relatively dry environment such as cereal grains.

VIII. SUGGESTIONS FOR FUTURE RESEARCH

A. The unique functional properties of banana starch indicate that it is of potential importance to the food industry as an alternative to cross-bonded starches. The next obvious step in the investigation of the usefulness of banana starch would be to test the behavior of banana starch when substituted for a cross-bonded starch in appropriate processed foods such as soups or pie fillings. This would be a direct, practical test of the effect of other food components (salts, sugars, lipids, etc.) and of the effect of processing procedures (aseptic canning, freezing and thawing, stirring, etc.). If the products are comparable, then banana starch could be used as a replacement for the cross-bonded starches. If, for example, the banana starch showed thinning in a food product of high sugar content, then further laboratory tests of the effects of sugars on pasting properties would be necessary. Ultimately, these studies would define the limits of usefulness of banana starch in food products.

B. Coinciding with or perhaps prior to the above study, there should be an economic investigation of potential markets and production costs. For banana starch to be competitive on the market, the price, in relation to other food starches now available, is crucial. A

preliminary analysis may indicate that the price will be too high, even assuming that the functional properties are ideal and that the Food and Drug Administration removes cross-bonded starches from competition. Practical economic data, such as quantity and cost of waste, green bananas, etc. were not available to us for such a study.

C. Studies similar to those outlined for banana starch should be undertaken for banana "flour". Then the functional and economic factors could be compared.

It is unlikely that freeze-drying will prove an economical method for producing banana "flour". Spray drying should be tried. It is not only a cheaper and more practical way of dealing with large quantities of tissue, but it might produce a better quality flour by eliminating (through application of dry heat), the brown color caused by enzyme activity (polyphenol oxidase). It would probably reduce the "green banana" aroma as well.

D. The instability of the banana starch gel at pH 2.4 suggests that it is not cross-bonded. In addition to acid stability, resistance to high speed shear is also characteristic of cross-bonded starches. (Kite et al., 1957). Shear tests should be conducted on banana starch and if it is confirmed that banana starch is indeed not cross-bonded, then it would be interesting to study why the

structure of banana starch granules is so much more stable than other tuber starches.

E. From a physiological standpoint, it would be interesting to study the significance of multiple starch grain sizes in banana tissue. The starch of wheat grains also has two distinct granule sizes (Wivinis and Maywald, 1967). Perhaps a comparative study of the development and degradation of the starch granules in these two quite different tissues would provide some clues as to their origin and function in the tissue.

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BIOGRAPHICAL NOTE

Eunice Marks Carson was born in Boston, Massachusetts, on November 19, 1947, the first child of a U.S. Navy Chaplain, James Russell Marks and Mrs. Marks. She grew up in Winchester, Massachusetts, with summers and holidays spent in Wolfeboro, New Hampshire. One sister, Susan, was born when Eunice was three. When Eunice was fourteen her family was transferred to the Great Lakes Naval Training Station in Illinois where Eunice attended the Ferry Hall School in Lake Forest. While in the ninth grade there, her first article was accepted for publication in the Chicago Tribune. She also won a national high school award for proficiency in mathematics. When her family returned to Boston, they moved to Chestnut Hill, where Eunice attended the Beaver Country Day School from which she was graduated in June, 1965, and two years later received an Associate in Arts degree from Pine Manor Junior College. For three years, she was a member of the Mademoiselle Magazine College Editorial Board. However, since she found her greatest interests were in the sciences, she planned to transfer into the junior year at Simmons College in Boston, Massachusetts where she could major in nutrition, and study both biology and chemistry on an interdepartmental basis. She received a Bachelor of Science degree from Simmons College in 1969, and spent that summer traveling in Europe. Eunice

was accepted for graduate study at the Massachusetts Institute of Technology in the Department of Nutrition and Food Science and completed her master's degree requirements in 1971.

In June, 1970, Eunice was married to William W. Carson, a doctoral candidate in the Department of Mechanical Engineering at M.I.T. Since he was designer and co-captain of the M.I.T. Hybrid Electric Car entered in the 1970 Clean Air Car Race, Eunice became a member of the team and participated in the cross-country event.

Eunice was brought up in an atmosphere of educational incentive, travel, family love and respect for individuality. She believes that the microcosm of educational and living experiences which have filled her twenty three years have provided her with valuable keys. The unpredictable future may determine how she uses these keys, but use them she will, for she is convinced that knowledge is dead if not put to good use.