Apparatus for Monitoring Cake Structure Development During Baking[1]

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ABSTRACT

Apparatus is described that, during cake baking, monitors the cohesive forces developed by the cake structure, rising of the cake, cake temperature, and cake weight loss. The system responds to changes in ingredients. Preliminary results suggest that the apparatus provides useful information about the mechanisms of cake structure development during baking.

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At room temperature, cake batter is a fat-in-water emulsion (Howard et al 1968) with four bulk phases: aqueous, fat, gaseous, and solids. During baking, the batter changes from a fluid, aerated emulsion to a solid porous structure (Wooton et al 1967). This transition from fluid to solid is the least understood phase of cake baking. The roles for starch, protein, lipid and emulsifiers have been partially assigned from observations of their contribution to the final product (Russo and Doe 1970). Understanding of the structural development mechanism has been hampered by lack of reliable methods for assessing these physical and chemical events. Time-lapse photography was used to record the dynamic changes occurring during the baking (Bell et al 1975, Yamazaki and Kissell 1978), and differential scanning calorimetry has been of limited use (Donovan 1977). Frazier et al (1974) measured the compressive strength of the starch-protein gel structure of deaerated cake crumb. Although these tests showed differences in compressibility due to flour treatments, like many other approaches to cake testing (Brown and Zabik 1967; Funk et al 1965, 1970; Funk and Zabik 1969; Gruber and Zabik 1966; Mathews and Dawson 1966; Maxwell and Zobel 1978; Miller et al 1967; Morandini et al 1972), they measured an end result and did not account for factors contributing to structure during baking.

Gordon et al (1979) related the rate of moisture loss from a baking cake, by periodic weighing, to its microstructure.

This article describes the continuous recording of the cohesive forces developed by a rising cake batter and reports preliminary results to demonstrate the methodology.

MATERIALS AND METHODS

The apparatus (Fig. 1) is based on a laboratory oven with internal dimensions of 38 × 48 × 46 cm high. Air is circulated by convection up through the oven and returned via ducts at each side. The temperature control was replaced by an electronic unit with the thermistor sensing element (Fig. 1) placed below the cake. A window was installed in the door to observe the cake. To reduce oven temperature changes from opening the door, a drawer made of expanded wire mesh with an asbestos front and back was installed in the door. Cake pans were quickly placed in the drawer, which minimized air exchange and heat loss.

Development of cohesive forces in the cake structure was monitored by a horizontal stainless-steel probe (Fig. 1) mounted on a frame and suspended on a vertical fiberglass shaft that passed through the oven roof. The vertical shaft was suspended from a force transducer with a 2.3-kg capacity. The transducer was mounted on a carriage that moved vertically on a guide rod driven by a screw via a quick release split-nut mechanism. The screw was driven by a motor inside a housing via gears to move the probe at 1mm/min. A switch permitted the motor to be stopped or reversed at any time. The horizontal probe could thus be lowered into or raised from the cake in a vertical motion, automatically or manually. A microswitch, activated by the carriage, prevented the probe from being lowered to contact the cake pan or raised to exceed the carriage stroke during motor operation.

Cake temperature was monitored by thermocouples mounted on a horizontal bar (Fig. 1) and suspended on a vertical rod. This assembly was lowered by a handle above the oven to immerse the thermocouples to a preselected depth in the batter. The rising of the cake was monitored by a vertical rod that passed through a slide-

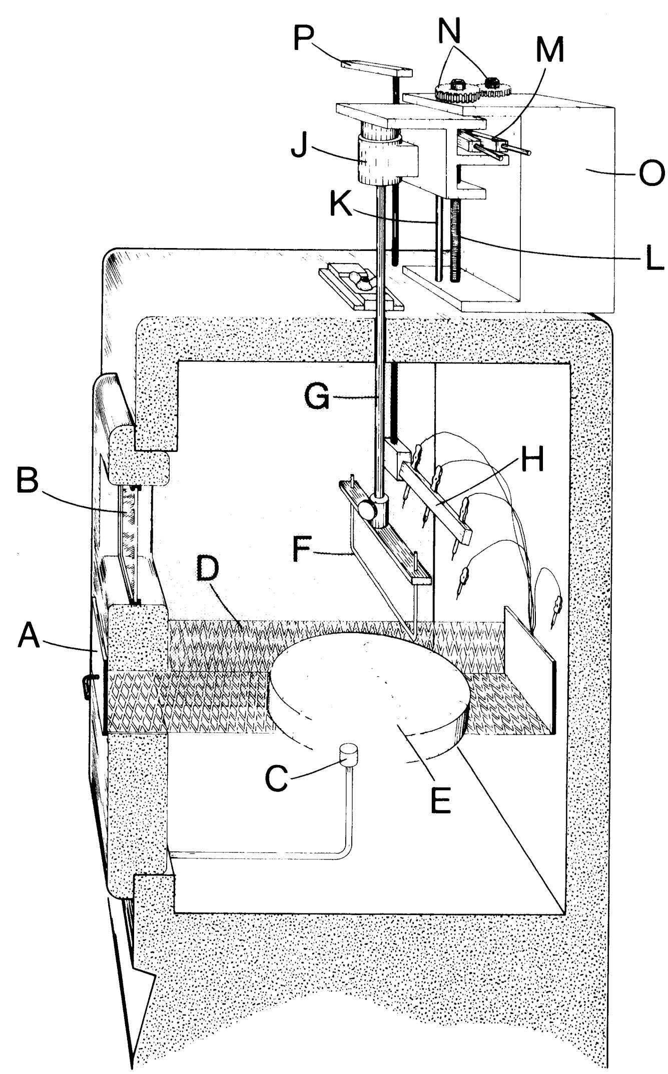

Fig. 1. Sectioned view of oven with instrumentation installed. **A,** asbestos front of drawer; **B,** heat resistant window; **C,** thermistor for controlling oven temperature; **D,** expanded wire mesh drawer; **E,** cake in aluminum pan; **F,** horizontal probe that is immersed in batter; **G,** fiberglass shaft; **H,** metal bar holding thermocouple(s) that are immersed in the batter; **J,** force transducer; **K,** carriage guide rod, **L,** rotating screw; **M,** split nut mechanism; **N,** gears; **O,** housing containing motor; **P,** handle for lowering thermocouples.

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clamp assembly at the top of the oven. The rod was lowered manually at selected times during baking until its tip touched the upper cake surface. The cake height readings were then plotted on the force-time record from the rod positions on a metric scale within 0.5 mm. The continuous height recording device described by Miller and Derby (1964) was not used because of the forces it imposes on the cake.

Immediately after the drawer was closed to install a cake, the split-nut mechanism was opened and the carriage-force transducer shaft assembly was manually lowered onto a rigid stop. This placed the probe at a preselected depth in the batter. The split-nut was closed immediately and the motor began to lift the horizontal probe upward. The force transducer was connected, via an amplifier, to a strip-chart recorder that recorded force against time. The force recording system had been previously calibrated by suspending weights on the probe (Fig. 1). Thus, the force required for the probe to cut through the cake during the baking was continuously recorded. On completion of baking, the probe and thermocouples were raised to clear the cake and the drawer was opened. The thermocouples and probe were cleaned after each test.

Cake and oven temperatures were recorded within ±0.14°C at the rate of 2 thermocouple readings per sec at 1 min intervals.

Cake weight loss during baking was recorded on separate sam-

TABLE I
Experimental Cake Mix Formulation

Component	Weight (g)
Cake flour	95.0
White granulated sugar	120.0
Salt	2.5
Double acting baking powder	5.0
Egg white powder	7.0
Skim milk powder	15.0
Water at 24–25°C	163.0
Oil mixture[a]	55.0
Vanilla	2.5

[a]Domestic vegetable oil, 83%; propyleneglycolmonostearate, 14%; stearic acid, 3%. Mixture was heated to 100°C, stirred regularly, and then cooled to 25°C.

TABLE II
Comparison of Mean Readings[a] from Stainless Steel and Ceramic Probes[b].

	Time (min)					
	To Appearance of Cohesive Structure		To Maximum Force		Maximum Force (g)	
Rod Material	Mean	SD	Mean	SD	Mean	SD
Stainless steel	18.8	0.9	36.2	1.2	108	8.4
Ceramic	18.6	1.2	37.5	0.2	114	6.5

[a]Readings from five replicate cakes made from an institutional mix.
[b]107.5 mm long and 3.2 mm diameter.

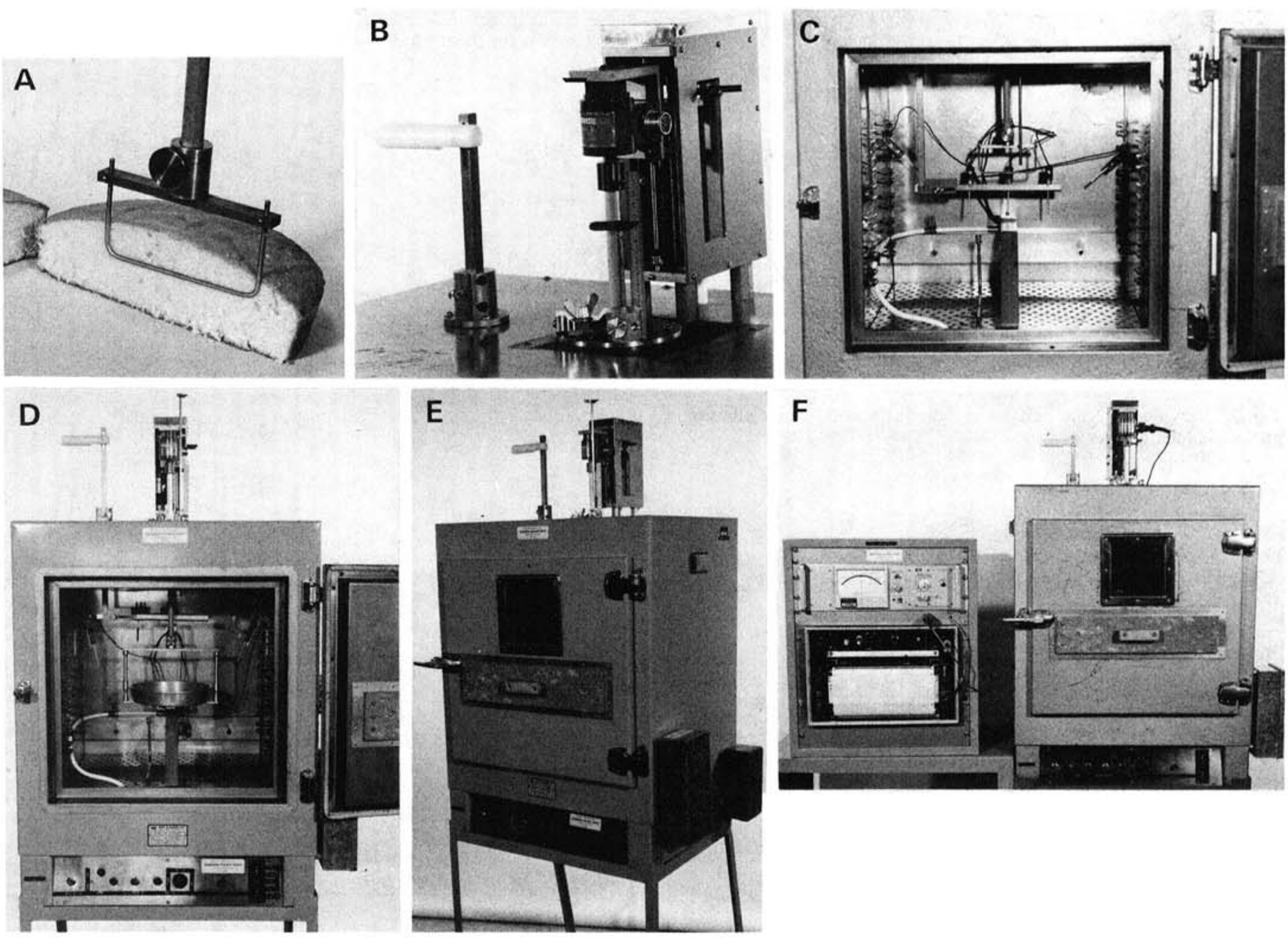

Fig. 2. Details of the apparatus. **A,** probe that is immersed in batter to detect cake structure development; **B,** mechanism and force transducer for raising the probe (metric scale used to measure rising of the cake); **C,** interior view of oven with door open; **D,** weight loss equipment installed in place of cohesion force accessories, **E,** overall view of modified oven; **F,** complete apparatus and recording equipment.

ples by replacing the probe assembly (Fig. 1) with a scale pan to support the cake. The initial weight of the batter and cake pan was tared from the recorded force by the amplifier controls to permit recording of the weight loss over the full scale of the recorder chart. The cake weight changes were detected by the force transducer and continuously recorded against time. For these tests, the drawer was opened fully so that its back sealed the opening and the oven door was used in the conventional manner.

The relative positions of the moving probe and the upper cake surface were determined by superimposing a straight line on the force-time record with a slope of 1mm/min. Additional details of the apparatus are illustrated in Fig. 2.

A 23-kg bag of institutional cake mix was used for preliminary tests. Unless otherwise stated, batters were prepared according to instructions. Each cake contained: 278 g of cake mix, 151 ml of water, and 1 egg weighing between 54 and 58 g. Commercial cake mixes were also prepared according to labeled instructions. Additional tests were performed with an experimental cake formula (Table I).

The ingredients were mixed in a Hobart mixer (Model N50) at speed number 2 for 4 min. After 2 min, the sides of the bowl were scraped down. The batter was poured into a 200 × 40 mm greased aluminum cake pan, filling it to a depth of about 24/mm, and the pan was immediately placed in the preheated oven containing the

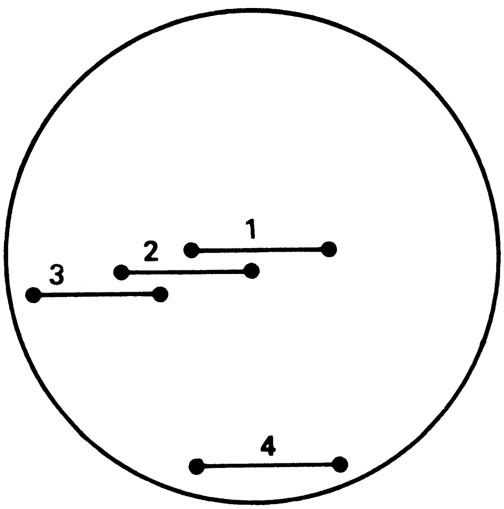

Fig. 3. Locations of probe relative to cake surface area, used to examine effect of probe position.

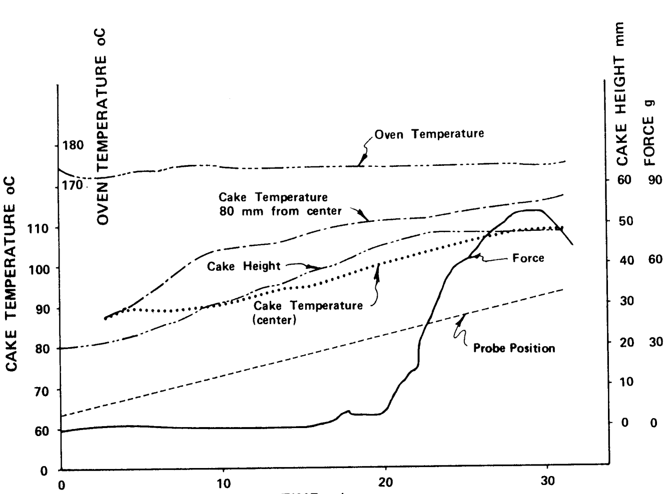

Fig. 4. Typical result obtained for an institutional cake mix shows data that can be obtained in each test.

probe. For this work, effects of batter viscosity, density, other factors (Trimbo et al 1966, Trimbo and Miller 1973) and baked cake quality were not considered.

RESULTS AND DISCUSSION

With the oven empty and the door closed, the temperature was controlled within ±0.14°C. Opening and closing the drawer immediately reduced the temperature by up to 3°C. Inserting the cake (which was at room temperature) into the preheated oven (175°C) reduced the oven temperature by up to 6°C. Data for 100 baking tests indicated that, overall, the baking cycle temperature had a maximum standard deviation of ±1.9°C. During the experiments, the mean oven temperature (of 31 determinations at 1 min intervals) for individual baking cycles ranged from 171.0 to 177.6°C.

A full-scale reading of 150 g was suitable for the force recording system. Calibration with weights, incrementally applied to the probe, showed that the relationship between force and chart reading was linear and repeatable within ±0.5%.

The rate at which the probe was drawn through the batter was

TABLE III
Effect of Probe Location Relative to Cake Surface Area[a].

Probe Location (Fig. 3)	Time (min) To Appearance of Cohesive Structure	To Maximum Force	Maximum Force (g)
1	16.5	36.2	100
2	16.8	37.4	101
3	19.1	34.5	110
4	12.4	32.6	118

[a]Readings for the institutional cake mix obtained with a 3.2 mm diameter probe 107.5 mm long.

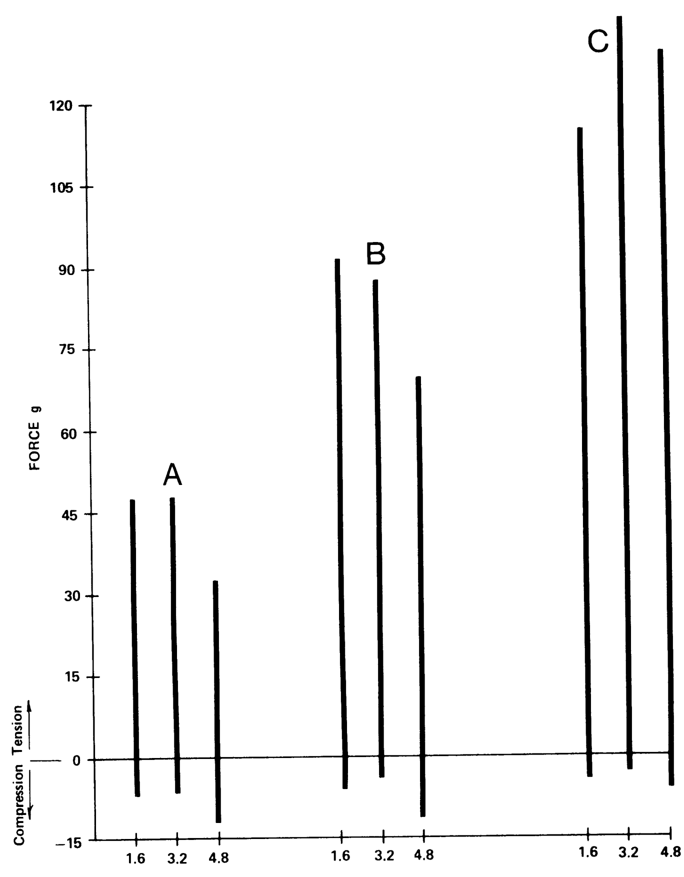

Fig. 5. Plots of maximum tensile and compressive (buoyancy) forces on the probe during baking of an institutional cake mix, using three probe diameters and lengths of **A**, 57.5; **B**, 107.5; and **C**, 162.5 mm.

important because it influenced the magnitude of the cutting forces. The rate selected was a compromise between: a) that which allowed the probe to remain immersed sufficiently in the batter so that the recorded forces were not influenced by the rupture of the surface crust, b) that which was greater than the rate of rise of the batter so that the batter was continuously undergoing rupture, and c) that which did not require the probe to start motion close to the bottom of the baking pan. A rate of 1 mm/min was adequate, with an initial clearance of 5 mm between the probe and pan. Under these conditions, surface crust rupture was not observed during probe motion.

The probe size and its position relative to the cake surface area were considered important because of the known nonhomogenous nature of the cake structure. Also, the probe material could affect the result because of the heat transmitted into the cake. Tests were conducted with probes made from stainless steel and ceramic rods 1.6, 3.2, and 4.8 mm in diameter with horizontal lengths of 58, 108, and 163 mm. Three readings were taken from the force-time curves: a) the time taken for measurable forces to increase above zero (assumed to indicate the initial formation of a detectable cohesive structure), b) the maximum force developed, and c) the time to reach the maximum force.

The differences introduced by using probes made of a heat transmitting material (stainless steel) and an insulating material (ceramic) were not significant (Table II). The ceramic probes were too fragile and therefore impractical.

Force readings at four locations distributed over the cake surface (Fig. 3) showed that the probe location had an effect. The maximum force increased from the cake center to the outer edges, reflecting the greater rate of heat penetration and cooking at the edges. The corresponding changes in the two time readings are shown in Table III. As observed by Gordon et al (1979), the cake temperature varied throughout the cake, being higher near the cake edge than at the center (Fig. 4). In recognition of these effects and to reduce the data to manageable proportions, we decided to locate one thermocouple close to the cake center and to center the probe along the cake diameter.

Maximum force increased consistently with increasing probe length (Fig 5A, B, C) but decreased with increasing diameter at two lengths (Fig. 5A, B). Diameter effects were inconsistent at the maximum length, possibly because this probe spanned a greater range of cake structural development. The times to the appearance of a cohesive structure and to the maximum force were not affected by probe lengths up to 107.5 mm but were markedly reduced at 163 mm, due to the advanced baking at the cake edges. Probe diameter did not affect the times. Before a cohesive structure appeared (ie, when the force pulling on the probe increased above zero), small negative forces (compression, Fig. 4) occurred and were assumed to be a buoyancy effect as the batter expanded on heating and pushed up on the probe. The maximum compressive force also was influenced by rod length and diameter (Fig. 5). Based on these results, a stainless-steel probe 108 mm long and 3.2 mm in diameter was adopted.

A typical result for the institutional mix (Fig. 4) demonstrates the information obtained from each test. With commercial and institutional cake mixes, the first indication of a cohesive structure appeared after baking times ranging from 12.1 to 17.4 min. The tensile force then increased nonlinearly to a maximum in 30.2–37.3 min and reduced as baking continued. The maximum force was assumed to be an indication of the maximum cohesive forces developed within the cake structure. Cake height increased almost linearly with time to a maximum and then remained constant. The maximum height was consistently reached before the maximum force. Cake temperature increased nonlinearly throughout baking with a short plateau occurring at a temperature that greatly depended on thermocouple location (105° and 95°C, Fig. 4).

In tests of four replicates of commercial and the institutional mixes, the repeatability of the time and maximum force readings was within acceptable limits (Table IV), with the exception of maximum force in one case. There were significant differences ($P < 0.01$) between some commercial brands.

The effect of formulation changes was illustrated by testing the experimental formulation and the same formulation with ingredients omitted in turn. The changes in the force-time curves were dramatic (Fig. 6). Sensitivity to minor formulation changes was illustrated by testing samples of the institutional mix and varying the water added in recipes containing 278 and 270 g of mix. At both weights of mix, the maximum cohesion of the cake structure was developed at the manufacturer's recommended water addition and the effect of a 5% change could be detected (Fig. 7). The reasons for reduced force readings at both insufficient and excess water are not clear, but obviously the amount of water is critical to structural cohesion.

Commercial cake mixes generally showed a steady reduction in cake weight (Fig. 8). The rate of weight loss changed during baking, but there was no evidence of the maxima reported by Gordon et al (1979) for their experimental mixes where weight loss was measured periodically.

TABLE IV
Means and Standard Deviations for the Three Major Characteristics of the Force-time Curves[a]

	Time (min)					
	To Appearance of Cohesive Structure		To Maximum Force		Maximum Force (g)	
Brand	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
1	15.6	0.8	35.4	0.7	99	6.4
2	13.2	0.8	32.3	2.0	91	4.7
2	12.1	0.8	30.7	1.2	82	10.9
3	17.4	0.4	37.3	1.0	84	6.4
4	16.7	0.8	34.9	1.8	92	4.6
4	15.1	1.4	32.2	0.8	97	7.5
Institutional	13.8	0.5	30.2	0.8	80	1.3

[a]Results obtained for four replicates from two packages of four commercial cake brands and four replicates of an institutional cake mix.

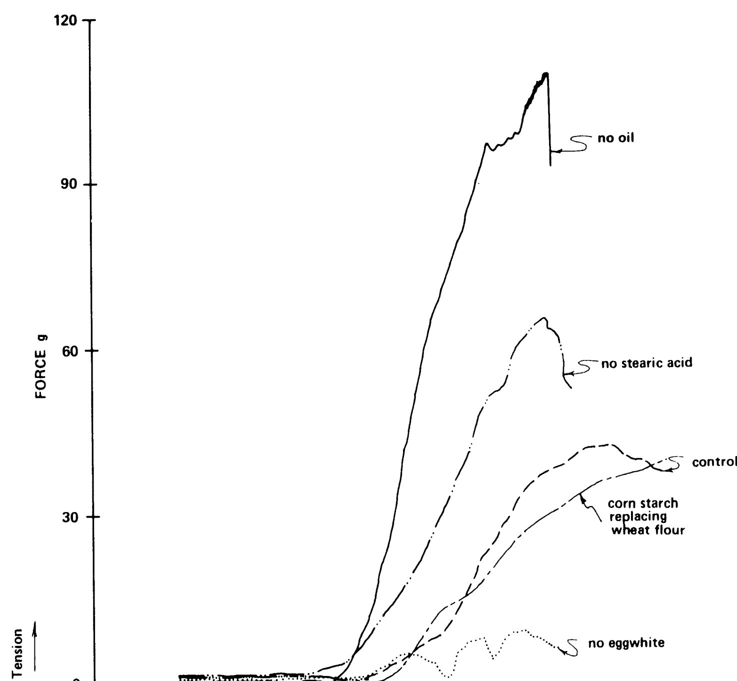

Fig. 6. Force-time records for an experimental cake mix formulation (Table I). One ingredient was omitted in each of four formulations.

Probe motion need not start on commencement of baking; the probe can be kept stationary or started any time before a cohesive structure appears. With a stationary probe or a delayed start of motion, the compressive forces (buoyancy) were larger than with continuous probe motion (Fig. 9). If motion was started just before structural cohesion developed, the forces pulling on the probe increased rapidly up to a point and then continued to increase at a slower rate (Fig. 9). Several maxima of short duration occurred, but there was no evidence of a peak.

If the probe was kept stationary, the forces on the probe were still pulling downwards as the cohesive structure developed (Fig. 9) and a peak occurred. We hypothesized that surface crust formed an encapsulating membrane. The pressure developed by expansion of the cake was exerted in all directions. The stationary probe 5 mm from the bottom of the pan detected the downward pressure, and the peak indicated when rupture allowed material to flow past the probe.

The different times until the appearance of the peaks (Fig. 9) in the three methods was attributed to the different positions of the probe relative to the cake depth, the influence of depth on the degree of cooking, and the effects of cake density at these locations.

The probe can be driven down into the cake instead of withdrawing it during baking. A maximum in the compression force then occurred sooner than did the maximum tensile force when the probe was withdrawn (Fig. 10) because the ingoing and outcoming probes are at different depths in the cake at different stages of baking. After the maximum, the compression force again increased as the probe entered the more baked layers near the bottom of the cake.

Force could be recorded directly against cake temperature using an X-Y recorder (Voisey et al 1977) so that the temperature at which structural cohesion started could be observed conveniently and manual plotting of the temperature data on the force-time records was eliminated. Ongoing work has demonstrated that useful additional information can be obtained by operating three parallel recording systems: force vs time, force vs temperature, and temperature vs time.

Because structure and temperature are not homogenous throughout the cake and because distribution of structural development and of temperature change continuously during baking, measurement of force and temperature is practical only at carefully selected locations.

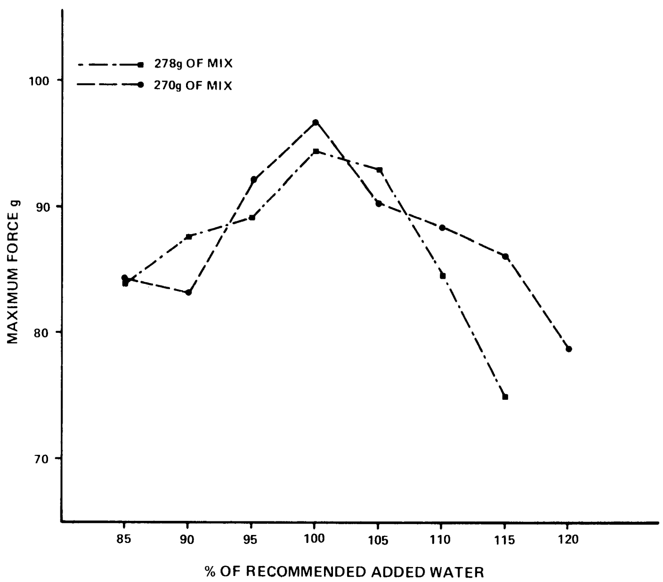

Fig. 7. Plot of maximum force development in cakes made from the institutional mix using greater or lesser amounts of added water than recommended at two weights of mix in the formulation. Each point is the mean of two replicates.

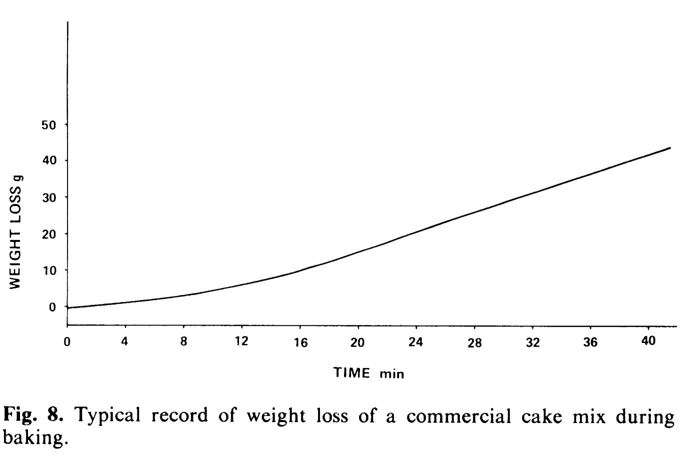

Fig. 8. Typical record of weight loss of a commercial cake mix during baking.

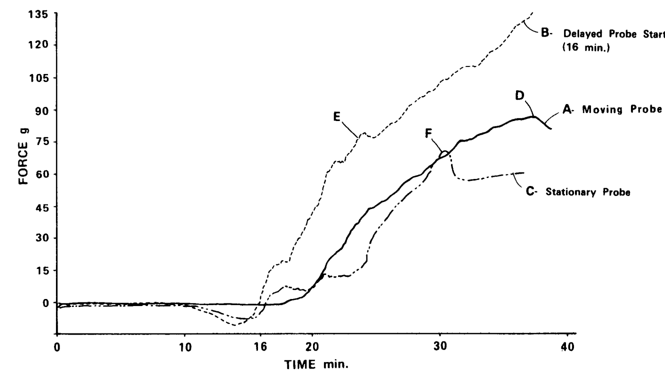

Fig. 9. Typical results for a commercial cake mix by **A,** the normal technique of raising the force probe at 1 mm/min from the start of baking; **B,** starting the probe motion 16 min after the start of baking; **C,** holding the probe stationary throughout baking. **D, E,** and **F** are the maxima.

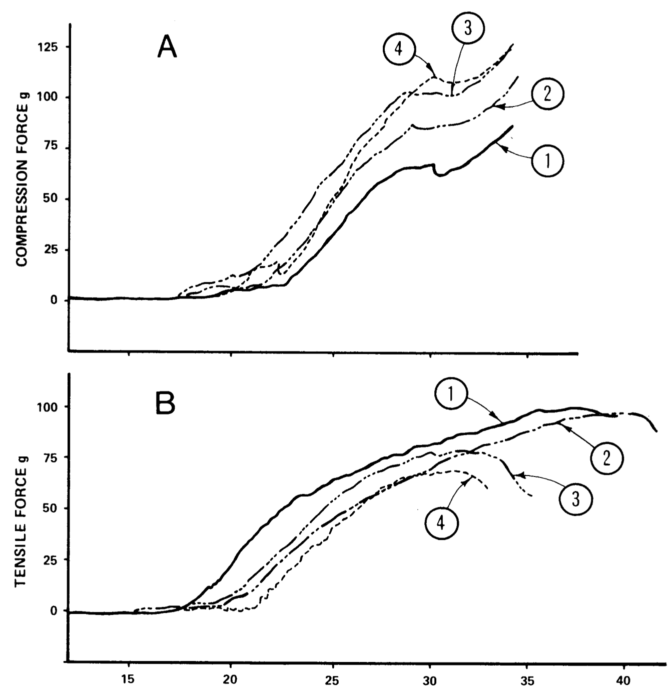

Fig. 10. Comparison of results obtained when the probe was: **A,** forced down into the cake; **B,** withdrawn from the cake during baking for four commercial cake mixes (1 to 4 in Table IV).

An artifact exists in the measurement of cake temperature where the thermocouple is initially immersed in a liquid and finally in a moist porous solid. It is not known whether the wet or dry bulb temperature is recorded. Moisture evaporation must affect the readings.

The plateaus in the temperature curves cannot be explained on the basis of starch gelatinization because the plateau temperature depends on thermocouple location. Other data (not shown) indicate that certain cake formulations do not give rise to temperature plateaus. The possible effects of water evaporation and migration, the difficulties of temperature detection and the definition of starch gelatinization confound the issue and make the plateaus difficult to interpret in physical terms. In a separate study, we are examining these factors and also heat and mass transfer in baking cakes.

The apparatus described is useful for characterizing cake structure development during baking. The test configuration must be standardized to make empirical comparisons. Readings repeatable within acceptable limits can then be obtained. Several procedural options remain to be fully explored. The equipment may assist in gaining new insights into the mechanisms of cake baking and the effects of cake formulation on the development of structure within the baking cake.

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