Water-Loss Rates and Temperature Profiles of Cakes of Different Starch Content Baked in a Controlled Environment Oven[1]

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ABSTRACT

Six levels of substitution of wheat starch for flour (0–50%) were tested in a research cake formula. Water-loss rates were determined gravimetrically throughout the baking period at 1-min intervals. The heat penetration rates were determined by monitoring the temperatures at four locations in the cakes continuously on a multipoint recorder. A specially constructed environmental oven was used to bake these cakes. The oven maintained an airflow rate of 10.2 m^3/hr and a temperature of 190 ± 1°C. Rates of water-loss and temperature increase were depressed in the temperature ranges associated with starch gelatinization. The degree of depression and the final temperature appeared to be related to starch level. Once the cake structure set and it entered the dehydration stage of baking, the water-loss rate began to rise again, accompanied by increasing internal temperatures, and continued in this manner until the end of the baking period. An inhomogeneous cake crumb structure was observed in the scanning electron microscope for the fully baked cakes, which indicated different degrees of starch gelatinization and gluten development in different positions of the cake. These were related to temperature, flow characteristics, and level of starch substitution in the cakes.

During baking of batters and doughs, heat causes chemical and physical modifications of the components of the batter or dough system to form a stable structure with subjectively desirable characteristics. It is appropriate, therefore, to consider the heat penetration and water-loss properties of the batter system and to relate them to the structure of the crumb. The changes in a batter during baking were studied by a variety of techniques including microscopy (Bell et al 1975, Carlin 1944, Derby et al 1975, Pohl et al 1968), systematic variation of formula as by Wilson and Donelson (1963, 1965), and transformations in specific ingredients such as the extent of starch gelatinization as studied by Howard et al (1968) and Cauvain and Gough (1975). Heat transfer was studied by Miller and Derby (1964), Charley (1951), and Shepherd and Yoell (1976), among others. Less numerous are studies in which heat penetration and water loss are related throughout the baking process and related to structural transformations.[3]

An environmental oven in which temperature profiles and water-loss rates can be measured during baking was constructed in our laboratory. It was used to study transformations in bovine muscle (Godsalve et al 1977a, 1977b) and potato (Galletti 1977). We report here its use in developing a model for the study of heat penetration and water loss in batter systems. For this purpose, the research formula of Kissell (1959) was used. Because flour, and in our experiment, added wheat starch are the only sources of proteins and starch, the interactions with the other components—shortening, sugar, and baking powder—are somewhat simpler than those in a complete shortened cake formula that includes egg and milk.

A series of batters was prepared in which up to 50% of the flour was replaced by wheat starch. Thus variations in starch level and in relative freedom from the protein matrix of flour were introduced. These were chosen since the practical problems in formulating starch cakes are well known. In addition, current discussions of batter structure have focused on the central role of starch in crumb formation (Howard et al 1968) and the accompanying balances in water absorption among the remaining ingredients.

MATERIALS AND METHODS

Cake Formula and Preparation

The formula in Table I was based on the lean formula of Kissell (1959). Levels of sucrose and water were adjusted for the flour used in preliminary trials. All ingredients except wheat starch were purchased in the retail market and were of household type.

Levels of starch substitution were established in preliminary trials and included the following flour/starch ratios: 100:0, 90:10, 80:20, 70:30, 60:40, and 50:50. Replacement of more than 50% of the flour resulted in extensive breakdown of the crumb into layers, so that the series was terminated at the 50% level.

Flour, starch, and baking powder were sifted together four times. Shortening and sucrose solution were added to the dry ingredients and the batter was mixed in a Hobart Kitchen-Aid (Model K45) for 30 sec at setting 1 (low speed) and 3 min at setting 5 (medium speed). The sides of the bowl were scraped after 30 sec at low speed and 2.5 min at medium speed. The remaining distilled water was added and the batter was beaten for 30 sec at low speed and 1.5 min at medium speed. The sides of the bowl were scraped after 30 sec at low speed. Batter (220 g) was added to an aluminum layer pan (15.2 cm diameter × 3.2 cm deep). Thin waxed paper was placed in the pan, and the paper and sides of the pan were greased with 1.4 g of shortening. All cakes were baked for 21 min at 190°C in a specially designed controlled environment oven. Cakes in a series were baked in random order, and three replications of each series were baked.

Controlled Environment Oven

Details of the design and operation of the controlled environment oven are given by Godsalve et al (1977b). Briefly, the purpose of the oven is to provide a uniform and controlled environment for cooking experiments. The oven consists of a cooking chamber heated by electrical resistance and a piping network that circulates air at a controlled rate and permits continuous humidity determination of the air before and after it passes through the oven chamber. Therefore, the temperature, air flow, and humidity are known at all times. For all of our experiments, the flow rate was set at 10.2 m^3/hr. Godsalve et al (1977a, 1976) estimated that the flow rate in household convection ovens is between 4.0 and 5.0 m^3/hr. We chose the 10.2 m^3/hr flow rate because lower rates gave erratic air flow behavior with our system.

The rate of heat penetration in the baking cake was determined by monitoring the temperatures with thermocouples at four locations in the cake: center, 2.5, 5.1, and 6.9 cm radially from the

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[3] L. T. Kissell, personal communication, disclosing unpublished research reports of J. T. Wilson and D. H. Donelson, covering thermal-analytical studies of starch gelatinization and cake baking, Soft Wheat Quality Laboratory, Wooster, OH (1958–1959).

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center. All were positioned 7 mm above the pan base. The thermocouple readings all began from a batter that was room temperature as it entered the oven. The oven had two interchangeable doors, one of which was fitted with a frame to hold the cake pan and the thermocouples. The thermocouple wires were introduced into the oven chamber through a bulkhead fitting in the oven door. The assembly is shown in Fig. 1. Oven temperature was measured by a thermocouple placed in the oven near the heat controller. The oven temperature was maintained at 190 ± 1.0°C. Temperatures were recorded continuously on a multipoint recorder.

Water emission rates were measured gravimetrically in separate experiments from those monitoring temperature. For these measurements, the cakes were placed on a cradle of wire mesh that was attached, through an opening at the top of the heating chamber, to an aluminum frame hanging from a balance (Sartorius Type 1104, capacity 1,000 g, minimum division 0.1 g). Readings were taken at 1-min intervals.

Measurements of Batter and Crumb Characteristics

Specific gravity of the batter was determined, as well as an index to the volume of the final cake, based on the area of the cross section of the tracing of the center slice of the cake. Area was determined as the average of quadruplicate readings with a Hewlett-Packard digitizer. Contour measurements were based on the difference between the center height and the average of the two side heights as measured from the tracings of the center slice.

Scanning Electron Microscopy of Batter and Cake Crumb

A thin film of batter was spread on an aluminum stub and exposed to osmium vapor overnight in a desiccator. Samples of cake crumb from the edge, top, bottom, and internal positions of the cake were mounted on aluminum stubs with a thin layer of silver glue and treated with osmium overnight in a desiccator. The stained batter and crumb samples were coated with palladium-gold coating prior to viewing in a Cambridge 600 Stereoscan scanning electron microscope (SEM) operated at 15 kV.

RESULTS

Temperature Profiles

Time-temperature profiles averages of three replications at four positions in the 0–50% starch-substituted cakes are given in Fig. 2. In each case, temperatures at the edge of the cake were higher than those in the interior. Temperatures at the edge of the cake showed a rapid rise to about 93°C, a slower rate of increase in the 93–102°C range, and an increase to a final temperature of 124–127°C. Presumably these temperatures are associated with a period during which the temperature rises to the boiling point, a period during which a boiling point is maintained, and a period during which dehydration begins, which permits a subsequent rise above the boiling temperatures. Similar surface behavior was reported by Godsalve et al (1977b) for bovine muscle and by Marston and Wannan (1976) for bread.

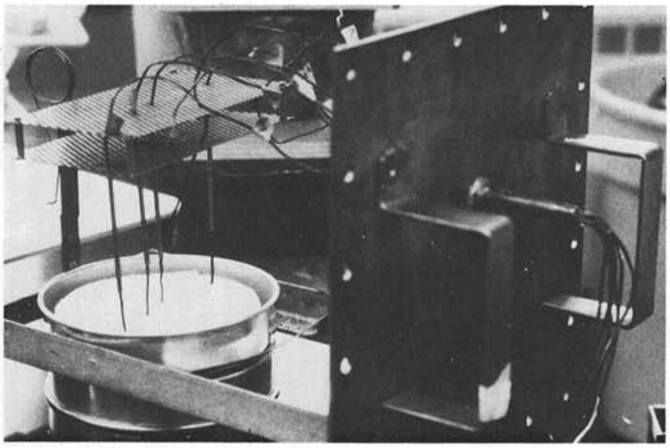

Fig. 1. Door of oven, showing frame to position cake pan and thermocouples, and thermocouple leads.

Temperatures in cakes with 50% flour replacement by wheat starch were higher than those for cakes with lower levels of starch substitution. Temperatures in cakes with lower levels of substitution, however, showed no consistent relationship to starch level in the early phases of baking. In the final period when the temperatures rose above 104°C, the 100% flour cake had the lowest temperature.

Temperatures at the three positions in the cakes were lower than those at the edges and generally followed a pattern of rapid temperature increase to about 85–88°C (7–8 min of baking) and a slower rate over the 88–104°C range, followed by an increase to the final temperature. During the first 7–8 min of rapid temperature increase, the temperatures at the three positions were superimposed or that at the center of the cake was higher than that at 2.5 or 5.1 cm from the center radius. A transition appeared at 8–9 min and, during the remainder of the baking period, a gradient from edge to center was established.

The effect of replacing part of the flour with starch on the temperatures in the interior positions in cakes was similar to that observed for the edge temperatures. Temperatures in the cakes with 50% flour replacement were highest at each position during most of the baking period, but those in the 100% flour cake were lowest only toward the end of the baking period.

Water-Loss Rates

Water-loss rate averages of three replications are given in Fig. 3. The rate of water loss increased for 7–8 min, then decreased for 1–3 min, and finally increased. In a few cases (10 and 50% starch-substituted cakes), there was some evidence of the beginning of a falling rate period in the last few minutes of baking.

The rate of water loss at the first maximum as well as the time to reach this maximum seemed to be related to the starch level. The rate for the 100% flour cake was 0.63 g/min and rates for starch-substituted cakes were 0.67, 0.63, 0.60, 0.60, and 0.47 for 10–50% substitutions, respectively. The time to reach these maxima also decreased as the concentration of starch was increased and ranged from 9 min for 100% flour cake to 6 min for the 50% starch-substituted cake. As a consequence of the lower water-loss rates and the shorter time to reach the first maximum in the high starch cakes, the cumulative moisture losses up to the first maximum were smaller in the high starch cakes (3.53 g in 100% flour cake vs. 1.70 g in the 50% starch-substituted cake as shown in Table II). This is exactly half the rate with twice the starch content. By the end of the baking period, the cumulative moisture losses were similar for the various levels of starch substitution.

Cake Characteristics

The mean specific gravities were not significantly different when an analysis of variance was calculated with starch levels and replications as sources of variations. The mean value was 0.94.

TABLE I
Test Formula

Ingredient	Amount (g)	% by Weight	% Flour Basis
Cake flour[a] Wheat starch[b]	150.0	25.3	100
Baking powder[c]	7.1	1.2	4.7
Shortening[d]	41.8	7.1	27.9
Sucrose solution sp gr 1.29, 212 ml			
Sucrose	167.4	28.2	111.6
Distilled water	107.0	38.2	151.0
Distilled water	119.5		

[a] Softasilk, General Mills, Inc.
[b] Aytex, General Mills, Inc.
[c] Calumet, General Foods Corporation.
[d] Crisco, Procter and Gamble.

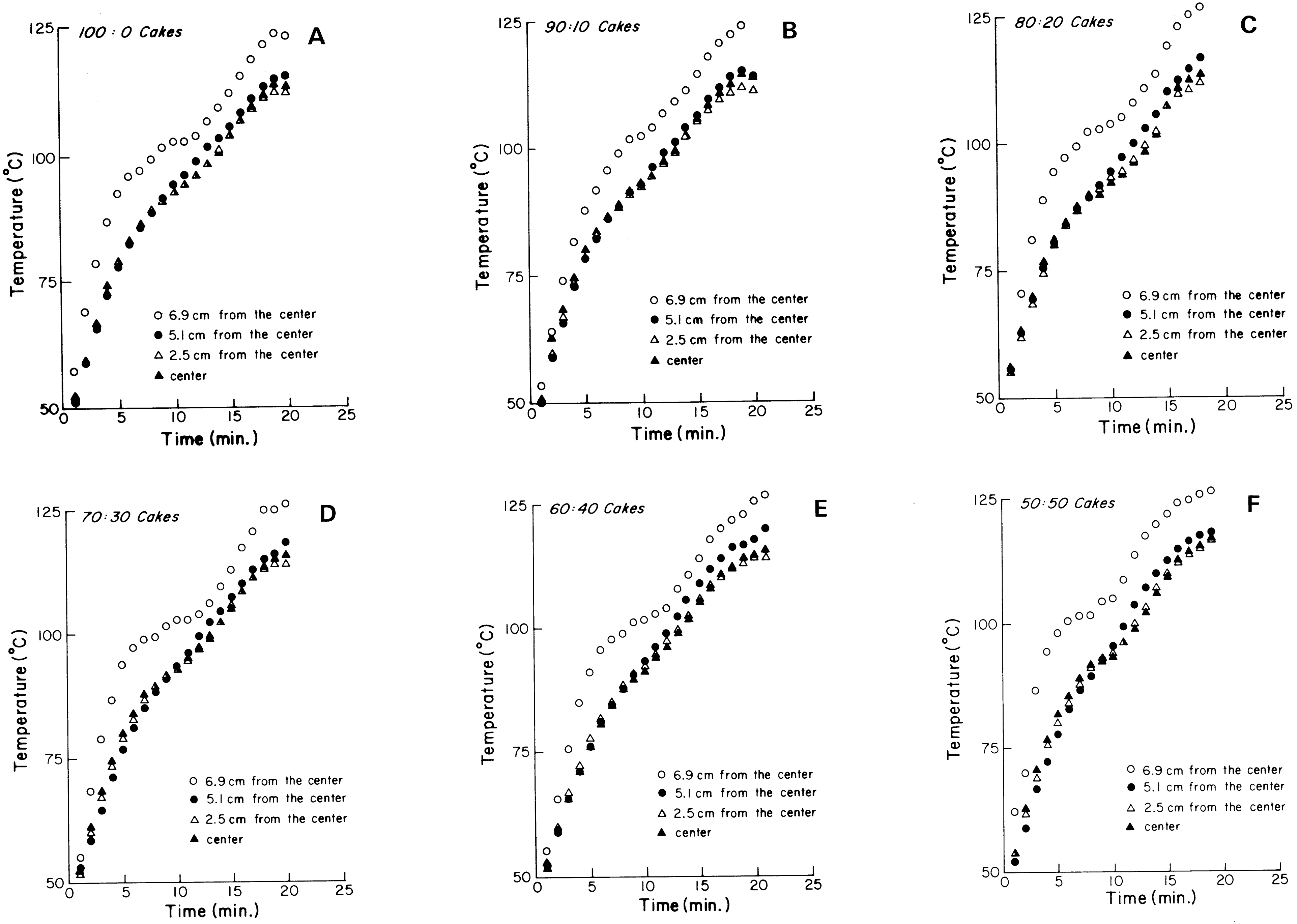

Fig. 2. Temperature profiles for cakes with a flour-to-starch ratio: A, 100:0; B, 90:10; C, 80:20; D, 70:30; E, 60:40; F, 50:50.

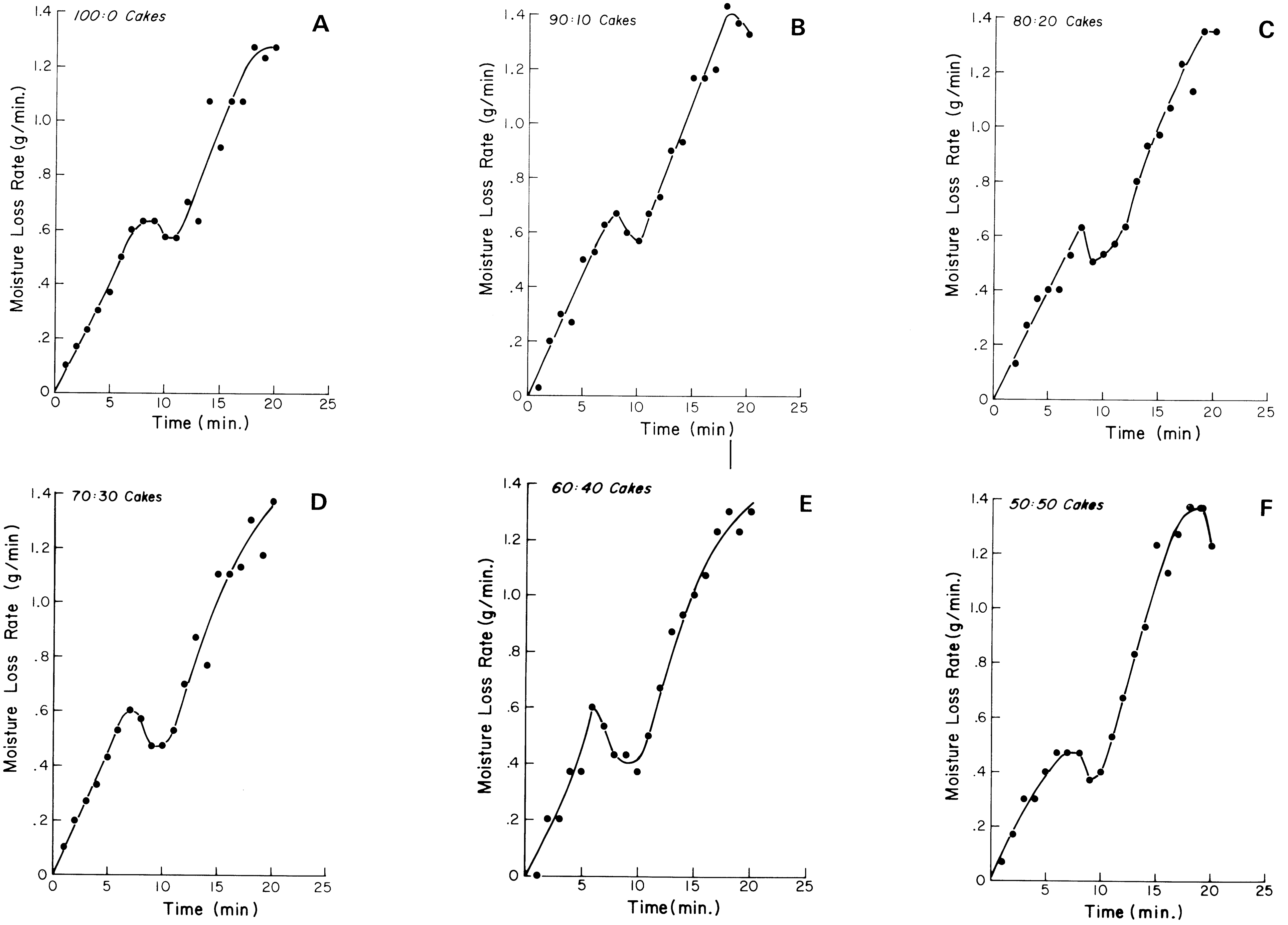

Fig. 3. Moisture loss rate versus time for cakes with a flour-to-starch ratio: A, 100:0; B, 90:10; C, 80:20; D, 70:30; E, 60:40; F, 50:50.

Cross-sectional areas were not significantly different and averaged 35.3 cm^2. Contour measurements in terms of the difference between heights of cross-section at the center and edges also were not significantly different.

Although the cross-sectional areas were not that dissimilar in the cakes with different starch levels, the overall appearance of the final cake showed some variations on the top surface, internal grain, and bottom layer of the 50% starch-substituted cakes compared with the other less free starch-substituted cakes. More specifically, the 50% starch-substituted cake had irregularities across the top surface that seemed to be related to excessive bubbling at the surface that occurred midpoint in the baking period. The bubbles then collapsed, but surface irregularities remained. Also, the grain of this 50% starch level cake was characterized by vertical breaks and, in some cases, by formation of a solid layer at the bottom of the cake.

Scanning Electron Microscopy of Batter and Crumb

General characteristics of the batters are shown in a representative SEM micrograph in Fig. 4. Starch is suspended as lumps in the batter matrix and there is some indication of air bubbles that may be incorporated during the first stage of batter mixing and could be the source of air bubbles near fat-starch pools. The appearance of the batter does not differ pronouncedly from one starch level to the next.

Representative crumb micrographs of the baked cakes sampled from the outer edge to the center of the cake are shown in Fig. 5. This particular set is for a 100% flour cake; however, the other starch level cakes gave similar results. The micrographs show differences in starch granules and cake matrix that are probably due to the differences in temperature and degree of hydration at these different locations. Figure 5a, representing the outer edge of the cake, shows granules in various stages of swelling and a matrix that is not fully developed. Figures 5b and c, 0.5 and 3.5 cm from the edge, respectively, show extensive starch swelling and appear to swell or join with other granules to form extended areas that follow the interstices of the developed matrix. Granules at the center of the cake (Fig. 5d) show less and more varied swelling than at the 0.5 and 3.5 cm positions but more than at the edge position. The matrix also appears more fully developed at the center than at the edge.

TABLE II
Cumulative Moisture Loss in Grams for Cakes With Various Levels of Starch Substitution

Time (min)	100:0	90:10	80:20	70:30	60:40	50:50
1	0.1	0.0	0.0	0.1	0.0	0.1
2	0.3	0.2	0.0	0.3	0.2	0.2
3	0.5	0.5	0.3	0.5	0.4	0.5
4	0.8	0.8	0.7	0.9	0.8	0.8
5	1.2	1.3	1.1	1.3	1.1	1.2
6	1.7	1.8	1.5	1.8	1.7[a]	1.7[a]
7	2.3	2.5	2.0	2.4[a]	2.3	2.2
8	2.9	3.1[a]	2.6[a]	3.0	2.7	2.6
9	3.5[a]	3.7	3.1	3.5	3.1	3.0
10	4.1	4.3	3.7	3.9	3.5	3.4
11	4.7	4.9	4.2	4.5	4.0	3.9
12	5.4	5.7	4.9	5.2	4.7	4.6
13	6.0	6.6	5.7	6.0	5.5	5.4
14	7.1	7.5	6.6	6.8	6.5	6.3
15	8.0	8.7	7.6	7.9	7.5	7.6
16	9.0	9.9	8.6	9.0	8.5	8.7
17	10.1	11.1	9.9	10.1	9.8	10.0
18	11.4	12.5	11.0	11.4	11.1	11.3
19	12.6	13.9	12.3	12.6	12.3	12.7
20	13.9	15.2	13.6	14.0	13.6	13.9
21[b]	13.7	14.9	13.4	13.7	13.4	13.8

[a] Points at which the first maxima in rates of water loss occur.

[b] Cumulative water loss weight at 21 min is inaccurate due to buoyancy effect on balance as the door is unscrewed for cake removal.

Figure 6 shows how the granules and matrix varied in appearance when the sections at the top, immediately adjacent to the top, immediately adjacent to the bottom, and at the bottom were examined. Because the 100 and 50% cakes showed similar changes from top to bottom, these differences are shown in representative micrographs taken from the 50% cakes; the 50% cakes also had a compact layer at the bottom that the 100% flour cakes did not have. At the top (Fig. 6a), both the granules and matrix appear compressed. This could be caused by the pressure created as the cake rises and bubbles are formed in the initial stages, which was then followed by a settling of the crust in later stages of baking. Immediately below this area (Fig. 6b), less swollen and plasticized granules are encompassed in a less developed matrix. Immediately adjacent to the bottom (Fig. 6c), plasticized starch granules are seen in a slightly developed matrix that seemed less developed with a greater number of starch granules than seen in Fig. 6b. Granules in the compact layer (Fig. 6d) are dense, but some outlines of granules can be seen. As would be expected, there is no evidence of the gluten matrix.

Galletti (1977) found that starch granules in the outermost layer of potato tuber heated in the environmental oven also did not swell, although some fragmentation occurred. Varriano-Marston et al (1977) reported similar results for the granules from the crust of bread. Granules from the crust showed less evidence of gelatinization, on the basis of x-ray diffraction, starch damage tests, and polarizing microscopy, than did granules from the center. In these cases and also in that of the granules from the edge of the cake, the stress of high temperature and partial dehydration apparently fixes the crystalline structure that is not subsequently altered even though water must pass through these areas during later stages of heating.

In the micrographs granules from the interior portions of the cake showed some resemblance to the swollen granules reported by Hoseney et al (1977), but the relationship to the matrix cannot be seen from micrographs of extracted starch. In addition, the swelling pattern may be affected by the presence of K, Cl, S, P, Na, Ca, and Al ions in the batter system and flour since Davis and Gordon (1978) showed, by fluorescent x-ray microanalysis, the transfer of K, P, S, and Cl ions from cell wall to starch granules during cooking of potatoes. Plasticized granules in various stages of swelling also were seen by Davis and Gordon (1978) in partially cooked potatoes examined without fixation or coating in the frozen hydrated state.

DISCUSSION

In considering the relationship between water-loss rates and temperature profiles and the use of these relationships in

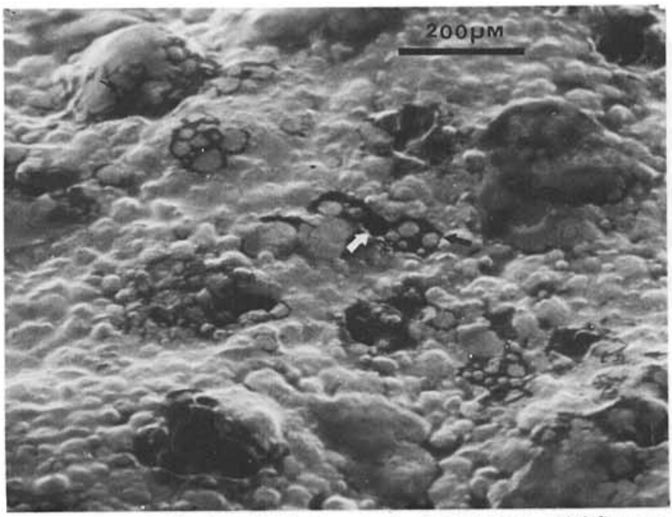

Fig. 4. Low magnification SEM micrograph of cake batter, 100:0 flour-to-starch ratio. White arrow = air bubbles; black arrow = fat-starch pool.

understanding the development of structure, water-loss rates and temperature can be viewed as interacting throughout the baking period.

Heat transfer is effected from the sides and bottom of the pan and the surface of the batter. In the early phases of baking, evaporation at the batter surface tends to cool it. The sides and bottom of the pan are not affected directly in this way and continue to be influenced by the heat transferred through the metal pan. At the same time, the batter begins to expand, and movement of the batter occurs. During this period, the edge temperatures are higher than those in the interior of the batter, but well-defined temperature gradients from the edge to center are not established.

After 6–9 min, a local maximum rate of water loss is attained and temperatures of at least 81°C are established in the batter. Bean and Yamazaki (1973) reported 80°C as the gelatinization temperature for wheat starch in 50% sucrose solutions and about 90°C in a lean cake formula similar to the one we used[4]. The decrease in water-loss rates in the period defined by the local maximum and subsequent local minimum represents a slowing due to 1) competition between evaporation and gelatinization for the heat being transferred from the oven to the cake or 2) a decreased water activity from gelatinization, or a combination. Furthermore, the rate of temperature increase is reduced by the endothermic nature of the process of gelatinization (Banks and Greenwood 1975). In addition, this period becomes more sharply defined as the level of free starch is increased. Charley (1951) attributed flattening of heat penetration curves to starch gelatinization. Shepherd and Yoell (1976) also showed a flattening at 50°C for Madeira cakes.

After this period, the heat transfer and water loss mechanisms appear to change. Temperature gradients from the edge to the center of the cake are established. A moisture gradient at the surface also is established and the beginning of crust formation is visible at the edges. The surface cooling effects of evaporation therefore remain operative at the center of the cake. These temperature gradients probably account for the pattern of gelatinization from edge to center shown in the micrographs.

As structure formation proceeds, water must travel through a developing porous structure to reach the surface. Bell et al (1975), using cine and television microscopy, reported that diffusion of gas from air bubbles continued until 87–98°C, and in some cases the matrix was not set until 98°C.

The nonuniform character of the starch gelatinization, shown in the SEM micrographs, could contribute to the complexity of water-loss mechanisms in the latter part of baking. At the cake surface, a barrier to evaporation can develop as a consequence of both the distortion of the granules and the matrix being not fully developed. Channeling as a result of bubble formation did occur, however. This could provide an alternate path for movement of water out of the batter.

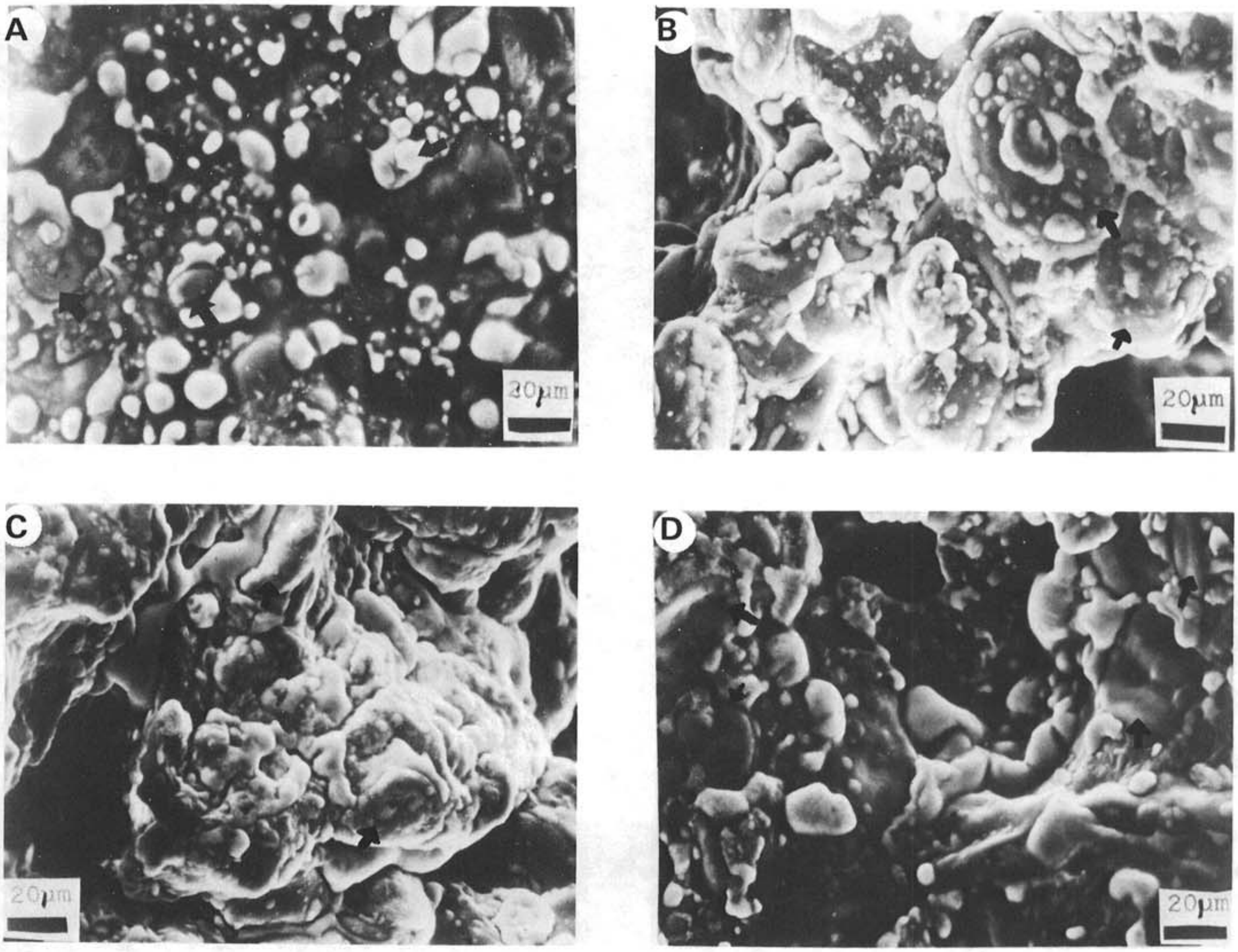

Fig. 5. High magnification SEM micrographs of cake crumb coming from cakes made with 100% cake flour, sampled from the middle of the edge to the center of the cake. Arrows locate starch granules. A, Outer edge; B, 0.5 cm from the edge; C, 3.5 cm from the edge; D, center.

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[4] M. M. Bean, personal communication.

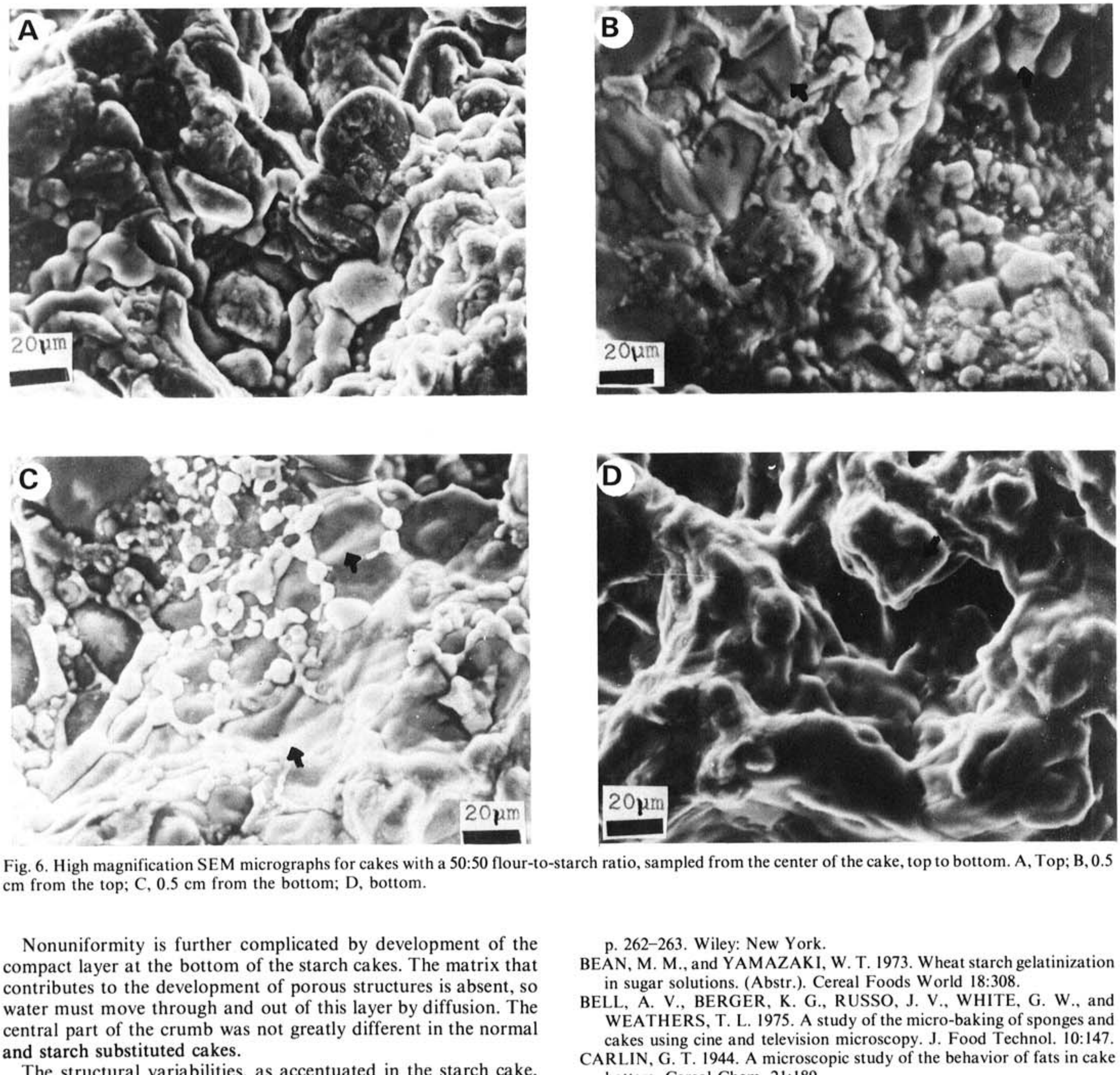

Fig. 6. High magnification SEM micrographs for cakes with a 50:50 flour-to-starch ratio, sampled from the center of the cake, top to bottom. A, Top; B, 0.5 cm from the top; C, 0.5 cm from the bottom; D, bottom.

Nonuniformity is further complicated by development of the compact layer at the bottom of the starch cakes. The matrix that contributes to the development of porous structures is absent, so water must move through and out of this layer by diffusion. The central part of the crumb was not greatly different in the normal and starch substituted cakes.

The structural variabilities, as accentuated in the starch cake, may be a major factor contributing to the differences in water emission rates as seen from 100% flour cakes to starch-substituted cakes. For example, the time of occurrence of the water emission peak associated with gelatinization relates to the thermal diffusivity of the cake matrix and the thermal diffusivity in turn depends on the structure of the cake matrix. More specific factors may affect the gelation properties and subsequent cake structure. These could be the changes in the ratio of the small-to-large starch granules as the free starch concentration is increased and the presence of isolated starch granules that have their surface stripped of lipids in the higher starch level cakes.

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