PHYSICAL TESTS OF FLOUR QUALITY

C. H. Bailey
University of Minnesota

Doughs and pastes prepared from wheat flour have peculiar properties which differ decidedly from those of doughs made from other cereals or any other materials. In fact, it may be asserted that it is these physical properties, rather than distinctive biochemical or nutritive values, which have given wheat its relatively prominent place in the dietaries of certain races of people. Practically from the inception of scientific research on wheat flour, an effort has been made to identify the constituent or constituents responsible for these physical characteristics, and to trace the occasion for and magnitude of variations in their concentration and properties.

CONTENTS

Only recently has a concerted effort been made to measure in a direct manner those physical properties that are of significance. In this respect the technology of cereals has lagged behind that of many other industrial materials such as metals, cement, and textiles. One of the reasons for this lag might be found in the difficulty of definitely identifying those fundamental physical properties which are of primary significance in the instance of flour doughs. Another reason has been the lack of convenient and readily standardized mechanical instruments or testing devices which will measure those properties directly and quantitatively. Actually, this ideal in instrument construction has not yet been wholly achieved.

Reliable physical tests of flour quality have come to be much more in demand of recent years, particularly in countries which have adopted national policies of self-sufficiency in bread grains. Severe limitations on the importation and use of high-quality foreign wheats for blending, and forcing millers and bakers to use largely native wheat, have intensified the search for procedures that would yield reasonably satisfactory baked products despite recognized deficiencies in the quality of the grain used. The interest in such developments, however, has extended to other countries, such as Great Britain and the United States, where a wide variety of wheats are available but where great variations in their milling characteristics appear within a season and from year to year. The common objective is to find efficient, economical ways of using the varied raw materials so that the final products can be kept up to satisfactory standards. This has led to extensive scientific investigations and application of their results in milling laboratories. The present technical monograph presents an analytical review of the scientific progress in this field.

The precise definition of the two principal terms, "physical" and "quality," is not always entirely clear. Thus the term "physical" might be used in such a broad sense as to include many operations of the chemical laboratory. For the purposes of this discussion, the term has been applied as essentially synonymous with "mechanical," at least in evolving the description of the instruments and testing devices to which attention is directed. Also it has been confined to the application of such devices to measurements of "quality" as herein defined.

It is still more difficult to define the term "quality" in this connection. Thus variations in moisture content are actually reflected in quality, if that term is used in an inclusive manner. If the determination of moisture content were to be covered in this discussion, it would have to include description of the several electrometric moisture-testing devices as well as other physical methods for measuring moisture content. Actually the term quality has not been interpreted to include moisture content, and accordingly such instruments are not discussed.

On the other hand, it was decided to include

a discussion of "absorption," or the quantity of water required to produce a dough of proper consistency for bread baking. It might be contended that this is not a criterion of flour quality any more than many characteristics that have been omitted. In defense of the policy that has been adopted, it should be emphasized that the property of dough viscosity or plasticity is so closely associated with elasticity, ductility, extensibility, and other physical properties as to make it essential to include viscosity in the discussion, and the proportion of water used in mixing a dough, or flour absorption, is intimately related to dough viscosity.

Accordingly, for convenience, the discussion has been divided into three major sections: (I) Absorption, and the measurement of dough viscosity or plasticity; (II) Physical tests of crude gluten; (III) Physical tests of wheat flour dough. In certain instances there is an overlapping, particularly in the case of those devices which deal with dough viscosity, and with other dough properties. In such cases the devices are discussed under more than one head. References to literature are numbered consecutively throughout; footnote citations are not repeated within any section.

In the process of converting dry flour into yeast-leavened bread, a number of interrelated physical, physico-chemical, and biochemical phenomena are involved. In chronological sequence certain of these include:

(1) Hydration of flour colloids as water is added to the dry flour to form the dough. Time becomes a factor in completing the hydration, particularly when the quantity of water used is equivalent to less than two-thirds of the weight of the flour. This, in turn, probably results in

(2) Coacervation of the hydrated flour proteins, with the formation of a coherent and elastic gluten in the flour particles.

(3) Mechanical agitation or mixing, which accompanies the addition of water, and results in the formation of a continuous gluten matrix in the dough. A carefully adjusted kneading process brings the hydrated gluten micelles into juxtaposition, so that they coalesce to form a continuous reticulum if the quantity of gluten is sufficient and lipids or other materials do not interfere with the process.

(4) Aging of the dough as fermentation progresses. The aging of the dough, in turn, might be described as:

a) Further hydration of the flour colloids with the lapse of time.

b) Reorganization of the gluten matrix which spontaneously ensues when the mechanical mixing of the dough is stopped.

c) Stretching of the dough in consequence of the expansion effected by the CO_2 of fermentation. This effect is reduced by partial degassing or light kneading by the baker.

d) Effect of the accumulating H-ions upon the flour proteins. pH of dough made from high quality ("patent") flour tends to decrease during fermentation.

e) Partial proteolysis effected by the dough enzymes including those contributed by the flour, yeast, and other dough ingredients and as controlled or regulated by oxidizing reagents and pH.

I. FLOUR ABSORPTION

Initial adjustment of the proportion of water used in preparing bread doughs is essential to the production of bread of good quality. Too much water results in a sticky dough that does not move normally through the machines, is liable to collapse or fall in the final stages of fermentation or in the oven, and commonly results in coarse-grained, unattractive bread. Too little water is likewise unfortunate, and leads to a heavy, poorly leavened loaf. Moreover, the quantity of water required to produce a dough of optimum physical properties is rather highly correlated with the yield of bread per unit of flour. In other words, the higher the absorption, the more pounds of bread of a given type per barrel or sack of flour. Accordingly, absorption becomes a factor of flour quality in its relation to (*a*) dough properties and (*b*) bread yield.

Concepts and Formulas

Physical properties of dough have been variously described under such terms as: (1)

viscosity (η, fluidity, plasticity, consistency, mobility, stiffness), (2) elasticity (modulus of elasticity [n], rigidity, resiliency), (3) extensibility (ductility), (4) tensile strength (shortness), (5) stickiness or adhesiveness, (6) "spring" or recovery after deformation, which may be associated with relaxation time (η/n).

The synonyms or antonyms included in the parentheses may not fit perfectly in every case, but appear to be closely associated as they are employed in the literature. Certain of these may be fundamental physical properties, while others are composites. As a matter of fact, it is difficult to separate certain of them in a discussion of dough properties, since they are modified conjointly as one applies various treatments to this complex material.

Before attempting to describe the action of specific dough-testing devices, an attempt can well be made to define certain physical terms to be employed in this connection, and at the same time to introduce the mathematical formulas involved in their derivation.*

Viscosity (η) refers to the ratio of shearing stress to rate of shear in true fluids. There is no universally accepted definition of viscosity in systems other than true fluids. The conventional unit is the poise, or its fraction, the centipoise. If between two plates having a shearing area of 1 cm.^{2}, a film of the fluid to be tested is placed, with a film thickness of 1 cm., and a force of 1 dyne is required to maintain a velocity of 1 cm. per second, the fluid is said to have a viscosity of 1 poise. Viscosities of liquids are sometimes expressed in terms of their ratio to the viscosity of water at the same temperature and under the same conditions of measurement, and recorded as *specific viscosity*. At 20° C. the η of water is about 1 poise.

Fluidity (φ), or *mobility* is the reciprocal of viscosity or $1/\eta$ and is expressed in rhes, so that 1 rhe $= \dfrac{1}{1 \text{ poise}}$.

Scott Blair, in his recent book, cited above, states that the dimensions of viscosity are derived as follows:

$$\eta = \frac{S}{-dv/dr}$$

where S has the dimensions of Mass $\times$ Length^{-1} $\times$ Time^{-2}, v (velocity) has the dimensions of Length $\times$ Time^{-1}, r has the dimensions of Length, and dv/dr has the dimensions of Time^{-1}; or η = Mass $\times$ Length^{-1} $\times$ Time^{-1} which may be described as dynes per cm. per sec., which is the poise.

The volume (V) of a viscous fluid extruded per second from a tube of radius (R) and length (L) under a pressure (P) recorded in dynes/cm.^{2} (i.e., pressure in centimeters of mercury $\times$ density of mercury $\times$ 931) becomes:

$$V = \frac{P\pi R^4}{8\,L\eta}.$$

Halton and Scott Blair (1) estimated the viscosity of dough (η) by subjecting a dough cylinder of length l_1 to a shearing stress S (dynes/cm.^{2}) for t seconds so that it increased to length l_2. Then the stress was removed so that the length decreased to l_3, the permanent, nonelastic change in length then being $\dfrac{l_3 - l_1}{l_1}$ cm. per cm. and the rate of viscous flow $\dfrac{l_3 - l_1}{l_1} \Big/ t$. The viscosity η of the dough thus became:

$$\eta = S \times t \Big/ \frac{l_3 - l_1}{l_1}.$$

They point out that in practice the viscosity of dough never stays constant during an extension, so that $\dfrac{l_3 - l_1}{l_1} \Big/ t$ must be regarded as a mean rate of flow, and η as a mean viscosity.

* For general discussions of physical properties of materials, including dough, the reader is referred to *An Introduction to Industrial Rheology*, by G. W. Scott Blair (P. Blakiston's Son & Co., Inc., Philadelphia, 1938); *Elasticity, Plasticity, and Structure of Matter*, by R. Houwink (Cambridge University Press, Cambridge, England, 1937); *Les qualités plastiques des pâtes*, by H. Nuret and A. Ougrimoff (Imprimerie de Publications Periodiques, Paris, 1934); *Modern Cereal Chemistry*, by D. W. Kent-Jones (3d ed., Northern Publishing Co., Liverpool, 1939); *Mechanische Methoden zur Bestimmung der Backfähigkeit von Mehl*, by Gerhard Mueller (Konrad Triltsch, Würzburg, Germany, 1937).

1. P. Halton and G. W. Scott Blair, "A Study of Some Physical Properties of Flour Doughs in Relation to Their Bread-Making Qualities," *Cereal Chemistry*, March 1937, XIV, 201–19.

Moreover, the viscosity of many materials, including dough, tends to fall with increasing stress, thus exhibiting "structural viscosity," and rises with increasing strain, as in the "work hardening" of metals. In measuring dough viscosity it thus becomes necessary to record the exact conditions of stress and strain under which the measurement was made.

Reference is made in several parts of this monograph to special methods for measuring viscosity (or plasticity) of dough, the significance of these observations in baking technology, and the relationship of these constants to other dough properties.

Plasticity, or "mold-ability," represents the capacity to withstand molding and retain shape under the force of gravity. Its dimensions are analogous to those of viscosity, save that, as emphasized by Bingham, it is assumed that a force (f) known as the "yield value" must be applied to a plastic material before flow starts. This yield value is presumed to be that portion of the shearing force which is used up in overcoming the internal elastic stresses. In a lyophilic system the derivation of plasticity or viscosity becomes difficult or even indeterminate, and the values recorded are merely relative at best. This is the consequence of the conjointly operating properties of the lyophilic sol, of the dispersion medium, and of changes occurring in the proportions between the two which may be of an indefinite value. This becomes even more significant in such a mixture of lyophilic materials as flour dough, where the dispersion medium or water may be undergoing an exchange or transfer between the several lyophilic materials, as between gluten and starch.

Elasticity. An *elastic deformation* is one which disappears upon release of the stress which causes it, stress being defined as the force producing or tending to produce deformation in the body, and commonly measured as the force applied per unit area. Elastic deformation is studied in solid materials by the stress-strain relations, when strain is defined as the deformation resulting from a stress measured by the ratio of the change to the total value of the dimension in which the change occurred. In certain cases and with moderate or small stresses, the stress is proportional to the strain, as in Hooke's law, and $\frac{\Delta l}{l} = \frac{S}{E}$, where l = the length, S = tension, E = the modulus of elasticity or Young's modulus.

Young's modulus $E = \frac{mgl}{\pi r^2 s}$, where m = mass of weight applied, l=length, g=gravitational constant (acceleration due to gravity), r = radius, and s = elongation. It may be described as the shearing force in dynes per cm.^{2} divided by the stretch per unit length.

Elastic recovery is $\frac{l_2 - l_3}{l_3}$ cm. per cm., where l_2 is the length in centimeters to which the piece is stretched before the stress is removed, and l_3 is the length in centimeters to which it contracts. The *shear modulus* (n), as the term is used by Scott Blair *et al.,* then becomes:

$$n = \frac{S}{l_2 - l_3/l_3}$$

or the ratio of the shearing stress (S) in dynes/cm.^{2} to the elastic recovery, and is really one-third of Young's modulus (Y). For convenience throughout the remainder of this monograph this constant will be referred to as the *modulus.*

The mechanical device employed by Scott Blair *et al.* in measuring n will be described in another section.

It is apparent that the time during which the stress is applied and the magnitude of the stress are both significant in determining the amount of the elastic recovery of a body. This is particularly true of materials like dough, in which a high degree of plasticity is combined with varying and moderate elasticity. Maxwell's "time of relaxation" (tr or λ) may be of value in this connection. It is the time necessary for the tension to decrease by the unit $1/e$ (e = energy unit) of its original tension (S). With doughs it is a function of stress and of the degree of extension. Actually $\eta = ntr$, or $tr = \frac{\eta}{n}$ and, in another section, this ratio may be correlated with technological values of flour doughs.

Shortness, or the tendency to tear easily, is a function of *tensile strength,* and ductility. Special methods for estimating this property,

and extensibility, will be discussed in the third section of this paper.

Special expressions are introduced in the literature of this subject which do not permit of precise definition in physical constants, and can be described only in terms of the devices or machines employed in the specific determination.

Dough Viscometers

One of the simplest and most direct methods for determining the relative viscosity of dough was decribed by Jago (2). His viscometer consisted of a cylinder having a weighted and graduated plunger and an aperture in the bottom through which the dough was forced. He measured the time required to express a unit quantity of dough as indicated by the descent of the plunger through a unit distance. It was observed that such viscometer tests not only show the quantity or proportion of water required to prepare a dough of standard consistency, but also the relative rate of change in viscosity effected by increments of water. Flours were observed to vary decidedly in the latter respect.

While Jago's (2) first book merely describes his viscometer, a later book by the same author (3) contains a diagram (p. 506) illustrating the details of its construction. Two tests above and below the estimated optimum absorption are advised, with an estimate of the correct absorption by interpolation.

Kedzie's farinometer was described by Wiley *et al.* (4) as patterned upon the plan of Jago's viscometer, and was likewise employed to determine the water absorption of flour.

C. H. Briggs (5) provided a simple dough "viscometer" which included a small portable vacuum tank, a pump for reducing air pressure in the tank to the requisite level, and a glass tube of appropriate diameter graduated for 150 mm. of its outer length. The open end of this graduated tube was applied to the dough surface, and when the other end was attached to the air tank in which the pressure had been reduced, atmospheric pressure moved the dough into the tube. Its flow was allowed to continue until the material ceased to rise, and the distance that it moved into the tube was taken to be an index of dough viscosity. No data relative to the relations between the values thus secured and the baking behavior of dough have appeared in the literature.

Halton and Fisher (6) elaborated somewhat upon the Jago and Jago device for measuring changes in dough properties as a function of added water. As shown in Figure 1, they employed a cylinder with a piston resting upon the dough, but avoided certain unknown losses of force through friction of the piston stem against the sides of the top guide by allowing the rod attached to the piston to pass down through the lower aperture where it was surrounded by the dough. A suitable weight was attached to the lower end of this rod to provide the necessary force.

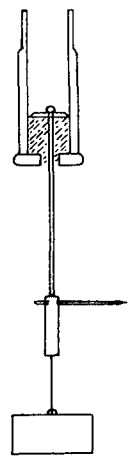

Fig. 1.—Halton and Fisher dough viscometer, re-drawn from their British patent

By measuring the rate of extrusion of the dough through the lower aperture (the exact dimensions not being given in the patent specifications) under the force of the applied weight (also not revealed), the amount of water required by a flour to give a dough of required *elasticity modulus* may be determined. Halton and Fisher (6) state that "the rate of extrusion is affected by both the *elasticity modulus* and by the *viscosity* of the dough, but the results of a prolonged series of experiments indicate that the elasticity of the dough is in fact the predominant factor; e.g., it can be shown that doughs from different

2. William Jago, *The Chemistry of Wheat, Flour, and Bread and the Technology of Bread Making* (Brighton, England, 1886).

3. William Jago, *The Science and Art of Bread Making* (London, 1895).

4. H. W. Wiley *et al.*, *Foods and Food Adulterants, Part Ninth: Cereals and Cereal Products* (U.S. Dept. Agr., Div. Chem., Bull. 13, Part IX, 1898), pp. 1269–71.

5. "Briggs' Perfekdo Viscometer," *Northwestern Miller*, Jan. 23, 1918, p. 275.

6. Philip Halton and Ernest A. Fisher, "An Improved Process for Determining the Baking Qualities of Wheaten Flour Dough and Apparatus Therefor" (British Patent 492,049, Sept. 14, 1938).

types of flour having identical rates of extrusion have different viscosities."

As in other instances of this general type of instrument, several determinations must be made at different levels of added water, and by interpolation it becomes possible to estimate the amount of water required to produce a dough of standard properties so far as revealed by this instrument.

Stamberg and Bailey (7) used an extrusion type of plastometer, diagrammed in Figure 2,

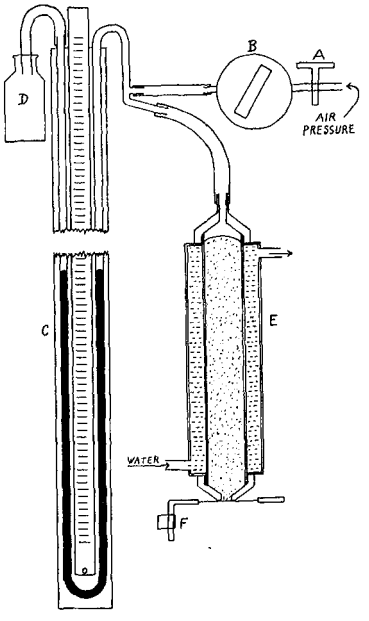

FIG. 2.—Stamberg and Bailey dough viscometer

provided with a jacketed dough cylinder for maintaining the dough at constant temperature by circulating water from a thermostat through the jacket. Compressed air, controlled to constant pressure as indicated by a mercury manometer, effected the extrusion of the dough through an aperture 6 mm. in diameter. It was observed that the logarithm of the time in seconds required to extrude a unit quantity of dough was a linear function of the proportion of water in the dough. Doughs were prepared from three flours of different protein content, and at several levels of water additions to the doughs, with the results shown in Figure 3.

From these graphs it would be possible to interpolate to a standard or uniform level of dough viscosity and to estimate the water absorption at this level. In this, as in other methods of measuring dough viscosity, the question arises: What constitutes optimum viscosity? Probably this can be standardized for the practices of individual shops, based upon formula, fermentation time, mechanical treatment, and type of bread desired, providing flour of uniform and unvarying properties is used. When either the flour type or baking practices are varied, it may prove necessary also to vary the level of dough viscosity, particularly in the instance of freshly mixed dough.

Van der Lee (8) designed a dough viscome-

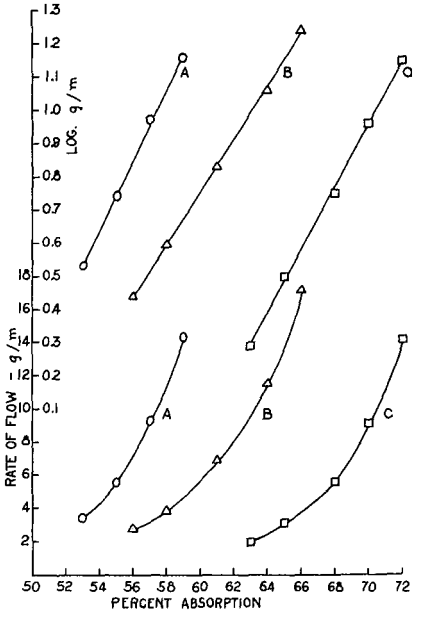

FIG. 3.—Rate of flow of dough through the Stamberg and Bailey viscometer; doughs made from three flours containing (*A*) 8.3 per cent, (*B*) 11.6 per cent, and (*C*) 15.5 per cent crude protein. Rate of flow plotted as ordinates in grams per minute in lower graphs, and the logarithm of grams per minute in upper graphs, against the water used in percentage as abscissas.

7. Olof E. Stamberg and C. H. Bailey, "Plasticity of Doughs," *Cereal Chemistry*, January 1940, XVII, 37–44.

8. G. van der Lee, "New Laboratory Apparatus for the Determination of the Dough Consistence and Bread Volume," *Proceedings of the 1st International Conference on Flour and Bread Manufacture in Prague*, Sept. 22–25, 1927 (Prague, 1929), pp. 333–53.

ter based upon the principle of the penetrometer. Provision was made for noting the time in seconds required for the round-headed cylindrical plunger to penetrate a unit distance into a mass of dough. Refinements of construction included provision for first bringing the surface of the dough to the point of contact with the plunger, for the sudden release of the latter at the time of starting the stop watch, and for magnifying the measurement of downward movement of the plunger by means of a windlass provided with a dial moving around the circular face of a graduated scale. The agreement of replicated readings is indicated by tests of an Australian flour from which three doughs were prepared, each with 53 per cent of water. These doughs were allowed to stand 45 minutes, and the tests made by allowing the plunger to penetrate for 240 seconds. The three readings, in terms of the arc through which the windlass shaft was turned, were 153°, 152.5°, and 150° respectively. An American flour required 62 per cent of water to convert it into a dough which gave equivalent readings. With a series of four flours, three increments of water were added to each so that the least mobile gave a scale reading approaching or passing through 150°. When these readings were plotted against the water added in percentage, the resulting curve is approximately a straight line with flours A, C, and D, and deviates slightly from a straight line with flour B.

A penetrometer designed by Harrel (9) consisted of a flat-ended brass cylinder 310.5 mm. long by 21.14 mm. in diameter and adjusted to weigh 1,070 g. It was suspended 2.8 meters from the surface of a quantity of dough, and was allowed to fall vertically under its own momentum and to penetrate the dough. Its penetration in centimeters was noted from graduations on the cylinder itself. Harrel observed that elevating the temperature of a dough reduced its viscosity, while the inclusion of increments of salt up to 4 per cent of the flour increased dough viscosity progressively. In a series of observations involving four levels of water used in preparing dough from each of several flour samples, it was noted that the penetration of the weighted cylinder was approximately a linear function of the water used. Harrel suggested that the tangent of the angle formed with the horizontal, on plotting penetration as ordinates and water used as abscissas, may be of significance, as a measure of capacity of the flour to resist "slacking" when increments of water are added.

Halton (10) found that both viscosity (η) and the elastic modulus (n) of doughs (see Section III) were lowered by increasing the water content of doughs; also that both of these physical constants diminished with time as the doughs aged. A plot of the logarithm of viscosity against the logarithm of the elastic modulus of a series of doughs made from the same flour but with varying proportions of water gave a straight line. In other words:

$$\log \eta = \times \log n + K_1.$$

The value of the ratio η/n^x, where x has a value of from 1.8 to 2.0, was found to be a constant for any given flour and varied only with the quality of the flour. It was independent of dough age and water content, and is the best relationship of η to n to use as a measure of flour strength.

Bohn and Bailey (11) applied their stressmeter, described in detail in Section III, to the study of the effect of variations in the water content of doughs upon stress readings, in comparison with certain characteristics of farinograms, with the results shown in Table 1 (p. 250). It is evident that the stress readings are influenced substantially by the proportion of water present, decreasing about 1.2 g. per 1 per cent increase in the amount of water in the instance of the strong flour used in this test. Using a medium-strength flour the same general relation maintained, although all the stress readings were lower and decreased at the rate of 0.7 g./per cent water.

9. C. G. Harrel, "A Gravimetric Penetrometer for Measuring Stiffness or Toughness of Doughs," *Cereal Chemistry*, July 1927, IV, 283–90.

10. P. Halton, "Relation of Water Absorption to the Physical Properties and Baking Quality of Flour Doughs," *ibid.*, May 1938, XV, 282–94.

11. L. J. Bohn and C. H. Bailey, "Effect of Mixing on the Physical Properties of Dough," *ibid.*, September 1936, XIII, 560–75.

Swanson and Working (12) described a procedure which they have used to estimate flour absorption. A suspension of 100 g. of flour in 600 cc. of water was passed through a Sharples super-centrifuge running at 15,000 r.p.m., and an additional 400 cc. of water was used to wash all the flour into the centrifuge bowl. The weight of flour and water in the bowl could then be used to determine the quantity of water held by 100 g. of flour. They found that this represented the quantity of water required to give a dough of optimum consistency for baking.

TABLE 1.—EFFECT OF INCREMENTS OF WATER IN DOUGH MADE FROM STRONG FLOUR UPON STRESS AND FARINOGRAPH READINGS, AS REPORTED BY BOHN AND BAILEY, 1936

Water used (%)	Time to maximum point on farinograph (*minutes*)	Height to maximum point on farinograph (*units*)	Stress readings (*grams*)			
			15 sec.	30 sec.	1 min.	2 min.
62	13.5	590	25.1	18.3	15.1	11.9
65	15.0	535	21.9	16.4	13.1	10.0
68	19.0	485	18.2	14.2	11.3	8.9
71	23.0	445	14.6	11.7	9.0	7.3

Fifield (13) found that the Swanson and Working centrifugal method for measuring absorption invariably gave results substantially below the baker's absorption, and that this difference was increased when the flours were soaked in the water suspension for 30 minutes instead of 5 minutes as first proposed. Moreover, the difference between the centrifugal and the baker's absorption tests was not constant, even within the same class of wheat.

12. C. O. Swanson and Earl B. Working, "Testing the Quality of Flour by the Recording Dough Mixer," *Cereal Chemistry*, January 1933, X, 1–29, esp. p. 21.

13. C. C. Fifield, "A Mechanical Method for the Determination of Adsorption in Bread Doughs," *ibid.*, November 1933, X, 547–54.

14. Earl B. Working, "The Determination of the Water Absorbing Capacity of Flour by Means of the Super Centrifuge," *ibid.*, September 1934, XI, 567–68.

15. Thomas Kosutány, *Der ungarische Weizen und das ungarische Mehl* (Budapest, 1907), esp. p. 248.

16. Marcel Chopin, "Relations entre les propriétés mécaniques des pâtes de farine et la panification," *Bulletin de la Société d'encouragement pour l'industrie nationale*, March 1921, CXXXIII, 261–73.

17. C. H. Bailey and Amy M. Le Vesconte, "Physical Tests of Flour Quality with the Chopin Extensimeter," *Cereal Chemistry*, January 1924, I, 38–63.

Working (14) modified the original procedure, which involved soaking the flour in water for 5 minutes, by extending the time to 30 minutes, which minimizes the errors due to variation in the granulation of flour and to enzyme activity. When the revised method was checked against the results of baking tests, about two-thirds of the absorption determinations made with the centrifuge agreed within 0.5 per cent of the quantity used by the baker, and about three-fourths fell within 1 per cent. The larger errors were apt to appear in testing new varieties not suited to bread production, and in flours milled from wheats grown under abnormal conditions.

Rejto's dough ductility machine, described by Kosutány (15), enabled him to measure the relative force required to extend doughs containing varying proportions of water. In a typical series of doughs prepared from one flour, but with varying proportions of water, the "Zugkraft" was determined and recorded as follows (Kosutány, p. 262):

Water (*per cent*)	Zugkraft (*grams*)	Logarithms of Zugkraft
45	937.75	2.97208
46	852.50	2.93069
47	775.00	2.88930
48	676.73	2.83042
49	596.75	2.77579
50	530.10	2.72436

The plot of the logarithms of Zugkraft against the water used approaches a straight line somewhat more exactly than the plot of the Zugkraft, expressed linearly, against water used.

Chopin's (16) extensimeter provided means for observing the force required to extend a sheet of dough incidental to measuring extensibility. Reference will be made in Section III to the latter property.

Bailey and Le Vesconte (17) applied this instrument to the determination of the tenacities of a series of doughs prepared from one hard wheat flour in which the water used was varied from 59 cc. to 67 cc. per 100 g. of flour. Tenacity as thus measured represented the maximum pressure (P) on the air line used to inflate a thin (3 mm.) sheet of dough into a bubble, as registered in millimeters of increase in the level of water in a simple

manometer.* At 69 per cent water, the manometer reading reached 125 mm. and at 67 per cent water, 92.3 mm. In the instance of this flour sample the maximum extensibility was reached when the tenacity was equivalent to about 100 mm., but the studies were not sufficiently extended to establish the optimum viscosity as thus determined.

Scott Blair and Potel (18) accepted the conclusion that the value P as measured with the Chopin extensimeter is primarily related to the water-absorbing capacity of the flour.

St. John and Bailey (19) varied the water added in preparing several doughs from the same flour, and found the force required to effect extension of the dough with the Chopin extensimeter was 135 mm. (of hydraulic head) when the water used was 63 per cent of the flour, and 40 mm. when it was 77.1 per cent. While the observations are limited in number, they indicate a log/log relationship between these two variables.

Naszalyi (20) presented in tabular form the quantity of water to be added to each 100 g. of flour with moisture content of the latter as a variable along one axis, and ranging from 10 to 17 per cent, and the coefficient (C) as the other axis, when $C = \frac{\text{total water}}{\text{dry matter}}$. He also indicated in graphs and a table, the effect upon the force required to extend doughs made from a certain flour, and their extensibility as measured with the alphitograph, with the coefficient (C) as the variable. The significant constants are recorded in Table 2.

Ougrimoff (21) used the Chopin extensimeter in a study of the effect of varying the water content of doughs upon those properties disclosed by that instrument. The pressure (P) was an exponential function of the water present in the dough when the latter was expressed as the percentage of the dry matter. The same was true of the relation between the total work done in inflating the dough bubble, and the percentage of water used in its preparation. Extensibility or "gonflement" (G) passed through a maximum as the percentage of water was increased, the position of the maximum varying for different flours, and then decreased sharply on further additions of water.

TABLE 2.—CHARACTERISTICS OF THE CURVES DRAWN BY NASZALYI'S ALPHITOGRAPH, WITH COEFFICIENT (C) AS THE VARIABLE, 1935

Coefficient (C)	Quantity of water per 200 g. flour (cc.)	Results of the experiment		
		Height of curve (cm.)	Length of curve (cm.)	Surface of curve (cm.²)
0.765	100.3	17.5	72	6.3
0.733	95.0	25	58	6.5
0.704	90.0	34	47	6.8

It seems probable that those devices which operate in a somewhat similar manner in testing doughs, including the Buhler comparator (see Kosmin, 22) and the Borasio and de Rege (23) pneumodynamometer, could be employed to indicate relative levels of dough viscosity. Reference will be made in the last section of this monograph to other applications of these instruments.

Bailey (24) wired a laboratory watt-hour meter into the circuit supplying electric current to the motor driving a small dough-mixing machine. By noting the work-input for 100 revolutions of the empty machine, and 100 revolutions of the same machine filled with dough, it was possible to estimate the work done, as recorded in watt-hours, in moving the mixing blades through the dough for a unit distance. When the water added in preparing the dough was the variable, a curvi-

* In a later model this was replaced by a recording pressure gauge.

18. G. W. Scott Blair and Pierre Potel, "A Preliminary Study of the Physical Significance of Certain Properties Measured by the Chopin Extensimeter for Testing Flour Doughs," *ibid.*, March 1937, XIV, 257–62.

19. J. L. St. John and C. H. Bailey, "The Effect of Dry Skimmilk upon the Water Absorption of Doughs and the Plasticity of Flour Suspensions," *ibid.*, March 1929, VI, 140–50.

20. N. Naszalyi, "Étude sur les qualités plastiques des pâtes," *Bulletin des anciens élèves de l'école française de meunerie*, January 1935, No. 35, pp. 4–9.

21. A. Ougrimoff, "Influence de l'hydration de la pâte sur les résultats extensimetriques," *ibid.*, November 1937, No. 63, pp. 273–79.

22. Natalie P. Kosmin, *Das Problem der Backfähigkeit* (Leipzig, 1936).

23. L. Borasio and F. de Rege, "Das Pneumodynamometer, ein Apparat zur Qualitätsbestimmung der Mehle," *Das Mühlenlaboratorium*, June 1934, IV, 77–82.

24. C. H. Bailey, "A Method for Measuring the Relative Plasticity of Doughs and Pastes," *Journal of Rheology*, 1930, I, 429–32.

linear relation was observed between the water used and work-input, and attention was called to the fact that a plot of the logarithms of the readings in watt-hours against the percentage of water used tended to approach a straight line.

This suggested that the absorption of flours could be measured quantitatively through the use of this device. Accordingly, a series of studies was instituted which disclosed that the optimal absorption for all flours was not at the same level of plasticity thus measured. These results were not published, however, since the study was repeated later with the farinograph; and detailed reference will be made in a later section to these observations.

Hankoczy, of the Royal Hungarian Cereal and Flour Testing Station in Budapest, developed a succession of devices which could be employed in the study of dough consistency and flour absorption. These have been described by Tibor (25) in the order of their appearance. The first instrument possessed features somewhat analogous to those of the Chopin extensimeter. Thus it provided for the application of air pressure to one face of a sheet of dough, which was stretched or extended until it ruptured. The force required to extend the dough, as registered in terms of air pressure, indicated whether or not its consistency was in the optimum range.

Hankoczy next employed a small dough-mixing machine driven by an electric motor to which a wattmeter was attached. As in the instance of Bailey's studies in America, the wattage proved too variable from reading to reading to constitute a very satisfactory index. Accordingly, the instrument was further developed to include a watt-hour meter. This was more satisfactory than the attempt to read fluctuating wattages, but it followed, perforce, that the reading must be taken over a time interval or for a unit number of revolutions of the dough mixer. A graph of work-input in watt hours versus absorption had the same characteristics as the typical curve published by Bailey (24), and by interpolation the absorption was computed.

Still later Hankoczy attached a simple tension dynamometer to the shaft which transmitted power from the motor to the dough mixer. This, in fact, possessed the essential mechanical features of the Hankoczy-Brabender farinograph, and the valorigraph now manufactured in Budapest, except that no recording device was provided.

The latest stages in this sequence are represented by the two devices just mentioned. Brabender, in Duisburg, Germany, applied a different type of dynamometer which is a part of the synchronous motor that drives the mixer. In its first form, appearing about a decade ago, the farinograph did not provide for the control of dough temperature, but the later models included a water jacket for the dough mixer which results in an approach to thermal control of the dough. This necessitates including a more or less elaborate water thermostat in the ensemble, with pumps for circulating water at constant temperature through the jacket of the dough mixer. The instrument will be described in greater detail in Section III. The force applied in the initial stages of mixing rises more or less rapidly to a maximum, which is maintained for varying periods of time, and then gradually recedes at varying rates, depending upon certain dough properties. It has been suggested that the level of "maximum consistency," or minimum mobility reached in the initial stages of mixing, constituted an index of flour absorption.

Near and Sullivan (26) found that the quantity of water required to produce a dough registering 580 units on the farinograph consistency scale agreed within about 0.5 per cent with the absorption recommended by a skilled baker. Their comparisons included flours ranging from 9.3 to 15.6 per cent crude protein, although only two flours containing less than 10.5 per cent crude protein were included in the series. Merritt, in the author's laboratory, computed the coefficient of correlation between the absorption as determined by the farinograph and the bakers' absorption values reported by Near and Sullivan, and found $r = +0.987$, which means that the rela-

25. Istvan Tibor, *A Buza- és Lisztminőségvizsgálatok* (Budapest, 1933), esp. pp. 65–118.

26. Cleo Near and B. Sullivan, "The Use of the Farinograph as an Accurate Measure of Absorption," *Cereal Chemistry*, September 1935, XII, 527–31.

tionship was very close. Moreover, the correlation between protein content and absorption as determined by the farinograph was also high ($r = 0.894$) in this series.

Merritt and Bailey (27) selected a series of flours of widely varying baking strength and protein content and found that the optimum consistency in farinograph units was substantially lower for the weak than for the strong flours. In making these comparisons five levels of water additions ranging through 5 per cent were made to each flour to insure that the optimum absorption was reached in each instance, and this optimum was assigned upon the basis of loaf-quality scores. Moreover, the author has observed a tendency to produce doughs of higher mobility, i.e., lower consistency on the farinograph scale, in those countries which employ relatively low-strength flours in bread production. In this study an average increase of 15 farinograph units of consistency accompanied each 1 per cent change in water used in the range of optimum absorption.

Tibor (25) found that he could compute the quantity of water required to adjust the plasticity of dough to a definite farinograph value, say 500 units, when the first farinograph test resulted in a value somewhat above or below the desired mobility. He presented (p. 117) a tabulation of the corrections required in such instances for the flours usual to his country, but suggested that the correction might not apply exactly in all cases, for example, with Canadian flours. It accordingly appears that the alteration of mobility by a unit increment of water is not uniform for all flours. Consequently any computation of increase (or decrease) in the proportion of water required to change the mobility of a dough through the desired range (in farinograph or other units) must be based either upon one or more trials with the flour in question, or upon some knowledge of its properties that would assign it to a particular type, the behavior of which is known.

Markley and Bailey (28) found that the logarithm of the point of minimum mobility (maximum consistency) of the farinogram plotted against the logarithm of the ratio of flour to water in a dough resulted in a straight line for any particular flour. The slope of the curve was not the same with different flours, however. While the data available are scarcely adequate for drawing general conclusions, it was noted that with a weak, low-protein flour (7.9 per cent crude protein), each increment of water effected a larger increase in mobility than with strong, high-protein flours. There is some evidence that this accords with commercial experience, and it merits further investigation with more samples.

Discussion

The terms "absorption" and "water content," as applied to the proportion of water to flour in dough, have been used as synonyms by many technicians and bakers. As emphasized independently but concurrently by Halton (10) and by Markley and Bailey (28), "absorption" should be defined as the proportion of water to flour in dough which results in bread of optimum quality. While the English group tends to report absorption in terms of gallons per sack—a very awkward practice indeed, since neither the gallon nor the sack is a uniform constant outside of a small territory—the tendency in America and many other countries is to report it in "per cent," i.e., parts of water by weight per 100 parts of flour. This might be further refined by stating it as the ratio of dry matter in the flour to the total water in the dough, including the water contributed by the flour; or its equivalent, the water added per 100 grams of flour at a constant level of moisture content, after first providing the quantity of water necessary to adjust the flour to the standard moisture level.

A considerable variety of methods have been employed in the effort to measure and standardize dough consistency in so far as it is determined by the proportion of water used. By all odds, the most common procedure in commercial practice is to use the sense of

27. P. P. Merritt and C. H. Bailey, "Absorption-Mobility Relationships in Wheat-Flour Doughs," *ibid.*, May 1939, XVI, 377–83.

28. Max C. Markley and C. H. Bailey, "The Colloidal Behavior of Flour Doughs. II. A Study of the Effects of Varying the Flour-Water Ratio," *ibid.*, May 1938, XV, 317–26.

touch in the trained human hand. Actually the trained hand is no more sensitive than that of an unskilled person, as shown by Scott Blair (29). Its advantage lies solely in the fact that it recognizes whether or not consistency falls within the range regarded as optimum for the baking practice in vogue. Incidentally, Scott Blair also observed that the threshold for psychological detection of the compression modulus is only about one-third of that for viscosity of dough, and the latter is approximately 30 per cent of the actual viscosity involved.

Of the mechanical methods applied to dough, the extrusion methods of measuring "consistency" are simplest and require the least expensive special equipment. In these, as in other procedures, the difficulty of interpreting the findings lies in the lack of a definite optimum value which applies to all flours alike. Regardless of how the measurement is made, it must be recognized that flours of varying composition, and consequently of varying physical properties, must be adjusted to levels of consistency suited to their individual characteristics. In fact, as pointed out by Working (14), the optimum absorption for a single flour may be a function of the mixing treatment, the fermentation schedule, and the type of bread that is desired. Accordingly, cognizance must be taken of these variations in bake-shop programs. He emphasizes that the consistency at the time of molding the loaf is more important than that of the freshly mixed dough, although the tendency in technological practice is to endeavor to estimate absorption at the time the dough is first mixed. The result is that many baking test reports carry entries reading "dough slackened off," or similar notations, implying that the plastic and related properties at the time of molding the dough were not optimum for the preparations in question.

Actually, the situation in practice is not as difficult to meet as may be suggested by the foregoing comments. Most bakeries use flours falling within a relatively narrow range of variability, since the mills from which they purchase flour arrange to supply fairly uniform products. Accordingly such adjustments of absorption as must be made from time to time are applied to flours which will yield doughs of reasonably constant plasticity at optimum absorption. At the beginning of new crop seasons, or when the bakery changes its flour-purchasing program or the types of bread produced, it may be necessary to alter the dough plasticity to secure the desired results. Also, readjustments of plasticity may be required when new types of machinery are added to the mechanical equipment of the bakery. Generally speaking, these are not common or frequent occurrences in the normal operation of a bakery, however, and if the shop is provided with any one of several types of plasticity-measuring devices, it can make a scientific approach to the measurement of absorption of different lots of flour, once the baker has determined what level of plasticity is optimum for the baking process which he employs.

In addition to the relation of the proportion of water in dough to its plasticity and shear modulus, absorption is of practical interest to the baker in consequence of its relation to the yield of bread. It might be anticipated that, other things being equal, the more water used in mixing a bread dough, the larger the weight of bread baked from a unit weight of flour. Mangels (30) computed the coefficient of correlation between absorption and the weight of loaves baked from a unit of flour, over a period of four crop seasons, and found this correlation to be significant and fairly high. His data are tabulated below

Crop season	Number of samples	Coefficient of correlation (r)
1923	217	0.593 ± 0.029
1924	297	0.652 ± 0.022
1925	262	0.795 ± 0.015
1926	273	0.863 ± 0.010

It seems probable that the relation in commercial baking would be even higher than was observed in Mangels' laboratory studies. In

29. G. W. Scott Blair, "Psychorheology in the Bread-Making Industry," *Cereal Chemistry*, November 1939, XVI, 701–11.

30. C. E. Mangels, "Relation of Water Absorbing Capacity of Flour to Protein Content, Baking Quality, and Loaf Weight," *ibid.*, January 1928, V, 75–77.

laboratory baking the measurement of yield of bread is complicated and interfered with by the variations in loaf volume, and by difficulties in uniformly baking the various-sized loaves involved.

Since the gluten of flour evidently requires more water than does starch to yield a mixture of unit plasticity, it has been assumed that absorption might be positively correlated with gluten or protein content of flour. The data of Near and Sullivan (26), as computed by Merritt, supported such an assumption. Mangels' values for the coefficient of correlation with absorption and protein content as the variables were not high, in the instance of the samples involved in the 1923–26 crop seasons to which reference has been made. Thus r ranged from 0.095 ± 0.040 (1926) to 0.275 ± 0.038 (1925) in these four seasons. It is possible, however, that all of Mangels' doughs were not adjusted to the same actual viscosity, since if his experience with the doughs was similar to that of Merritt and Bailey (27) it may be that the low-protein flours were converted into more mobile doughs. In that event, the effect would have been to reduce the correlation between protein content and absorption as measured by the baker's experience rather than by a constant η.

Singh and Bailey (31) observed a higher correlation between water absorption and protein content of flour, viz., $r = +0.67 \pm 0.066$, in the instance of a series of Punjab wheats recently studied. Such differences in findings are not altogether surprising, however, since much depends upon the range of flour types represented in the series involved in individual studies.

The discussion of absorption would not be complete without including reference to a hypothesis which endeavors to account for the fate of the added water. As in the instance of many other complex gels, a flour dough includes several hydrophyllic substances. Prominent among these are the flour proteins and starch, although the actual behavior of these may be influenced if not largely controlled by the amount and kind of various ions, the level of pH, the lipids, and the degree of degradation effected by proteases and amylases during mixing and fermentation. It seems probable that at least a portion of the water used in preparing the dough becomes "bound" by these hydrophyllic substances, and hence is not free to function as a solvent for the various water-soluble solutes, such as salts and sugars, in the dough. Consequently the concentration of these solubles in the "dough-solution" is higher than would be estimated from the total water known to be present in the system, since only a portion of the latter is "free" to serve as a solvent.

Certain of the investigations of water-binding capacity of the flour colloids that were made with highly diluted or mobile flour suspensions are scarcely valid as quantitative indices of the water bound in an ordinary dough. Measurements in the latter medium are not easy to make. Skovholt and Bailey (32) applied the conventional cryoscopic method to bread doughs, and estimated that 42–45 units of water were bound by each 100 units of dry matter in flour. Consequently all water present in excess of that ratio was assumed to function as solvent for the water-soluble dough solutes.

More recently Vail and Bailey (33) applied a comparatively new technique to the measurement of the freezing-point depression in doughs containing varying proportions of added sucrose (sugar). The doughs were frozen, and then the temperature was noted at which their dielectric properties changed substantially when the ice in the dough melted. It seems probable that the data thus secured are freer from errors than those based upon the older freezing-point determination. On the basis of such data it was estimated that about 29 per cent of bound water was held by the dry matter of dough. This would imply that more free water functioned as solvent in the dough solution than was originally assumed.

31. Rattan Singh and C. H. Bailey, "A Biochemical and Technological Study of Punjab Wheat Varieties," *ibid.*, 1940.

32. Oscar Skovholt and C. H. Bailey, "Free and Bound Water in Bread Doughs," *ibid.*, July 1935, XII, 321–55.

33. Gladys E. Vail and C. H. Bailey, "The State of Water in Colloidal Gels. Free and Bound Water in Bread Doughs," *ibid.*, 1940.

II. PHYSICAL TESTS OF CRUDE GLUTEN

Expansion by Heat

Boland (34, 35) appears to have designed the first device for quantitatively estimating the expansion of moist crude gluten when heated, which device he termed the "aleurometer." Provision was made for a metal cylinder which could be lowered into a heated oil bath maintained at 150° C. Gluten was washed from 30 g. of flour in the usual manner, and lowered into the closed lower end of this cylinder. A metallic piston provided with a graduated stem was placed upon the wet gluten. The latter was allowed to expand under the influence of the heat of the bath for 10 minutes, the position of the graduated cylinder noted, and the gluten removed from the device. The relative expansion of a series of glutens so tested was reported by Boland to range from 29 to 50 "degrees" on his empirical scale.

Many years later, Maurizio (36) reviewed the experiences of Kreusler, Maercker and Beseler, Thomas, Thubert, and Boutroux, as well as his own which led to rather unfavorable impressions of the aleurometer.

Kunis's "Aleurometer" or "Klebermesser," as described by Nobbe-Tharand (37) apparently followed the design of the Boland instrument and was applied in a similar manner.

Liebermann's (38) device was described briefly by Neumann (39). Apparently the moist gluten was immersed in oil, in a chamber provided with a graduated neck so designed that when the oil bath was heated to 170° C. the ascent of the oil in the neck could be measured and recorded as the displacement of the expanded gluten. Neumann commented that the method is so full of errors as to make the resulting measurements of doubtful value.

Foster's (40) gluten tester or aleurometer described by Wiley *et al.* (41) also was essentially similar to Boland's aleurometer, except that it made provision for testing two samples at the same time, and the cylinders were designed to be heated in an air oven instead of an oil bath. Glutens washed from 50 g. of flour were placed in the bottoms of each of the greased cylinders (Fig. 4), the piston lowered over the gluten, and a weight (apparently of about 100 g.) placed on top of the piston rod. The entire device was then transferred to a heated oven at a temperature of 450° F. (232° C.) and baked for 20± minutes. The crisp, baked glutens were then removed, and their length measured as an index of relative quality. They could also be weighed, or further dried to constant weight and weighed, and the quantity of crude gluten be thus determined.

Recovery from Compression

Matejovsky (42) designed an apparatus for determining the relative elasticity of moist crude gluten. A quantity of the crude gluten ranging in weight between 2.5 and 3.5 g. (the exact quantity not being important) was placed upon the lower of two disks. The upper disk was then lowered by an appropriate mechanism until it made contact with the rounded mass of wet gluten. The position of an indicating needle on the face of the graduated dial was then read (A). The weight of the disk and its

34. Boland, "Mémoire sur les moyens de reconnaître et d'apprécier les propriétés panifiables de la farine de froment à l'aide de l'aleuromètre, instrument inventé par M. Boland, ancien boulanger à Paris," *Bulletin de la Société d'encouragement pour l'industrie nationale,* 1848, XLVII, 704–09.

35. Boland, "Verfahren die relative Tauglichkeit des Weizenmehls zum Brodbacken mittelst des Aleurometers zu bestimmen, eines von dem Bäckermeister Boland in Paris erfundenen Instruments," *Dinglers polytechnisches Journal,* 1849, CXI, 117–23.

36. A. Maurizio, "Die Backfähigkeit des Weizens und ihre Bestimmung," *Landwirtschaftliche Jahrbücher,* 1902, XXXI, 179–234.

37. Nobbe-Tharand, "Über Mehl-prufungen," *Landwirtschaftlichen Versuches-Stationen,* 1885, XXXI, 184–85.

38. L. Liebermann, "Apparat und Verfahren zur Bestimmung der Qualität des Weizenklebers," *Zeitschrift für Untersuchung der Nahrrungs- und Genussmittel sowie der Gebrauchsgegenstände,* November 1901, IV, 1009–16.

39. M. P. Neumann, *Brotgetreide und Brot* (3d ed., Berlin, 1929), p. 470.

40. Eimer and Amend, "Foster's Gluten Tester or Aleurometer," *Bulletin No. 250,* New York.

41. H. W. Wiley *et al., Foods and Food Adulterants, Part Ninth: Cereals and Cereal Products* (U.S. Dept. Agr., Div. Chem., Bull. 13, Part IX, 1898), pp. 1272–73.

42. K. Matejovsky, "Genaue Bestimmung der Elastizität des Klebers. Ein neuer Apparat und seine Anwendung," *Das Mühlenlaboratorium,* 1937, VII, 163–67.

supports, amounting to 7 g., was then placed upon the gluten for a unit time, which served to compress the gluten and stretch it laterally. The weight was then removed, and the final position of the scale was read (B). The gluten could be rounded up and the test repeated. Matejovsky recommended triplicated measurements. The final calculation, based upon

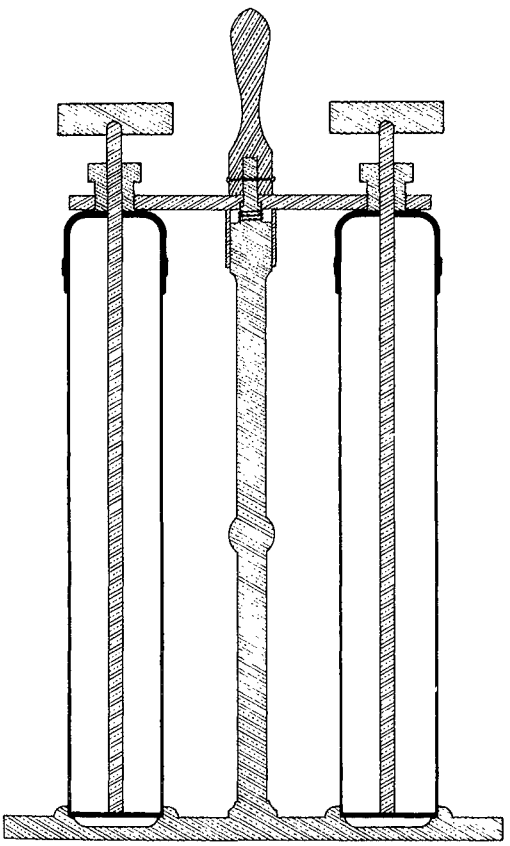

FIG. 4.—Foster gluten tester

the average of the several sets of readings, takes the form of dividing the first or original reading into the last or final reading thus:

$$\text{Elasticity} = \frac{\text{final scale reading } (A)}{\text{original scale reading } (B)} \times 100.$$

Values ranging from 39 to 67 per cent were reported upon a series of 13 flour samples, and it appeared that the values thus secured were in fair agreement with the results of baking tests of the same samples.

Auerman (43) described an elastometer which appears to be essentially similar to Matejovsky's instrument for measuring elasticity of gluten. A sample of the wet crude gluten was placed on the center of a round metallic table. By means of a knurled knob the table was raised until the gluten just touched a round disk situated above it, and its thickness or height registered on a scale (h). By pressing a handle, constant pressure was applied upon the upper disk and the gluten squeezed to a certain size, h_2. Pressure was maintained for 10 seconds, and then released, and the gluten allowed to relax. The height of the gluten was then noted (h_3). The regain in height, i.e., the final height (h_3) minus the height when compressed (h_2), was recorded, and this value divided by the original height (h_1) was computed as the measure of elasticity $\frac{h_3 - h_2 \times 100}{h_1}$. The magnitude of this elasticity index was found to range from 0 to 65 per cent.

Krtinsky (44, 45) described his elastoscope for mechanically measuring the elasticity of gluten. The latter was placed on a platform, and a certain force applied to its surface by means of a disk attached to the outer end of a weighted lever. Then the weight was removed, and the elastic recovery of the gluten was registered on a scale. A second instrument called the fortiscope was also described. It provided means for inflating a bubble of gluten, measuring the force required to effect its extension (*Festigkeit*) and the magnitude of extension at the time of rupturing (*Dehnbarkeit*). Each of these three characteristics was rated on a scale of 5. When combined into a single numerical expression, the latter was found to be correlated with baking quality, and with water absorption. From Krtinsky's diagrams one would conclude that gluten *Festigkeit* was more prominent in determining baking quality than the other characteristics that were measured.

43. L. Ia. Auerman, "The Definition of Gluten Quality by Natural Methods," *Bread Baking Industry* (U.S.S.R.), [translated titles], April 1939, I, 13–15.

44. Karel Krtinsky, "Stanoveri vlastnosti lepku pristroji," *Chemické Listy pro vědu a průmysl*, 1932, XXVI, 611–14.

45. Karel Krtinsky, "Die Prüfung der Eigenschaften des Klebers," *Das Mühlenlaboratorium*, June 1933, III, 97–104.

Extension of Crude Gluten

Hankoczy's gluten tester was described by Kosutány (46) and later by Hankoczy (47). It provided means for pressing the moist crude gluten into a thin sheet between two plates, each having a round opening 2 cm. in diameter in the middle. These plates were then mounted in a device which joined the lower plate with a vessel into which air could be compressed, while the upper plate became part of another vessel from which air would be displaced, as shown in Figure 5. Compression of air in the

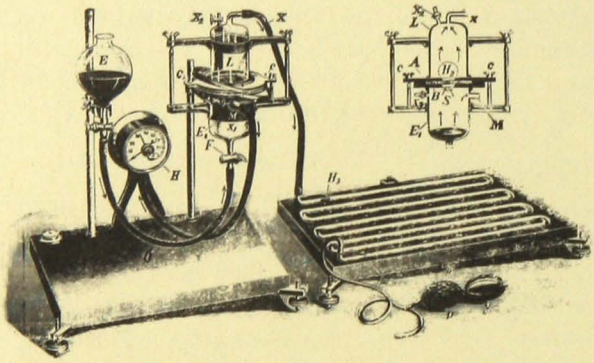

Fig. 5.—Hankoczy gluten tester

lower vessel was effected by introducing mercury from a bulb at the necessary elevation to start the stretching of the gluten. This pressure was noted and recorded. Air displaced from the upper cylinder, in consequence of the expansion of the gluten bubble into it, was measured by means of the simple gasometer shown in the illustration. The maximum volume attained by this gluten bubble before it burst could be thus measured. The last model of the Hankoczy gluten tester also provided means for automatically recording, on a chart, the pressure and the extension of the gluten.

Hankoczy reported the ductility ("Dehnbarkeit") of a series of glutens from different wheat types through a range of from 5 to 80 cm.^{3}, and the force required to extend them ranged from 0 to 29 mm. (mercury head).

Kress (48) described a simple device designed by James for testing glutens. The washed crude gluten was pressed into a disk 1/8 inch thick, and this was clamped between two horizontal plates having 3/4-inch holes through their center. Against the upper surface of the exposed sheet of gluten was placed a round-faced plunger 1/2 inch in diameter, and this was forced downward against the tension of a coiled spring by means of an arm attached to it, at a constant speed of 10 cm. per minute. The force applied in grams, and the distance that the plunger traveled in stretching the gluten sheet to the point where it ruptured, were recorded on a ruled chart by means of an inked stylus. Kress stated that the differences between glutens from various flours were very striking.

James and Huber (49) reported the results of tests made with this device. Gluten washed from Montana dark northern spring-wheat flour required 170 g. to extend it, while gluten from Washington club wheat flour required only 125 g. The distance that the gluten was extended did not vary greatly, however, being 2.5 and 2.2 cm. respectively. Clear grade flour gluten required substantially less force to extend it than was required for gluten washed from the patent flour produced at the same grinding. Normal treatments with NCl_3 and Cl_2, as in flour bleaching and chemical maturing, tended to increase the force required to stretch the gluten.

Barbade's (50) "Aleurographe" is a rather complicated machine for automatically measuring and recording the force required to extend a film or sheet of wet crude gluten and the volume attained by the extended bubble. A piston actuated by a motor, moving slowly through a cylinder, provides the steady flow of air into the chamber under the sheet of gluten which is forced up into another cylinder. Both the pressure and the relative volume of the gluten bubble are recorded on a chart. Crude glutens for such tests are washed automatically from suitable doughs by means of a "Glutex" which is part of the equipment.

46. Thomas Kosutány, *Der ungarische Weizen und das ungarische Mehl* (Budapest, 1907).

47. E. V. Hankoczy, "Apparat für Kleberbewertung," *Zeitschrift für das gesamte Getreidewesen*, 1920, XII, 57–62.

48. C. B. Kress, "Gluten Quality," *Cereal Chemistry*, September 1924, I, 247–50.

49. T. R. James and L. X. Huber, "A Study of the Physical Properties of Washed Gluten," *ibid.*, November 1927, IV, 449–60.

50. Pierre Barbade, "Nécessité de 'mesurer' les qualités du gluten," *Atti del I° Congresso Internazionale di Panificazione*, Rome, 1932, pp. 362–77.

Barbade presented a series of gluten-test curves in comparison with curves resulting from testing doughs by means of the Chopin extensimeter (see Section III). In the instance of four flours milled from widely diverse types of wheat, there appears to be a general correlation between the two sets of data.

Munz (51) communicated privately the description of a gluten-testing device as yet unpublished. Emphasis is laid upon the necessity of preparing uniform pieces of gluten for the determinations of stress-strain relationships. A gluten-washing machine was used to separate crude gluten from a simple flour or wheat-meal dough. The latter was used when tests were applied directly to wheat. The dough is prepared with a 2 per cent NaCl solution, and is allowed to stand for 30 minutes after mixing, before the gluten washing is begun. The washed gluten has the excess water removed by pressing ten times between dried glass plates, and two portions weighing 1.6 g. each are rolled into cylinders and placed in a lacquered brass pan (at *O* in Fig. 6). The pans are slightly oiled in advance to prevent sticking. The pans containing the gluten are covered, and immersed in water for one hour at 29° C. During this time the gluten assumes the shape of the vessel, and also relaxes from the tension to which it had been subjected in forming it into cylindrical shape.

At the end of the hour of rest, Munz removes the gluten to the clamp (*N* in Fig. 6) made of hardwood, to which the gluten adheres better than to metal. The clamp is then placed upon the top of the water-filled thermostat (*K*), which is so arranged that the gluten strand is completely immersed. The hook at the top of the weight (*I*) is slipped over the gluten strand, and the latter is thereby extended downward through the water in the bath under the equivalent of a weight of 20 g. Its rate and extent of progress is recorded by the stylus (*E*) upon the chart (*A*), which is rotated by a kymograph clock (*D*).

A typical diagram resulting from a gluten test by the Munz procedure is shown in Figure 7. The portion of the curve marked *A* involves a decreasing rate of extension of the gluten strand. Portion *B* is plotted while the extension proceeds at a uniform rate. In portion *C* the extension rate is accelerating and at point *D* the strand has severed. It is assumed by Munz that elastic properties of the gluten strand are manifest during the early period of extension (*A*), while subsequently plastic flow is involved through portion *B* of the curve. When portion *C* is entered, gluten fibrils may have begun to rupture, which ultimately results in a complete severance of the strand at *D*.

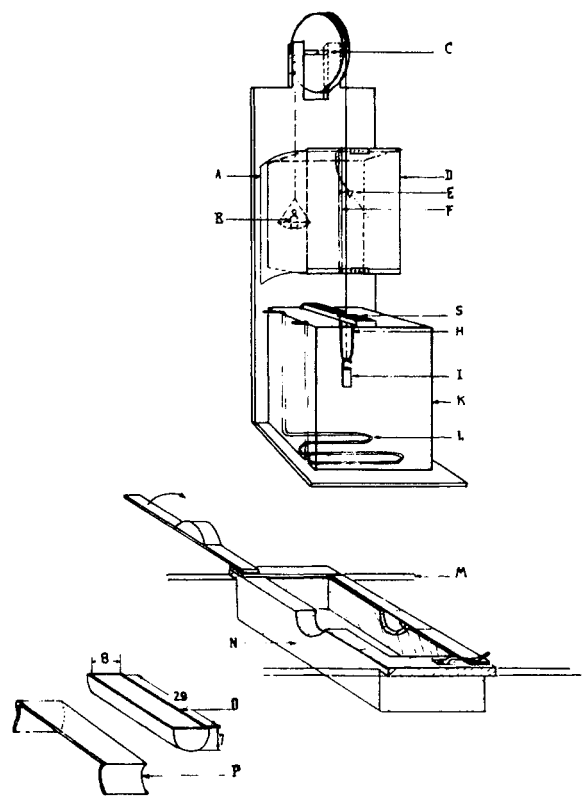

FIG. 6.—Diagram of Munz gluten tester

Extensibility is expressed as the vertical distance from the beginning of the curve to the intercept of tangent *t* with time *D* plus half the distance from the latter point to point *D* where the gluten strand broke. It was observed by Munz that practically all of his gluten preparations could be stretched to 12 cm., or 8 times their original length. Accordingly it appeared desirable to begin the classification of extensibility at this point. Very

51. Emil Munz, "Determination of Gluten Quality" (1939). Privately communicated from his laboratory at Bottighofen, Thurgau, Switzerland.

extensible glutens could be extended to 25 times their original length. On allowing for the experimental error of such measurements, it appeared feasible to divide this interval (from 8× to 25×) into ten classes when duplicate tests are made.

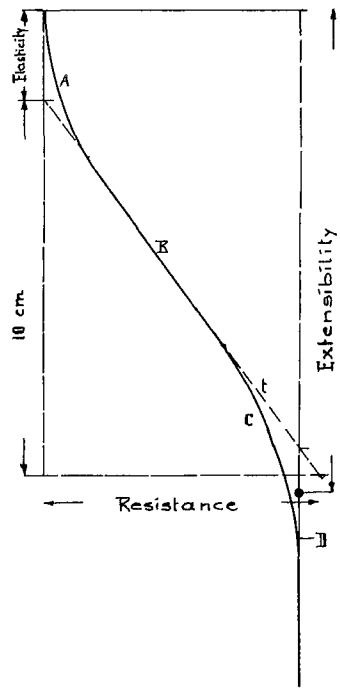

FIG. 7.—Schematic diagram of the result of a test of gluten made with the Munz device diagrammed in Figure 6

Resistance to extension is expressed by the slope of the tangent (t). On the chart this is indicated graphically by the time from the beginning of the test to the estimated time represented by the intercept of the tangent (t) with a horizontal line representing a gluten extension of 10 cm. (see Fig. 7). Again, as in the instance of extensibility, it is convenient to divide glutens into ten classes on the basis of resistance which, however, was not uniformly spread as were the extensibility classes. This was necessitated by the fact that when flours were blended, the resulting resistance was not the arithmetic mean of their individual resistance values. Accordingly the classes were enlarged progressively using the formula

$$a + (a + b) + (a + 2b) + (a + 3b) + \ldots . (a + [n - 1]b)$$

where $a = 15$ mm. resistance on the graph paper or 30 seconds and $b = 8$ mm. resistance on the graph paper.

A consolidation of data thus computed, with resistance and extensibility expressed in classes (R = resistance to extension), for a number of flour types is recorded in Figure 8.

Kosmin (52), in her studies of the relation of various flour characteristics to the properties of gluten, indicated graphically the substantial differences in ductility of her gluten preparations. These gluten tests involved forming a rounded ball of the wet crude gluten, attaching a 2 g. weight by a wire hook to the under side, supporting the upper side by a similar hook attached to a fixed or rigid support, and then noting the relative elongation of the gluten with the lapse of time through, say, 1½ and 3 hours.

Kranz (53) elaborated upon this idea, and suggested supplementary equipment and operating details, providing a fairly simple procedure so that the Kosmin-Kranz method has had considerable application in portions of Europe. Kranz emphasized the necessity for a standardized gluten-washing practice, including composition of the wash water, temperature, and mechanical treatment. The latter has been facilitated recently by providing a gluten-washing machine. He recommended washing out the nongluten material from a dough with 2 per cent NaCl solution at 18° C. for ten minutes.

The last portions of the starch were removed by hand manipulation until the wash water was clear. Excess water was then removed by pressing between glass plates. Then a 2 g. portion of the gluten was weighed off and rounded into a ball. This was suspended upon a small hook attached to a fixed support, and a similar hook attached to a 4 g. weight was inserted through the lower portion of the gluten ball. Each hook was inserted about one-third of the distance across the diameter of the gluten ball. A glass tube of suitable length (35 cm.) was then brought up around

52. Natalie P. Kosmin, "Reifung der Weizenmehle und ihre biochemischen Grundlagen," *Das Mühlenlaboratorium*, February–March 1934, IV, 17–32.

53. W. Kranz, "Kleberdehnbarkeit, Messmethode und Verhalten bei der Weizenkonditionerung," *ibid.*, November 1935, V, 161–66.

the gluten ball. This tube was filled with 2 per cent NaCl solution at 25° C., and the arrangement was then such that the gluten mass could elongate under the force of the attached 4 g. weight and thus be stretched downward through the saline solution. Graduations alongside of the tube made it possible to measure the elongation of the gluten with time. An assembly of several such tubes in a thermostat at 25° C. made it possible to conduct several comparative tests at the same time.

Kranz divided glutens into five groups based upon their behavior when thus tested. These ranged from (I) glutens which retained their original form for 2 hours, to (V) glutens which elongated rapidly and promptly tore apart. It was observed that superior, strong hard spring wheats yielded glutens of type I, superior domestic (German) wheats were of type II, while winter wheats of the 1934–35 crop belonged in types III to V.

Kranz also demonstrated with graphs the effect of properly controlled heat conditioning of wheat upon the ductility ("Dehnbarkeit") of gluten. Thus the winter wheat included in his studies disclosed a progressively reduced gluten ductility (presumably an improvement) of substantial magnitude by heat-conditioning treatments at 45°–55° C. Summer (spring) wheat, on the other hand, was affected only slightly, and no more at the higher temperatures than at 40° C.

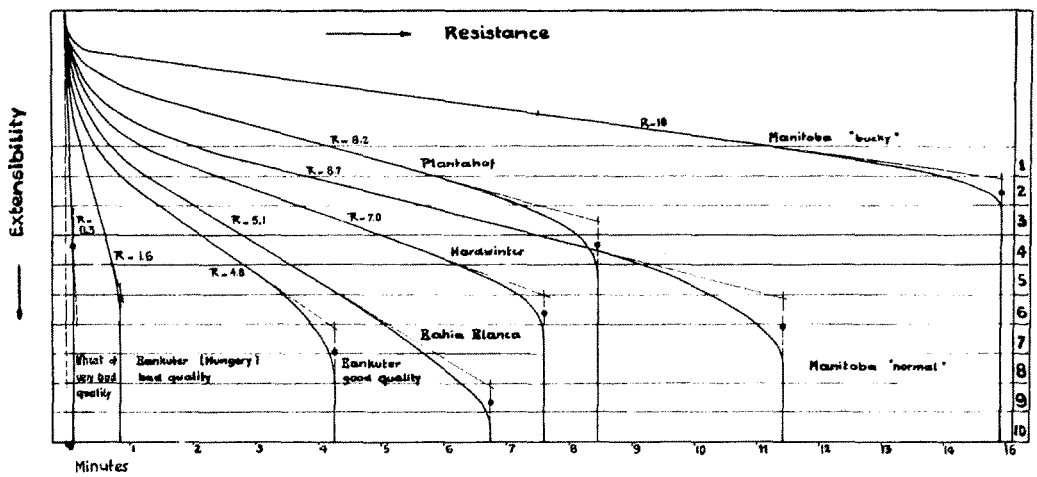

FIG. 8.—Consolidation of gluten extensibility and resistance data as determined with the Munz gluten tester, and expressed in classes for a number of flour types

Galter (54) proposed certain improvements in the Kosmin-Kranz technique, particularly in the matter of forming the original gluten mass. Galter objected to the hand manipulation involved in shaping the gluten ball, and suggested forming a gluten strand extruded through a 3 mm. aperture in a syringe. This was suspended in a suitable glass tube, with a 1 g. weight attached securely to the lower end. The rate of elongation of the gluten is then determined. Galter contends that the Kosmin-Kranz method is not exactly a measure of ductility, but rather is an index of stability, as the latter term implies a resistance to change in form under force.

Galter (54, 55) described an elaboration upon some of the earlier methods for measuring gluten ductility and related properties. He stressed the difficulties attendant upon forming or shaping the gluten mass to which the tests had been hitherto applied, and the consequent variability in replicated tests. His "Gluta-plast-process" involved placing the washed moist crude gluten in a glass-lined syringe having a 20 mm. barrel. This is provided with a metal tip such that a continuous strand of gluten 40 mm. long and 4 mm. thick can be extruded. Apparently this may be in-

54. Eberhard Galter, "Neue Prüfmöglichkeiten für Kleber," *Zeitschrift für das gesamte Getreidewesen*, November 1938, XXV, 217–22.

55. Eberhard Galter, "Die Wiener Kleberreissprobe," *Das Mühlenlaboratorium*, December 1938, VIII, 177–86.

cubated for 20 minutes at 40° C., in a special thermostat designed for the purpose, particularly when proteolytic action is to be measured.

To such gluten strands the "gluten extension test" (Kleber-Extenso-Probe) can be applied by a small testing machine, which has many general points of mechanical similarity, except in size, to the Brabender extensograph described in detail in Section III. Particular emphasis appears to be placed by Galter upon the force in grams required to effect extension of the crude gluten strand. In one series examined the range for different wheat types was as follows (54, p. 220):

Domestic (German) wheat	20 – 190 g.
Hungarian (German Theiss) wheat	40 – 195 g.
Bahia (Argentine) wheat	120 – 180 g.
Manitoba (Canada) wheat	160 – 200 g.

A "force-number" was applied to the results of these tests, with a scale range in which unity was the equivalent of 20 g. With one series of eight samples a high correlation was observed between the values thus determined and the results of farinograph tests (see Section III) applied to dough prepared from the same flours.

The Schopper machine, apparently designed for testing thread or yarn, was adapted by Mohs and Schmidt (56) to the measurement of the force required to extend, and the extensibility of, strands of wet crude gluten. From their data one would deduce that there was a fair correlation between the means of groups of flours of the stretching force as thus determined, the rate of extension of gluten strands as measured by the Kosmin-Kranz technique (which see), and the Berliner swelling number. More *individual* data, rather than means of groups, are needed for the appraisal of such methods. Moreover, a later paper by Mohs, Schmidt, and Frank (57) suggests that the Schopper device gave less satisfactory measurements than the glutograph when the force of extension is compared with baking results. In the case of neither instrument, however, are the recorded data adequate to a satisfactory estimate of these correlations.

A gluten-testing machine having some points of similarity to the Galter and the Munz machines has recently been announced in the advertising of Brabender O.H. of Duisburg, Germany, under the name of the "Glutograph." It has also been discussed by Mohs, Schmidt, and Frank (57). Whereas the Galter and the Munz testers used rod-shaped pieces of gluten, the glutograph is designed to test the ductility and certain other properties of a ring-shaped piece of wet crude gluten. The wet gluten is recovered from a wheat meal or a flour-water paste by a mechanical gluten-washing machine. It is then subjected to a definite pressure at a constant temperature in a special press designed for the purpose. A ring of gluten weighing about 2 g. is then stamped out. The pre-treatment of the gluten, or "homogenization" as it is termed by Mohs *et al.*, is quite definite and detailed. The ring is pressed out under 25 kg. pressure, held at 40° C. in the press for 30 minutes, then discharged and cooled at 18° C. for 20 minutes. Data indicating the effect of variations in this pre-treatment are recorded by Mohs *et al.*

The ring of gluten is then suspended by a hook which, in turn, is attached to a balance or weighing system provided with a recording mechanism. Another hook curved downward engages the lower inner rim of the ring. This is caused to move steadily downward by a motor-driven worm gear, and a curve is drawn by the stylus as shown in Figure 9. It will be noted that the "strong" gluten numbered 1 requires a greater force to extend it, as indicated by the vertical height of the graph. As it is extended, this force rapidly diminishes. Evidently the strong gluten cannot be stretched to the degree that is possible with a weak gluten, as suggested by the difference in the horizontal length of curves 1 and 3 in this figure.

While very limited data respecting the significance of such tests have appeared in the literature, Mohs *et al.* indicate a fair agreement between the glutograms thus obtained and the swelling number of gluten determined by Berliner's method, and with the baking number which involves the size or volume and

56. K. Mohs and E. A. Schmidt, "Eine Methode zur Bestimmung der Dehnbarkeit und Festigkeit des Klebers," *Zeitschrift für das gesamte Getreidewesen*, July 1938, XXV, 125–30.

57. K. Mohs, E. A. Schmidt, and H. V. Frank, "Die Bestimmung der Kleberdehnbarkeit mittels des Glutographen," *ibid.*, January 1939, XXVI, 23–30.

texture of test loaves. One discerns a commendable conservatism in the claims of its manufacturer for the glutograph, who states that it does not measure baking value, but

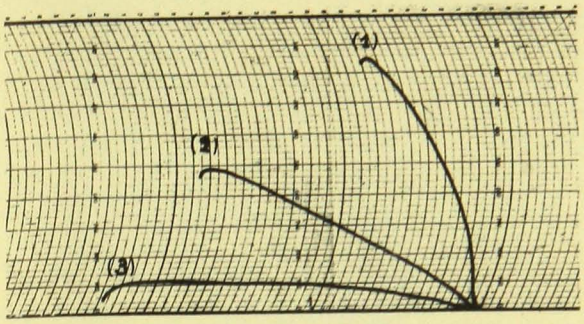

FIG. 9.—Typical glutograms as traced by Brabender glutograph for (1) strong, short gluten, (2) medium gluten, and (3) weak, ductile gluten

may be of service to plant breeders and others who are forced to test small samples of wheat (10± grams), and in investigations where it is desirable to separate the gluten and determine its properties apart from the other materials comprising flour or dough.

DISCUSSION

It is not surprising that efforts have been made to measure quantitatively the physical properties of gluten. Not only are the properties of gluten unique among the plant proteins, but there is evidence that many of the significant properties of dough are the consequence of the presence of gluten.

One vexing problem always presents itself to those conversant with protein problems, viz., the difficulties involved in removing gluten from a flour dough without altering its properties. Moreover, it has become increasingly apparent with the growth of our knowledge that certain observed characteristics of wet crude gluten are reflections of its environment. Accordingly, one is none too certain that crude gluten removed from dough by the conventional washing processes, mechanical or manual, actually retains the characteristics that it possessed while in, and hence imparted to, the dough.

The argument that it is often desirable to know what characteristics are possessed by a prominent component of a complex mixture, separate and apart from the other constituents, is a valid one. However much this is to be desired, the fact remains that it is difficult of attainment with existing facilities for effecting the separation of unaltered gluten from dough.

The argument may also be advanced that it is the dough with which we are actually concerned in bread making, rather than any single dough constituent or group of them. Accordingly our attention may profitably be directed to the properties of the dough itself, so long as we can proceed to analyze our findings intelligently. There may be occasions when we will do well to attempt to examine the constituents separately in an effort to learn more concerning the sequence of actual events in some manipulation. But it will probably become necessary to return to the dough itself before the true significance of such manipulation will be disclosed in the form in which it registers in the bread.

American cereal technologists, with a few exceptions, have in recent years turned away from the study of crude gluten, its quantity, and properties. Most of the contemporary studies are going forward in European laboratories, where crude gluten still attracts much attention. If an effort is to be made to appraise the properties of crude gluten as washed from dough, the efforts to devise testing machines may be fully justified. Then it should follow that a truly objective approach may be made to the analysis of the findings of such tests, but as yet adequate data have not been presented in the literature to permit of such an analysis.

III. PHYSICAL TESTS OF WHEAT FLOUR DOUGH

The mechanical testing methods applied directly to wheat flour dough have been many and diverse, and have been described under several names. Two general types of methods have been most prominent among them. These are: (1) the recording dough mixers such as the Hogarth mixer with recording dynamometer, the Hankoczy-Brabender farinograph and

valorigraph, the Swanson-Working recording dough mixers in the original large size and the more recent "micro" sizes, and the Malloch machine, also designed for small samples; and (2) those which are concerned with an effort to measure extensibility and resistance to extension, such as the Rejto "Zerreiszmaschine," the Chopin "extensimeter," the Naszalyi "alphitograph," the Buhler "comparator," the Borasio and de Rege "pneumodynamometer," the Schofield and Scott Blair "extensimeter," the Geoffroy "dilatomètre," the Issoglio "isterometer," the Brabender "extensograph," and the Halton and Fisher apparatus for measuring viscosity and tearing properties of dough.

Various other mechanical testing systems not directly included among the two foregoing types have been applied to dough. These include the scheme used by Schofield and Scott Blair for measuring rigidity modulus or elasticity, the pachimeter for a somewhat related application, Kosutány's "Belastungsprobe" or load test, Engledow's "distensometer," and others.

These devices will be described and, in several instances, illustrated in this section, and certain general conclusions respecting physical tests of dough will be included in the discussion at the end.

Recording Dough Mixers

James Hogarth (58) of Kirkcaldy, Scotland, was granted a United States patent for a mechanism for testing and recording the properties of flour which appears to have anticipated certain fundamental characteristics of several of the devices which made an appearance considerably later. Strangely enough Hogarth's invention attracted no interest at the time. So far as the author can learn, no reference was made to it in the literature between 1892 and 1930, nor were any results published based upon its application to flour testing. It was not until new models of recording dough mixers began to make their appearance during the past decade that the Hogarth patent turned up. Yet in a series of twelve plates and the attached specifications, Hogarth indicates provision for a small dough mixer provided with a dynamometer attached to the drive, and a stylus recording on a chart the force applied at all times throughout an extended mixing process.

In the specifications of his patent Hogarth mentions that provision has been made for measuring "the power of flour to absorb water to yield a dough of a given consistency," and also "the quality of the gluten entering into the composition of any given sample of flour."

Evidently the action of Hogarth's dough mixer must have been very light, presumably in consequence of a low rate of rotation of the mixer arms, since he notes the "loss of tenacity during a long test, say six to twenty-four hours" (p. 3, lines 102–03), and measured the quality of gluten in terms of the loss in tenacity per hour. In present-day types of recording dough mixers the action is so vigorous that the change in consistency *per minute*, rather than *per hour* is observed, and the whole operation is usually concluded in less than a half hour.

Hankoczy's succession of machines for determining water absorption, as described by Tibor (59), included devices which may have been used to observe progressive changes in dough consistency, although the evidence in the literature on this point is not entirely clear. Presumably the attention of Hankoczy and his colleagues was not strongly attracted to this possibility until the torsion dynamometer was attached to the dough mixer. This was early provided with a recording device, from which the curves began to appear that were later referred to as farinograms. Brabender, who operated a technical and scientific instrument factory in Duisburg, Germany, then began to elaborate upon the earlier Hankoczy machine, and, in addition to certain refinements of construction, provided it with a unique type of dynamometer, based upon the force applied through a constant-speed synchronous motor. This was first offered under the name of the Hankoczy-Brabender "farinograph," as manufactured in Germany. It also was developed in somewhat different form by Erdely and Szabo of Budapest and

58. James Hogarth, "Mechanism for Testing and Recording the Properties of Flour" (U. S. Patent 474,636, May 10, 1892).

59. Istvan Tibor, *A Buza- és Lisztminőségvizsgálatok* (Budapest, 1933).

called the "valorigraph," and the author understands that a similar instrument was manufactured and sold by a Belgian firm. At the moment no results of tests conducted exclusively with the last two instruments are available to the author.

The first farinographs offered for sale did not provide means for removing the heat of friction and of hydration from the dough during the mixing operation. In a study conducted by Skovholt and Bailey (60) a progressive decrease in "consistency" (better described as an increase in mobility) with rising temperature between 21° C. and 32° C. was graphically demonstrated. In general a "slack" dough (340 ± farinograph units) would increase in mobility by 12 ± units when the temperature was elevated through 1° C., while "stiff" doughs (670 ± units) increased about 40 ± units on a like increase in temperature.

In consequence of the prominence of temperature as a variable in such measurements, the later models of the farinograph provide a water jacket for the dough mixer, so arranged that water at constant temperature can be circulated through it. While this does not maintain an absolutely uniform temperature in the dough during the mixing operation, it is a decided improvement in design.

Since this principle of dough testing is to be discussed in some detail, a list of the essential parts of the farinograph in its present form, as illustrated in Figure 10, is necessary. It includes: (1) A water-jacketed dough mixer. This may be had in two sizes, for (*a*) 300 g. flour and (*b*) 50 g. flour. In fact, one model is so designed that either size of mixer may be used by making certain other adjustments in the recording mechanism. The blades of the mixing machine are mounted on two shafts which rotate toward each other with a differential of 3 to 2. Accordingly the power required to move these mixing arms changes through a cycle of several phases, which depends upon the changing relation of one set of mixing blades to the other set. This results in an irregular curve when the force exerted by the power supply is plotted graphically. (2) A dynamometer which is part of a synchronous constant-speed 3-phase A.C. motor. (3) High-grade bearings. (4) A lever system for amplifying the movement of the registering dynamometer and transferring this to the indicating and recording systems. (5) A damper to reduce the vibrations of this

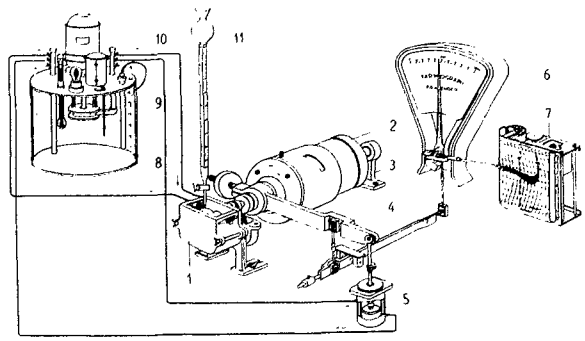

FIG. 10.—Schematic diagram of the Brabender farinograph

registering member. (6) A registering instrument which indicates the relative force applied by the driving mechanism at any instant of time. The force is expressed as grams at 20 cm. radius. (7) A recording system comprising a kymograph and inked stylus for drawing the farinogram. (8) A water thermostat which contains water at a constant temperature that is circulated through the jacket of the dough mixer and is provided with: (9) electrical heating elements, controlled by (10) a thermoregulator. (11) A special burette of large capacity, for measuring the quantity of water used in preparing the dough.

In using the farinograph it is best to have both flour and water at about the temperature desired in the dough itself, i.e., at the setting of the water thermostat. As was indicated in Section I, one of the principal applications of the recording dough mixer is to measure the relative plasticity or mobility of the dough, and, to be at all precise, this must be done at a constant temperature.

Since the first commercial exploitation of this device about ten years ago, it has natu-

60. Oscar Skovholt and C. H. Bailey, "The Effect of Temperature and of the Inclusion of Dry Skimmilk upon the Properties of Doughs as Measured with the Farinograph," *Cereal Chemistry*, September 1932, IX, 523–30.

rally followed that widely varying views have been expressed concerning its usefulness in testing flour and doughs. In the early 1930's, the significance of farinograms was sometimes overstated. With the lapse of time, and the experience that has been gained, increasingly conservative and more acceptable interpretations of the farinograms have made their appearance in the literature.

To begin with, it seems obvious that the *farinograph does not actually measure those dough properties which are of primary significance in baking.* Thus, at one time it was proposed that the *width* of the farinograph curve, as drawn by a properly calibrated farinograph, indicated the actual *elasticity* of the dough; but that interpretation has been largely laid aside.

As Markley and Bailey (61) showed, the width of the line is a function of mobility of the dough, the relation being slightly curvilinear when extended through a large mobility range. Also Markley's (62) wheat starch–water pastes gave wide farinogram lines, yet such pastes possessed little tensile or shearing elasticity. At no time has it been suggested that the farinogram actually disclosed certain other physical properties which probably determine the behaviors of dough in actual baking, such as modulus of elasticity, ductility, and tensile strength. The characteristics of the farinogram may be correlated with certain of these properties, although, as will be indicated later, there are specific instances when such correlations are not apparent.

Aside from indicating that complex property commonly termed "consistency," the farinogram has been employed by technicians as an index of two dough characteristics which are of concern to the baker, viz., (*a*) the relative time required for dough formation, or optimum mixing time, and (*b*) dough stability in mixing, or mixing tolerance. These are separate characteristics.

a) The first is indicated on the farinogram (see specimen curve in Fig. 11) by the slope

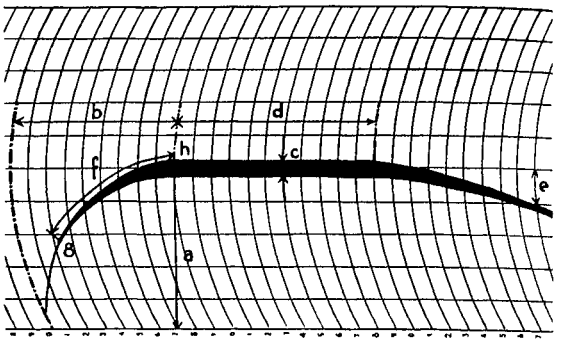

FIG. 11.—Schematic farinogram

of the first or ascending portion of the curve: i.e., by the time required to reach the peak or maximum consistency. Incidentally, it was the experience of Stamberg and Bailey (63) and others, who have given careful attention to this technical detail, that doughs are really overmixed when the farinogram curve has reached its peak, and that better bread will result if the mixing is arrested somewhat short of that stage. There may be a sufficiently constant ratio between the time required to reach the peak of the farinogram and the true optimum mixing time, so that the former may be used as a basis for the reasonable approximation of the latter. Care must be taken in interpreting the farinograms in this connection, however, since not all of them are as simple and easy to read as the type curve presented here. Thus if a dough becomes "sticky" or adhesive in the mixing operation, it may register a false maximum consistency. Fortunately this condition of the dough can be discerned by the skilled technician, who can thus avoid an improper use of the curve.

Using a Hobart dough mixer, Stamberg and Bailey (63) found that when the speed of the mixing arm progressively increased, the time required for optimum mixing treatment was shortened. Moreover, the total work-input, measured in watt-hours, was nearly the same for optimum mixing, regardless of mixer speed, when the latter was varied as much as

61. Max C. Markley and C. H. Bailey, "The Colloidal Behavior of Flour Doughs. II. A Study of the Effects of Varying the Flour-Water Ratio," *Cereal Chemistry*, May 1938, XV, 317–26.

62. Max C. Markley, "The Colloidal Behavior of Flour Doughs. I. The Thixotropic Nature of Starch-Water Systems," *ibid.*, May 1937, XIV, 434–36.

63. Olof E. Stamberg and C. H. Bailey, "Relationship of Mixing Speed to Dough Development," *ibid.*, November 1938, XV, 739–48.

400 per cent. The work-input varied substantially for different flours, however, being greater for strong than for weaker flours. While the mixer used in these studies was quite different in construction from the Brabender farinograph mixer, it is probable that the same general principle applies in dough mixing regardless of the type of mixer.

b) Dough stability or mixing tolerance is generally interpreted as that interval in sustained dough mixing (measured either in time, or in number of revolutions of the mixing blades) through which there is little change in consistency. To the baker, this property of dough is important, since it indicates the degree of precision which he must employ in conducting the mixing operation. Thus with a dough possessed of low mixing tolerance, there is the hazard of overmixing, which for obvious reasons imposes greater difficulties in practical baking operations.

There has been extended discussion in the literature, as well as elsewhere, of the significance of other features of the farinograph. Thus in the later portions of the curve, drawn after it passes through the maximum in terms of consistency, wide variations in its characteristics are disclosed (see specimen farinograms in Fig. 12). One extreme condition is represented by the "strong" curve at the right, which maintains a constant consistency for an extended mixing treatment. The other extreme is the "weak" curve at the left, which approaches a maximum consistency rapidly, and then recedes equally rapidly as mixing continues. Many stages intermediate between these extremes could be depicted. The issue then arises, how to describe these curves and to evaluate them numerically in interpreting them as a criterion of flour quality.

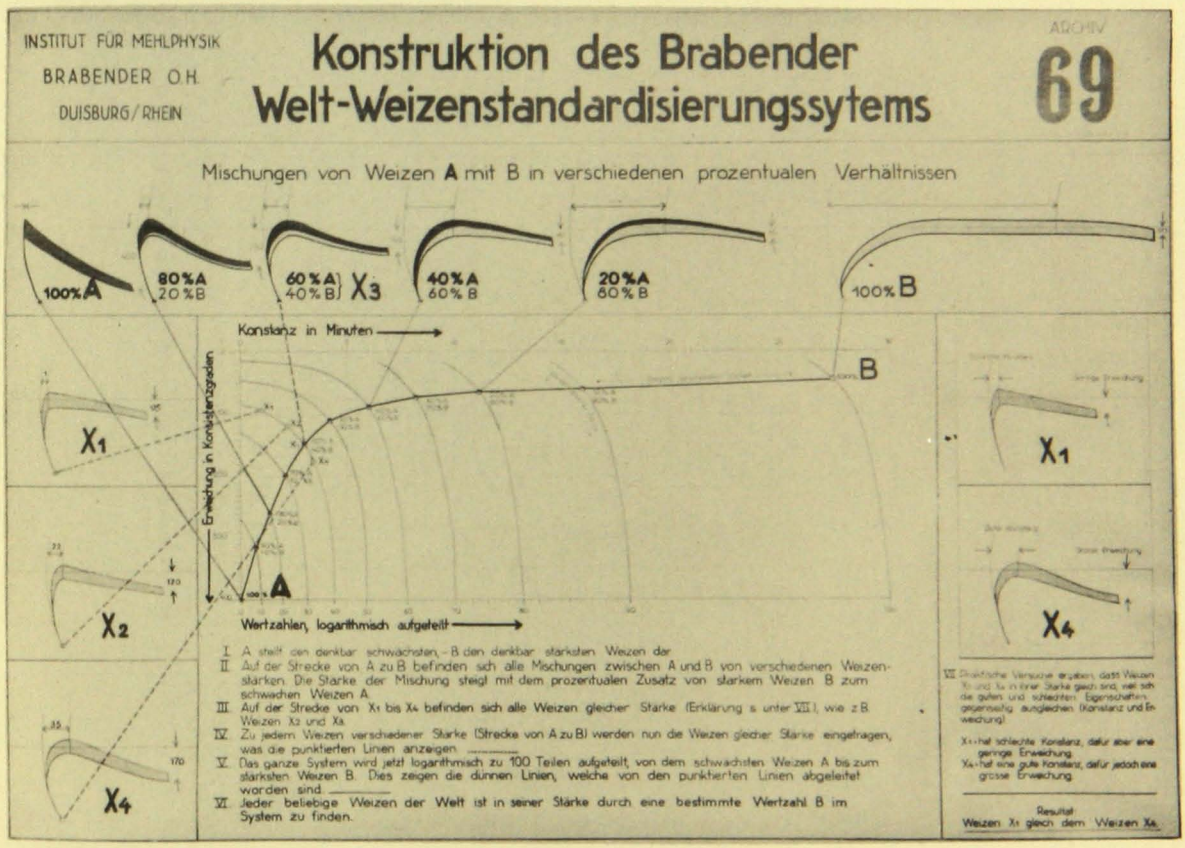

FIG. 12.—Types of farinograms

Early in the use of the farinograph in the author's laboratory at the Minnesota Agricul-

tural Experiment Station, a simple mathematical treatment of the farinograms was evolved. Beginning at the point of maximum consistency (or minimum mobility), the departure of the curve from the maximum was measured at intervals of one minute for 12 minutes, and these values were summated. This is essentially equivalent to measuring the area of the surface bounded below by the center of the curve, above by a horizontal line projected from the position of maximum consistency, and extending laterally through the distance on the chart representing 12 minutes of mixing. The smaller this value, the "stronger" the dough, as indicated by its mixing stability as defined above. Evidently Hankoczy, Kopetz, and Biechy applied essentially similar measures, differing in each instance in certain details as shown by Brabender (64).

Brabender elaborated upon this idea in his valorimeter to include a consideration of the characteristics of that part of the farinogram which represents the time required to reach and maintain the maximum consistency. This is referred to as the *Konstanz in Minuten* in Figure 13. Twelve minutes later the negative departure of the farinogram from this maximum, or the *Erweichung* (softening), is measured. One then enters the graphic measuring chart along the upper horizontal axis with the first or *Konstanz* value and moves down to the intercept with the *Erweichung* value. Here one picks up the third dimension of the figure represented by the

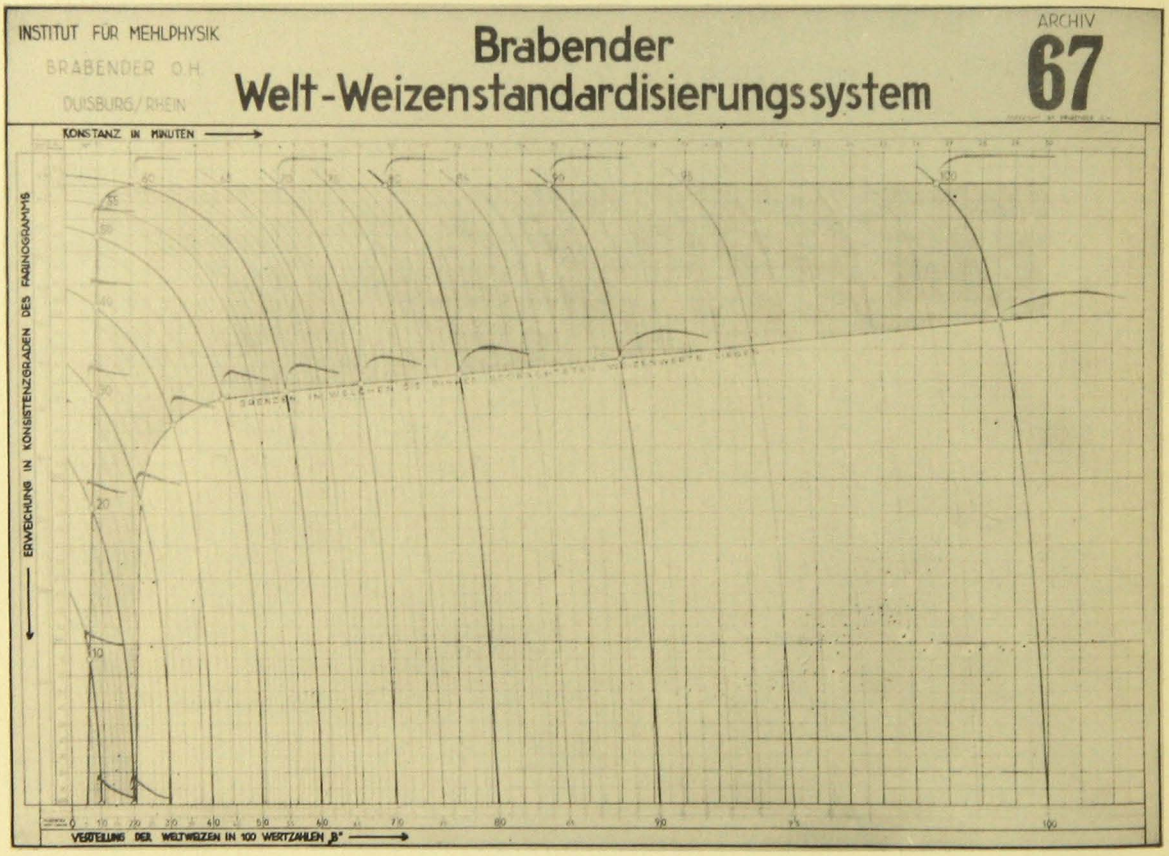

FIG. 13.—Brabender "valorigraph" for determining single figure values from farinograms

64. C. W. Brabender, "Beitrag zur Weizenstandardisierung. Ein Vorschlag für den Weltweizen-Standard," *Foredrag og forhandlinger ved Nordisk Cerealkjemikerforening og Nordisk Cerealistforbund Kongress i Oslo* (Oslo, 1937), pp. 152–63.

exponential curves drawn across the face of the chart, and follows down to the *Wertzahlen* recorded at the bottom of the figure. Thus, for example, if the *Konstanz in Minuten* is 5 minutes, and the *Erweichung* is 100 farinograph units, the *Wertzahl,* or arbitrary numerical expression of strength, is 55. Obviously, as the *Konstanz* increases or the *Erweichung* decreases, the *Wertzahl* increases, although not in simple arithmetical ratio, as is evident from the exponential registration of the curves projected through the third dimension of the figure.

By means of this somewhat elaborate measuring standard Brabender proposed a numerical evaluation of world wheats based upon farinograms. So far as the author is aware, no adequate statistical study of the values thus secured, and the results of comparative baking tests, has appeared in the literature. In this, as in many other appraisals of physical dough tests, broad generalities rather than comprehensive and detailed studies have been employed in attempting to ascertain their validity as a measure of baking qualities. Further reference to this matter will be made in the discussion at the conclusion of this section, where an effort will be made to outline a reasonably objective approach to the consideration of certain types of physical dough tests.

In general, the proportion of water to flour used in preparing the dough is a linear function of the logarithm of time required to reach the point of maximum consistency or minimum mobility in mixing dough in the farinograph, as shown by the detailed studies of Markley and Bailey (61). The same investigators (65) also made a statistical analysis of the data taken from farinograms, analyses, and baking tests of a series of spring-wheat patent flours. The computed coefficients of correlation of certain of these data are recorded in Table 3.

TABLE 3.—COEFFICIENTS OF CORRELATION OF BAKING, FARINOGRAPH, AND ANALYTICAL SCORES, AS REPORTED BY MARKLEY AND BAILEY, 1939*

†	*K*	*E*	*M*	*I*	*A*	*B*	*L*	*J*	*G*
C	+.49	—.50	+.35	+.12	—.27	+.62	—.24	+.82	+.01
K	...	+.29	+.08	—.09	—.02	+.09	—.08	+.33	—.19
E	...	...	—.26	+.10	+.11	—.53	+.22	—.49	—.19
M	...	...	...	+.13	—.02	+.45	—.13	+.49	+.48
I	...	...	...	...	+.62	—.20	—.08	+.01	+.26
A	...	...	...	...	...	—.33	+.73	—.25	+.38
B	...	...	...	...	...	...	—.08	+.49	+.52
L	...	...	...	...	...	...	...	—.33	+.25
J	...	...	...	...	...	...	...	...	—.07

$n = 28$ 5% point = .41

* Reference 65, p. 267.

† *C* = loaf volume, 2 minutes mixing; *K* = loaf volume, 5 minutes mixing; *E* = mixing stability score, a ratio between *C* and *K* together with a score for grain and texture; *M* = absorption in percentage of doughs mixed to a consistency of 550 farinograph units; *I* = gain in mobility or decrease in consistency in farinograph units after 40 minutes mixing; *A* = total gain in mobility in farinograph after 4 hours fermentation of a yeast leavened dough; *B* = the recovery in mobility at 4 hours in farinograph units; *L* = the gain in mobility due to fermentation only or *A–I*; *J* = protein content ($N \times 5.7$) of flour in percentage; and *G* = the maltose number or diastatic activity by the Blish and Sandstedt method.

It is evident that the gain in mobility—or softening action after 40 minutes mixing in the farinograph, i.e., the decrease in farinograph units from the maximum (the latter was commonly 550 ± units)—or *I* was not highly correlated with the baking results *C*, *K*, or *E*. It was significantly correlated with the increase in mobility or softening of the dough during fermentation, $r_{AI} = +0.62$. Actually the protein content was more highly correlated with the loaf volume after 2 minutes or 5 minutes mixing treatment, and with the mixing stability score, than was the farinograph test as here applied. It was also significantly although not highly correlated with "absorption" at 550 farinograph units, $r_{JM} = +0.49$.

Geddes, Aitken, and Fisher (66) recently presented the results of an extended study of the farinograph in testing western Canadian wheats. The following farinogram characteristics were taken from each curve:

1. *Dough development angle.* The angle between the line drawn from the midpoint of

65. Max C. Markley and C. H. Bailey, "The Colloidal Behavior of Flour Doughs. V. Comparison of the Increase in Mobility of Doughs upon Either Prolonged Mixing or Fermentation with the Effects of Varied Mixing Times upon Dough Characteristics," *Cereal Chemistry,* March 1939, XVI, 265–71.

66. W. F. Geddes, T. R. Aitken, and M. H. Fisher, "The Value of the Normal Farinogram for Predicting the Baking Strength of Western Canadian Wheat." Paper read at the convention of the American Association of Cereal Chemists, Kansas City, Mo., 1939, to be presented for publication in *Cereal Chemistry.*

the band at maximum dough development to where the curve meets the 400 consistency unit line and this line. (In certain instances, although not invariably, this might constitute a mathematical expression of Brabender's *Konstanz in Minuten.*)

2. *Weakening area.* The area in square centimeters, as measured by a planimeter bounded by a line drawn from the midpoint of the band at maximum dough development to the end of the curve parallel to the 600-unit line, and from this point down to the midpoint of the end of the curve and returning to the dough development point.

3. *Mean band width.* The total area of the band from the point of maximum dough development to the end of the curve after 15 minutes total mixing, divided by the length of the median line of this portion of the curve.

The correlations of three farinogram constants were determined individually with the protein content of the flour and the loaf volume as observed in baking tests. The resulting coefficients of correlation are recorded in Table 4. From these data it appears that

TABLE 4.—COEFFICIENTS OF CORRELATION (r) OF DATA RESULTING FROM TESTS OF FLOURS MILLED FROM 215 WESTERN CANADIAN WHEATS, AS REPORTED BY GEDDES, AITKEN, AND FISHER, 1939*

	Protein content of flour ($N \times 5.7$),% (P)	Dough development angle, in degrees (A)	Weakening area in cm.^{2} (W)	Mean band width, in cm. (B)
Loaf volume, cc. (L)	+0.903	−0.699	−0.619	−0.167
Mean band width, cm. (B)	+0.222	−0.354	−0.549	.....
Weakening area, cm.^{2} (W)	−0.652	+0.830	.....	.....
Dough development angle, degrees (A)	−0.735	.....	.....	.....

r at 5% point <0.195

* Reference 66.

the weakening area (W) was significantly negatively correlated with the loaf volume, $r_{LW} = -0.619$, although less highly so than the dough development angle, $r_{LA} = -0.699$, or the protein content (positive r), $r_{LP} = +0.903$. In fact, protein content appeared to be a better basis for prediction of baking results than the farinograms in this extensive series of tests. Moreover, the inclusion of the dough development angle, or the weakening area with the protein content, in a multiple correlation with loaf volume did not improve on the simple correlation of protein content with loaf volume. Using partial correlation techniques, with the protein content held constant the correlation of L with A, L with B, and L with W became insignificant and apparently tended to approach zero.

Mean band width was not sufficiently highly correlated with the loaf volume, or with the protein content, to justify attempting to use it in such studies. A small negative correlation was observed with the weakening area, $r_{BW} = -0.549$, the usefulness of which is not clearly apparent.

Within the farinograms there were some significant interrelationships; for example, between dough development angle (A), and weakening area (W), where $r_{AW} = +0.830$. This is interesting in view of Brabender's use of these two, or related constants *Konstanz in Minuten* and *Erweichung* (after 12 minutes), in his valorimeter. If these two constants are so closely related, it might be possible to dispense with the one that is the least accurately measurable and thus simplify the valorimeter; or another third constant might be introduced into the latter, which would increase its significance.

In an extension of this study involving three extensive series, Geddes *et al.* in a private communication, to be included in his publication later, indicated that protein content continued to be highly correlated with loaf volume. One exception was a collection of 48 plant breeders' samples divided into three groups. It was notable in these instances that the variability in protein content among the members of each group was small; accordingly, they may not constitute adequate populations for the measurement of the predictive significance of this variable. Moreover, in such genetic material the protein characteristics may not have been fixed, as in established varieties. In this series there was no significant correlation of the constants from the farinograms and loaf volume.

As in the first study, the relationship between the dough development angle (A) and

the weakening area (W) continued to be fairly high, r_{AW} being +0.822, +0.826, and +0.664 respectively.

In addition to tests applied to rather simple flour-water doughs, the farinograph has been used in testing the progressive changes in the properties of actively fermenting doughs with the lapse of time. Doughs are prepared according to some standard formula, including yeast, and are tested briefly at periodic intervals of, say, one hour, over a normal fermentation period or even longer. Generally the doughs tend to "soften" or become more mobile with the lapse of time during fermentation, as shown by Figure 14. A curve which

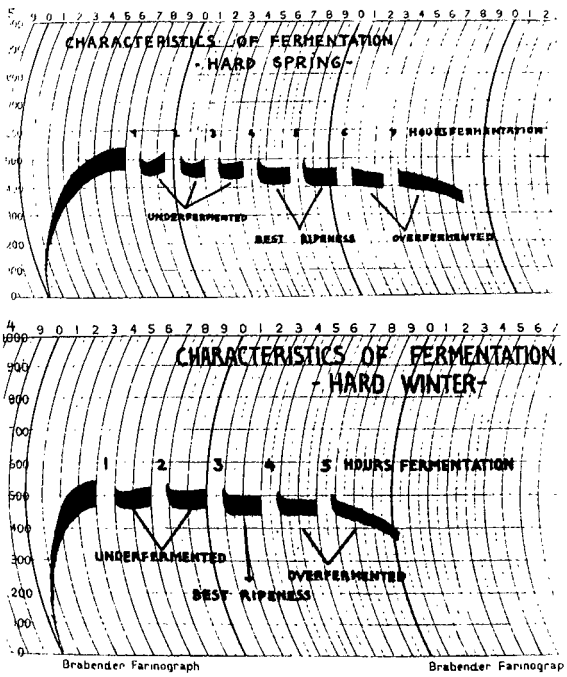

FIG. 14.—Farinograph tests made periodically during fermentation of doughs

records the maximum consistency in farinograph units during each mixing test, plotted against time of fermentation, slopes downward at an angle which, as has been proposed, may be regarded as an expression of stability. Through extended familiarity with such curves it might be possible also to estimate the optimum fermentation time for a particular dough, as deduced from the time required to effect the desired degree of "softening" or "mellowing" as it is known to the skilled baker. This is also suggested by the comments on the farinograms in Figure 14. As indicated already in the Markley and Bailey (65) study recorded in Table 3, the softening action in fermentation or gain in mobility (A) was fairly highly correlated with the softening action on prolonged mixing in the farinograph $r_{AI} = +0.62$, but not with the results of baking tests.

De Wever (67) proposed measuring flour quality V from farinograms by the application of the formula:

$$V = (a + c + e - d)q$$

where

a = percentage water absorption − 50
c = time stability
e = elasticity in millimeters, apparently based upon the width of the farinogram
d = time of dough formation
q = coefficient of weakening (an arbitrary value assigned to the departure of consistency from the maximum in a unit treatment. Thus for 0 departure, $q = 1.00$; for 20, $q = .90$; for 40, $q = .80$; . . . . for 200, $q = 0.00$).

Swanson and Working (68) adapted the dough mixer originally applied by them (69) to the mechanical modification of dough, to a mechanical system which registered and recorded the force applied at all times during the operation of mixing and overmixing a dough. The resulting record, as drawn on a chart, resembled somewhat the farinogram to which extended reference has been made. Thus there was a gradual increase in the force applied as the dough was formed, passing through a maximum and then receding at a rate which depended upon the properties of the flour and other constituents of the dough. The dough mixer employed differs substan-

67. J. de Wever, "Peut-on formuler des données du Farinographe?" *Bulletin de l'école officielle de la Meunerie Belge*, 1939, VI, 2–3.

68. C. O. Swanson and Earl B. Working, "Testing the Quality of Flour by the Recording Dough Mixer," *Cereal Chemistry*, January 1933, X, 1–29.

69. C. O. Swanson and Earl B. Working, "Mechanical Modification of Dough . . . .," *ibid.*, March 1926, III, 65–83.

tially from the farinograph mixer, however. It consists of a vertical cylinder (see Fig. 15), open at the top, and provided with four verti-

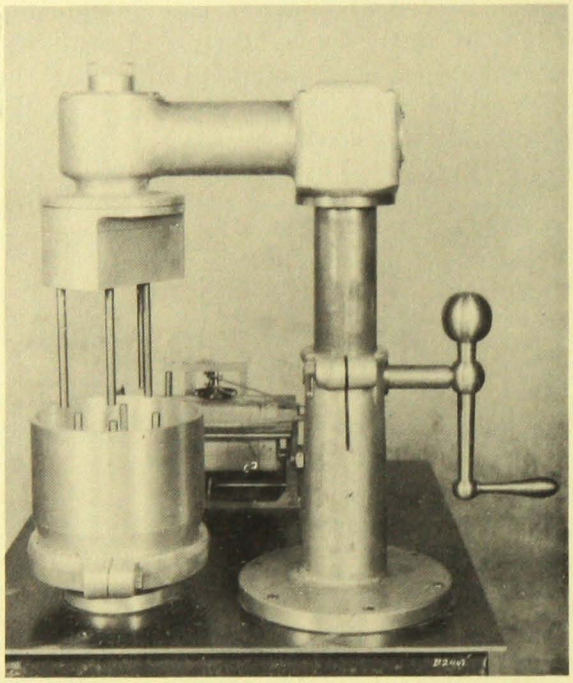

FIG. 15.—Swanson-Working recording dough mixer

cal stationary pins secured in the closed bottom. A rotating mixing head is provided which can be lowered into the bowl in such manner that the four pins attached to the head can be caused to move among the lower fixed pins with a planetary motion. The force required thus to circulate these moving pins exerts a pressure against the fixed pins, and hence against the base of the mixing bowl, so that the latter tends to rotate if free to do so. This rotation was impeded, either by a standardized spring or by a weighted lever, in such a manner that the torque of the base could be measured and recorded.

In the models which the author has seen, there is no provision for the control of the temperature of the dough during the mixing operation. Since dough plasticity has been repeatedly shown to have a substantial thermal coefficient, it is essential either that the dough be prepared and mixed at uniform temperatures, or that some correction be applied to the records of doughs which deviate appreciably from the standard temperature.

The mixing-force curves recorded in Swanson and Working's paper (68) disclosed the effect of varying the ratio of water to flour, and the temperature of the doughs. Also differences in flour-mill streams, in commercial flours, and in flours milled from different wheat varieties were disclosed. No detailed proposals were included in this paper for an analysis of the curves to extract a single-figure score. Supplementary discussions of such tests appeared later, notably in two papers by Swanson (70, 71). In the latter, an analysis of seven curve characteristics is presented, based upon Figure 16. This chart, and the discussion based upon the seven characteristics, appear in Swanson's recent book (72).

A represents dough development time, which may vary considerably from flour to flour. In other discussions of this property,

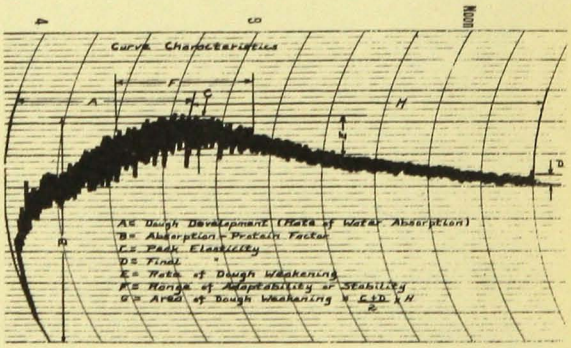

FIG. 16.—Schematic diagram of curve traced by Swanson-Working recording dough mixer

as well as in the experience of the author's laboratory with recording dough mixers, the interval to the maximum point of the curve is not in fact the optimum mixing treatment. Actually the dough is already overmixed for

70. C. O. Swanson, "Physical Tests to Determine Quality in Wheat Varieties," *Cereal Chemistry*, March 1936, XIII, 179–201.

71. C. O. Swanson and Rowland J. Clark, "Testing Flours by the Recording Dough Mixer," *Northwestern Miller*, Nov. 18, 1936, pp. 458–64.

72. C. O. Swanson, *Wheat and Flour Quality* (Burgess Publishing Co., Minneapolis, Minn., 1938), esp. pp. 207–09.

practical baking purposes, but the interval to the maximum may constitute an index of the mixing treatment that should be accorded a bread dough.

B, or the height of the curve, constitutes an index to the proportion of water required to produce a dough of standard consistency. That the latter should be constant for all flours is unlikely, however, as was indicated in the section on absorption (Section I).

C, and *D*, the relative width of the curves at the peak, and at the conclusion of a standard mixing treatment, are here regarded as indices of the peak and final elasticity. Whether these values actually afford a true measure of dough elasticity is now regarded by the author as problematical, the basis for this view being indicated elsewhere in this section.

E represents the rate of dough weakening. When the slope is reasonably uniform it can be measured in terms of the angle formed with the tangent drawn at the top of the curve, and the general slope of the curve beyond the peak. The greater this angle, the more rapid the breakdown, and vice versa.

F is defined by Swanson as the "range of adaptability," and has been referred to elsewhere as mixing tolerance. It is the interval in time of mixing, or in number of revolutions of the mixing arms or rods, through which the consistency varies only slightly from the maximum. It requires some further definition in terms of the range of consistency permitted within this zone.

G, "the area of dough weakening," is not shown graphically in the figure, but is defined as $C + D/2(H)$, or the sum of the "peak elasticity" and the "final elasticity" divided by 2 (in other words, the average of these two values), multiplied by *H*, or the horizontal distance, namely the time or extent of mixing, through which the observation is made. Assuming a fairly constant rate of decrease in the width of the curve, the value *G* as thus calculated constitutes an approximate measure of the area of the curve through the interval *H*. The issue then arises, how long *H* should be. Swanson proposed that it should extend from the peak of the curve to the point where the amplitude disappears or the curve becomes almost straight, a point not always easily discerned, in the author's opinion. Moreover, the value as measured is large where the weakening is really small, which creates an anomalous application of the term "weakening." Incidentally, it should be emphasized that Swanson's measure of weakening is thus based upon the width of the curve, whereas in Brabender's analysis of farinograms (discussed elsewhere in this section) the measure of weakening involves the departure of the central part of the curve from the maximum consistency, measured after a time-unit interval.

In his latest discussion of these curves, Swanson (73) mentions the same general features and calls attention, by means of various specimen curves, to the variability encountered in these several particulars. No single figure score is evolved from the several characteristics, however. In fact, in his concluding paragraph of this paper Swanson states that "the most serious aspect is that we have thus far no adequate method of evaluating these physical tests." He then emphasizes certain inadequacies in current baking-test procedures which might be correlated with such physical tests, and that the baking procedures often do not impose tests sufficiently severe to disclose all the elements of weakness in flour.

Recently the Swanson-Working recording dough mixer has been built down to a so-called "micro" size, which has many mechanical features in common with the larger machine but will handle 35 g. or less of flour. In addition, it is enclosed in a cabinet which permits of air-conditioning the environment of the device. Apparently the tests are completed in a shorter period of time than with the larger unit. Curves drawn by means of this micro-recorder are similar, in general, to those previously published from the larger machine, and presumably permit of like interpretation. A series of such curves covering six typical hard winter-wheat varieties grown in the southern Great Plains area is shown in Figure 17. These curves are especially significant, since flours at several levels

73. C. O. Swanson, "Variations in Dough-Development Curves," *Cereal Chemistry*, September 1939, XVI, 625–43.

of protein content were used in the instance of each variety. They accordingly demonstrate the effect of increments of protein upon the curve characteristics when the genetic constitution of the wheat is constant. They also permit of comparisons between varieties at the same level of protein content, and thus striking differences are disclosed.

Ferris (74) proposed a method of analyzing the curves from the *S-W* recording micromixer which involves the use of a celluloid scale to be fitted over the curve, and by means of which certain numbers can be taken off. One characteristic thus recorded is the distance along the horizontal axis to the "peak"

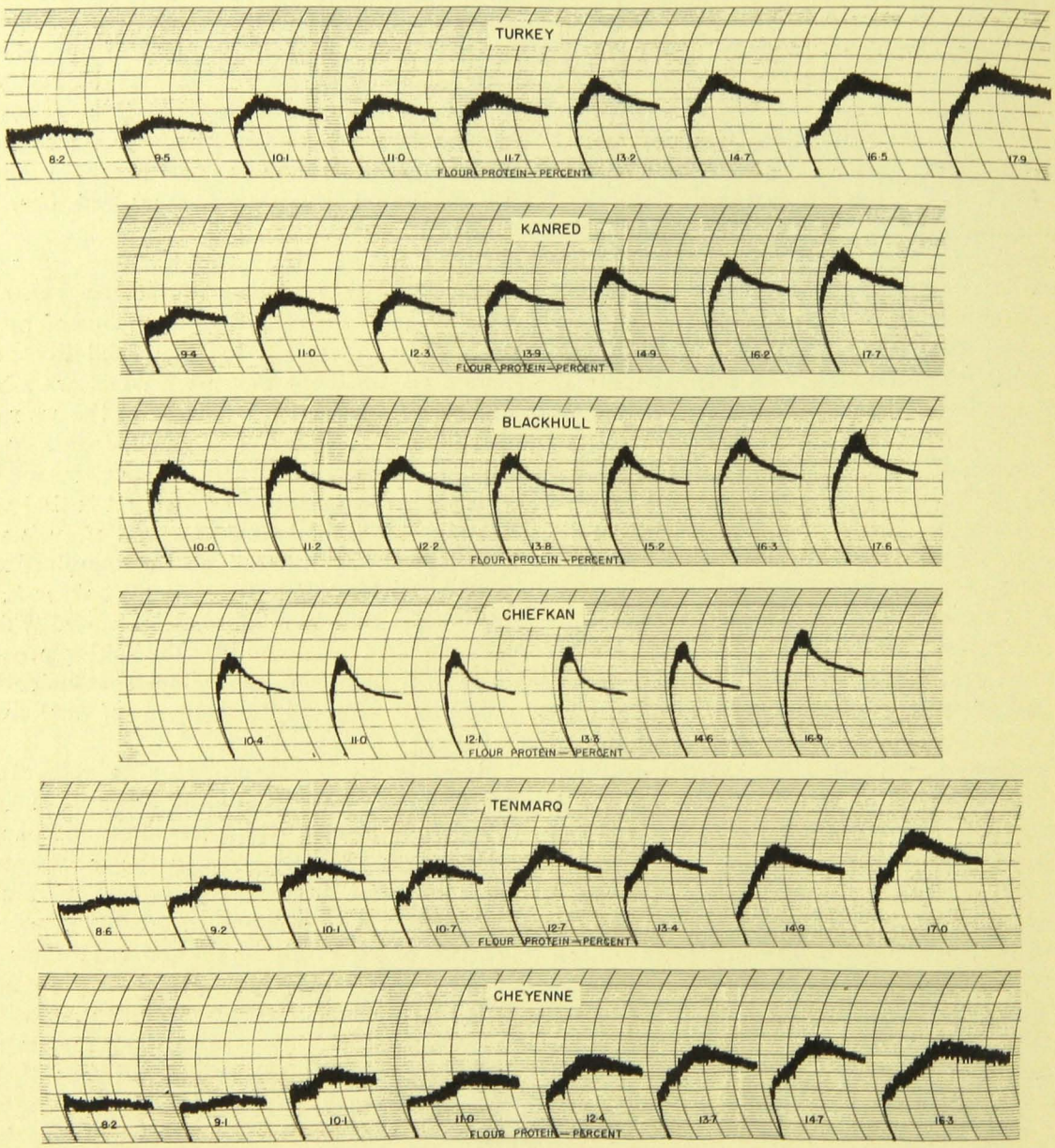

FIG. 17.—Curves drawn by Swanson-Working micro-mixer for six hard winter-wheat varieties at different levels of protein content

74. W. C. Ferris, "Curve Analysis Outlining the 'Ferris Reading' System" (National Manufacturing Co., Lincoln, Neb., Sheet No. 89, September 1939).

or maximum consistency. This is equivalent to *A* in Figure 16. A second characteristic to be measured is the angle with the horizontal of the slope of the curve after it passes the peak and to a point equivalent to 7 minutes of total mixing treatment. Also the fall of the curve, or softening, in units equivalent to *E* in Figure 16 is measured by the scale. Finally, the general width of the curve is recorded by reference to a series of type curves designated as *A*, *B*, *C*, etc., with plus or minus signs attached to indicate intermediate types. No suggestion is made for combining these four constants into a single figure score.

Malloch's (75) small recording mixer, at first glance, seems to have some features in common with the Swanson-Working micromixer. As may be seen from the sketches of the spindle and cup assembly in Figure 18, there are stationary pins attached to the base of the mixing bowl, and rotating pins propelled by the head. These pins are spiraled, however, and in addition there is a fairly massive central pin which tends to keep the dough out in the space through which the rotating pins travel.

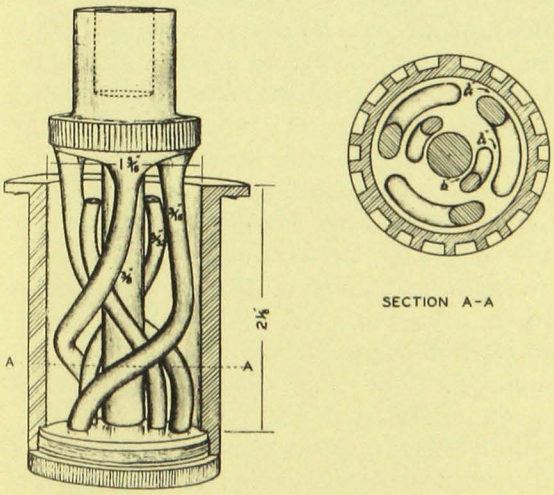

Fig. 18.—Diagram of the arrangement of the pins in the bowl of the Malloch recording dough mixer

The general design of Malloch's assembly has been elaborated since the publication of the paper cited, as may be seen by contrasting Figure 19 with the illustration in that paper (75, p. 424). Essentially the same mechanical principles have been preserved, however, namely, the measurement and recording of the torque exerted in the plane of the centers of the curved spindle pins when these are rotated at a definite speed. This torque, estimated to range between 1225 g. and 7500 g., is recorded by a stylus on a chart attached to the kymograph drum shown at the front right-hand corner of the instrument as illustrated in Figure 19.

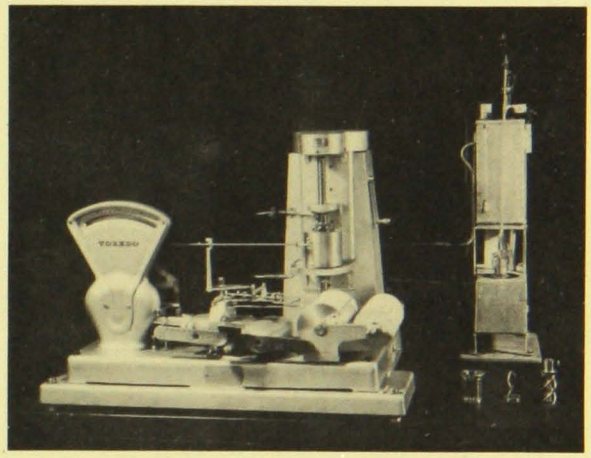

Fig. 19.—Malloch recording dough mixer, 1939 model

The charge of flour is smaller than with the other recording dough mixers, being equivalent to only 7 g. of dry matter. Also, the time required to complete a test is short, since Malloch states that one man with a single machine can complete eight tests an hour, except for the measurements of the curves.

Malloch's curves possess one very distinctive characteristic not observed in tests made by the other recording dough mixers. After the curves pass through the peak indicating minimum mobility, and start downward, they presently undergo a sharp inflection indicating a sudden increase in mobility. The amount of treatment required to reach this stage is variable with different flours, as will be observed by comparing the curves in Figure 20.

In conducting his tests Malloch placed flour equivalent to 7 g. dry matter and at 30° C. in the mixer cup. The latter is provided with a

75. J. G. Malloch, "Some Results with a New Recording Mixer for Use with Small Samples," *Cereal Chemistry*, July 1938, XV, 423–38.

water jacket for temperature control. Water at the same temperature is added from a burette. The kymograph is rotated a short distance to establish the base line, and the motor driving the mixer is then started. Time in seconds is registered on the horizontal axis of the chart, and torque along the vertical axis.

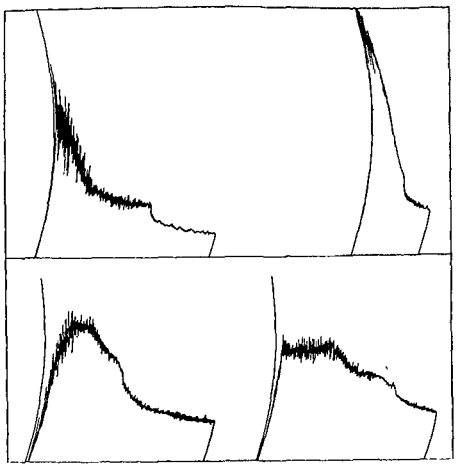

FIG. 20.—Typical curves traced by the Malloch recording dough mixer

The curve can be described by the height and time (*a*) of the maximum, the height and time (*b*) of the inflection or break to which reference has been made, the angle of the curve with the horizontal between time intervals *a* and *b*, and by equations for portions of the curve before and after the break. Height of the curve at the maximum was observed to be a function of the water added and the gluten content, but the time (*b*) to the breaking point was not a function of the water content of the dough within the range studied. Also it (*b*) was not affected by some dilution of the flour with starch (25 per cent), nor by weight of flour used between 7 g. and 9 g.; but it was increased by the inclusion of NaCl, and decreased by the inclusion of lactic acid and alcohol in the dough.

In Malloch's paper (75), which was actually read in May 1937, he indicated that up to that time a detailed study had been made of only one feature of the curve, namely, the break. It is very significant that when crude gluten was separated from seven flour samples, dried, and mixed with starch in the proportions of 20, 15, and 10 per cent, there was little effect on this breaking time as a function of gluten content; but the several glutens from various sources differed widely, as evidenced by the relative breaking-time values which ranged from 17 to 56 units of time in this series of seven preparations. This suggests that the time of inflection or break in the curve is determined by the properties of the gluten, rather than its concentration; accordingly, such measurements may afford a useful index of gluten characteristics, either native to it or induced by other dough constituents or manipulation in fermentation.

Malloch also explored the possibilities of applying this test to wheat meal and found the simple correlation of the breaking point of wheat meal doughs, and flour doughs from the same wheat, to be $r = 0.88$ (1% point = 0.45). While the relation was not close enough to permit certain prediction, it was useful in making rough classifications of wheat samples.

DUCTILITY MEASUREMENTS

Rejto's dough-testing machine was one of the first mechanical devices appearing in Europe. It was described by his colleague in Hungary, Dr. Thomas Kosutány (76), but outside of the latter's book there has been little reference to it in the literature. It is the author's understanding, based upon conversations with other Hungarian workers, that the original "Zerreiszmaschine" (breaking-strength machine) of Rejto was elaborated upon subsequent to the published descriptions, but the data resulting from the work done with the later models have not been made available.

In a letter from Dr. Wm. Misangyi, who was a student of Rejto's, it is indicated that Rejto had used the Hartig-Reusch machine in testing the tensile strength of thread. He then endeavored to transfer the same general principles to dough testing, with the results shown in Kosutány's book. It was so designed that a "dumbbell" shaped piece of dough, 7 cm. between the bulbs at the end, was grasped

76. Thomas Kosutány, *Der ungarische Weizen und das ungarische Mehl* (Budapest, 1907), pp. 249–83.

firmly by these bulbs and extended under known force. The device provided means for registering the force applied and the degree of extension effected before the dough strand was ruptured. From these data it was possible to compute the work done in thus extending the dough.

In Section I reference has been made to Rejto's records of "Zugkraft" as related to water used in preparing the dough. He also reported the ductility and work done in extending doughs prepared from various Hungarian flours as a function of the lapse of time after mixing. The data available are in themselves scarcely sufficient to afford a basis for laying down any general principles of the relationships between these observed physical properties and baking qualities. He did indicate that doughs prepared from flours with an average protein content of 13.1 per cent could be extended an average of 33.9 mm., while another series averaging 15.4 per cent protein content was extended an average of 38.1 mm. Attention was also called to the effect of adding a strong flour to a weak flour.

Misangyi's letter also states that Rejto later applied other physical tests to dough, including shearing tests and perforation tests; and when Brinell's tests became known they also were applied in Rejto's laboratory.

While these devices as used by Rejto did not find general application in flour technology, there seems little doubt but that this work gave impetus to the studies of physical dough testing in the institutions of Budapest that extended through the intervening years and are still in progress there.

Extensimeters

Chopin's extensimeter and the associated equipment, like several other dough-testing devices, passed through a process of evolution during a period of approximately two decades. In fact, it apparently inspired much thought and activity on the part of other individuals and groups, as will be suggested by the general similarity of other dough-testing machines. In the aggregate, these have had a very extensive application, particularly in Europe.

The first commercial model of the extensimeter as described by Chopin (77), whose paper was translated by Bailey and Le Vesconte (78), provided means for forming a thin film of dough 3 mm. thick and 58 mm. in diameter, which was secured around its rim by clamping it firmly between two metal plates. Air was then introduced from below through a small opening, and the dough surface extended by inflation upward through a larger opening in the upper plate 58 mm. in diameter. The entire device, including the dough sheet, was held at 25° C. by means of electrical heaters. A small mechanical dough mixer was provided for mixing the doughs to be tested.

As the dough bubble formed and was stretched by the air pressure, the actual pressure (P) exerted was noted upon a simple water manometer. Later a recording pressure gauge was substituted for the manometer. This value P is referred to by Chopin as a quantitative expression of "tenacity." At the time of rupture of the dough, the surface area in cm.^{2} (E) was read on a gauge which measured the volume of air introduced. This gauge was calibrated directly in terms of surface area of the bubble; thus the increase in this surface accomplished under the conditions of the test could be determined; hence the term "extensimeter" as applied to the device.

Chopin (77) compared the values thus secured with the loaf volume of test loaves baked from a series of 31 flour samples. He then subtracted the initial volume in cm.^{3} of unfermented dough prepared with 100 g. flour (V_o) from the volume in cm.^{3} of the baked bread from the same dough (V). The difference was found to be a linear function of a constant multiplied by the square root of E in all cases except two in this series. In other words $V - V_o = K\sqrt{E}$. The average error in thus computing K was 6.24 per cent. For the baking method used, the foregoing equation could be expressed as $V - V_o = KE^{0.4}$.

In this series of tests, the uniform ratio of water to flour used in preparing the doughs

77. Marcel Chopin, "Relations entre les propriétés mécaniques des pâtes de farine et la panification," *Bulletin de la Société d'encouragement pour l'industrie nationale*, March 1921, CXXXIII, 261–73.

78. C. H. Bailey and Amy M. Le Vesconte, "Physical Tests of Flour Quality with the Chopin Extensimeter," *Cereal Chemistry*, January 1924, I, 38–63.

for testing in the extensimeter, namely 333 g. flour (at 15 per cent moisture content) and 163 g. water, was little less than 50 per cent. It accordingly followed that the value for *P*, or maximum pressure applied in expanding the dough bubble, was quite variable among Chopin's 31 flours, since, as indicated in the discussion in Section I, the force required to thus extend the dough is a function of its relative viscosity or plasticity. The latter would not be expected to remain constant in a series of flours of varying composition when mixed with a uniform proportion of water. Chopin did not find any relationship between the tenacity value *P* and baking quality as disclosed by loaf volume.

Only a few of the numerous applications of the Chopin device, either in its earlier or more recent forms, can be presented here. Bailey and Le Vesconte (78) found the coefficient of variability in a series of replicated tests to be fairly high, which is not surprising in view of the mechanical difficulties involved in preparing thin dough sheets or membranes of uniform thickness and free from irregularities over their surface. It seems probable that this variability may have been reduced in those later practices that will be described presently.

Prolonged mixing of dough was observed to alter its extensibility when measured shortly after mixing. As flour was diluted progressively with starch, so as to reduce the gluten content of the mixture, the extensibility diminished proportionately. Extensibility appeared to pass through a maximum at pH = 6.1, when the pH was varied progressively by the addition of lactic acid or of sodium hydroxide solutions, respectively. This dough was slightly more alkaline than the untreated dough (pH = 5.8). Dough tended to lose its extensibility with the lapse of time in fermentation; the freshly mixed dough had a value of $E = 17.38$, and after four hours this had decreased to $E = 10.62$. In fact, Johnson and Bailey (79) used the extensimeter to advantage in following the changes in properties of cracker "sponges" and doughs during the progress of the long fermentation of such materials involved in commercial cracker baking.

In ten out of twelve cases, in a series of comparisons made by Bailey and Le Vesconte, there was a fairly constant ratio between the extensibility of dough and the results of simple dough-expansion tests when fermented by yeast in the expansimeter. The ratio between extensibility and the results of actual baking tests, however, was less constant with this series of flours. In fact, the author suspects that the extensimeter has been engineered to deal with flours distinctly on the weak side as judged by American bakers' standards. Data are not fully adequate to support this assumption, it must be conceded, but general observations point to such a conclusion. Moreover, it would be surprising if this were not true, in view of the situations in which the instrument has been developed and chiefly applied.

The Vilmorin family of French wheat breeders have apparently found the extensimeter to be of substantial practical service in guiding their work in breeding for quality in wheat, as indicated in the paper by J. and R. Vilmorin and M. Chopin (80). The author has also observed it in service in a like connection in the Centre Agronomique at Versailles, France, where Potel (81) reported upon certain of his observations. Kent-Jones also has made use of it in his laboratory at Dover, and has described the several Chopin instruments in his book (82). He records in chapter ii, Figure VI, what appear to be the results of extensimeter or related measurements of Canadian, Australian, Argentine, Russian, English, and other wheats. His stability and general strength figures recorded in the same chapter are (note statement on p. 374 of his book) "reduced and corrected 'P' and 'W' figures of Chopin obtained under the special conditions of the test in the author's laboratory." He also emphasizes the necessity of meticulous atten-

79. Arnold H. Johnson and C. H. Bailey, "A Physicochemical Study of Cracker Dough Fermentation," *Cereal Chemistry*, December 1924, I, 327–410.

80. Jacques and Roger Vilmorin and Marcel Chopin, "Les selections des blés au point de vue de la valeur boulangère," *Journal d'Agriculture Pratique*, June 15 and 22, 1929.

81. Pierre Potel, "Recherches récentes sur la qualité des blés et des farines," *Bulletin des anciens élèves de l'école française de meunerie*, March 1937, No. 57, pp. 79–81.

82. D. W. Kent-Jones, *Modern Cereal Chemistry* (3d ed., Liverpool, 1939), esp. pp. 369–79.

tion to the physical details of preparing dough for the test.

Merriam published a translation of a paper by Chopin (83) in which the interpretation of the extensimeter curves was further discussed. Referring to the specimen curve in Figure 21, *PQ* represents the maximum pressure applied in extending the dough or inflating the bubble,

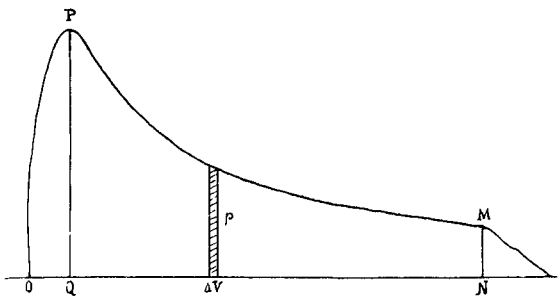

FIG. 21.—Schematic diagram of the curves traced by the Chopin extensimeter

and is commonly recorded as *P*. This is always registered early in the process. Length of the diagram, *ON*, from the first application of pressure to the point where the bubble surface ruptures and discharges air, affords a measure of coefficient of extension which is the square root of the volume of air entering the bubble at constant rate. This value can be confirmed by directly measuring this volume on the gasometer provided with the instrument (illustrated in Fig. 22), and is recorded as *G* (for "gonflement").

Area under the curve *OPMN* is then measured by means of a planimeter and recorded in cm.^{2} Since the vertical scale in millimeters of water can be converted into dynes per cm.^{2}, and the horizontal scale *ON* can be converted from cm. of length to the equivalent of increase in volume in cm.^{3}, the area of the diagram represents the work (*W*) done on the dough sample; or $\frac{\text{dynes}}{\text{cm.}^2} \times \text{cm.}^3 = \text{dynes} \times \text{cm.} = \text{ergs}$. In the computation, the conversion of area in cm.^{2} to units of work is effected by multiplying area by a constant which involves the relation between the number of cm.^{3} represented by each unit of length of the diagram, as well as the calibration of the pressure gauge.

The resulting quantity is the number of ergs expended in extending the dough sheet, the dimensions of which are arbitrarily chosen. It then becomes desirable to reduce this value in ergs to either a unit volume or a unit weight. Accordingly, at the completion of the test, the collapsed bubble is cut away from the dough clamped under the plates, and weighed. The total value for *W* may then be divided by the weight in grams of this dough sample, which gives a corrected value of *W* per gram.

Other details for the convenient measurement and interpretation of these constants taken from the curves are supplied by the manufacturer of the instrument.

Scott Blair and Potel (84) pointed out that the viscosity of flour dough falls with rising stress (structural viscosity) but rises with increasing deformation (work-hardening). Pressure applied through the process of expanding the dough bubble with the extensimeter obviously is not constant, and the variation in viscosity will thus be complex. Since the rate at which air is supplied to the bubble is predetermined, it seems probable that the magnitude of *P* will be correlated primarily with the viscosity of the dough.

In analyzing the significance of the value *G* (or square root of the volume of the bubble at the time it bursts), attention is called by Scott Blair and Potel to the fact that after the bubble bursts, the walls recover to about half their fully distended area. The total deformation is thus divisible into two parts: (*a*) recoverable deformation (σ_ϵ), and (*b*) nonrecoverable deformation (σ_η), η being the symbol for viscosity. The first, or σ_ϵ, will be defined by the ratio of shearing stress (*S*) to the shear modulus (*n*) (for definitions see Section I). Accordingly σ_ϵ for a given stress will increase with decreases in the modulus, *n*. Also, the higher the viscosity (defined as *S*/rate of change of σ_η), the greater the stress under the arbitrarily fixed rate of application of deformation, which,

83. Marcel Chopin (translated by C. F. Merriam), "Determination of Baking Value of Wheat by Measure of Specific Energy of Deformation of Dough," *Cereal Chemistry*, January 1927, IV, 1–13.

84. G. W. Scott Blair and Pierre Potel, "A Preliminary Study of the Physical Significance of Certain Properties Measured by the Chopin Extensimeter for Testing Flour Doughs," *ibid.*, March 1937, XIV, 257–62.

in turn, will make for a greater extension of the dough. And the higher the viscosity, the greater the proportion of elastic to total deformation. Thus the combination of high η and a low modulus n makes for a large elastic recovery, and is also the predominant factor which produces a high value of G, assuming that the dough is reasonably extensible. Scott Blair and Potel present a generalized equation for G,

$$G = (f)\ \frac{\eta_l{}^a}{n^b} - \frac{\eta_h{}^c}{\eta_l{}^d}$$

where η_l is the viscosity at low or normal stress, η_h is the viscosity at high stress, n is the shear modulus, and a, b, c, and d are exponents of unknown value.

The ratio of viscosity at low stress to viscosity at high stress or η_l/η_h was noted in a series of 34 doughs examined by Scott Blair and Potel and found to range from 9 in a very extensible dough to 28 in a very short dough.

In attempting to refine the equation for G, it was first assumed that $a = 9$ and $c = 1$. The equation then becomes $G = (f)\ \frac{\eta_h}{n^b}$. Various values for b were then tried in filling the equation, and it was found that when $b = 2.0$, there was a linear relation of $\frac{\eta_h}{n^2}$ and G in all instances except with unusually "dry" (i.e., stiff) and "wet" (presumably "slack") doughs.

Chopin (85, 86, 87) described a unique dough-mixing machine for use in his ensemble, which is provided with a hinged side so arranged that the force exerted against it by the dough in its passage between the mixing arm and the side of the mixer is registered by a recording stylus on a chart. This force is a function of the relative plasticity of the dough, and changes progressively during a sustained mixing operation. The result, when recorded upon a chart, is not unlike the records of other recording dough mixers. This facilitates the control and measurement of dough plasticity at the time of mixing, also the stage in the "mixing development" at which the dough is withdrawn for other physical tests.

On the other side of the mixing bowl, Chopin has provided a valve or gate which can be opened to create a horizontal slot 6 mm. wide. When the dough is ready to be removed from the machine, the motor is reversed, the gate opened, and a band or flat tape of dough is forcibly extruded under a roller onto a flat platform provided for the purpose. Portions are cut off, and flattened further with a metal roller between guides which determine their thickness; these are then available for tests with the extensimeter, or its later successor, the aleurograph. Chopin, in the privately printed bulletin, presents a series of graphs which demonstrate the substantial reduction in the variability of a series of replicated tests made upon doughs prepared as just described, when compared with the tests made by the older methods.

Chopin (88) also described in some detail the redesigned extensimeter, called the alveographe (illustrated in Fig. 22), and indicated the derivation of the constants P, G, and W from the data recorded in the progress of dough tests made with it. Since it is so similar in principle to the older extensimeter, it is not surprising that Chopin obtained very similar results with the two instruments. Accordingly the comments made respecting the extensimeter may be assumed to apply in the instance of the more refined instrument. With it, as with the extensimeter, it appears that the value of G is much more variable than the value of P.

For more detailed discussion of the applications of this method of dough testing, reference may be made to the polemic of Nuret (89), and Chopin's (90) rejoinder; Ougrim-

85. Marcel Chopin, "Pétrin enregisteur et extracteur de pâtes," *La meunerie française,* December 1935, LI, 276–80.

86. Marcel Chopin, "Nouveaux appareils pour la préparation et l'essai d'extension des pâtes de farines," *Bulletin des anciens élèves de l'école française de meunerie,* June 1937, No. 60, pp. 172–79.

87. Marcel Chopin, *Pétrin Enregistreur et Extracteur de Pâtes* (privately printed by Appareils de Laboratoires Instruments de Contrôle Industriel, Paris).

88. Marcel Chopin, *Alveographe* (privately printed by Appareils de Laboratoires Instruments de Contrôle Industriel).

89. H. Nuret, "À propos de l'extensimètre Chopin," *Bulletin des anciens élèves de l'école française de meunerie,* January 1937, No. 55, pp. 2–6.

90. Marcel Chopin, "À propos d'un article de M. Nuret relatif à l'extensimètre," *ibid.,* March 1937, No. 57, pp. 81–83.

off's (91) study of the effect of temperature and dough hydration upon extensibility, the characteristics of flours milled from different wheats as discussed by the same author (92),

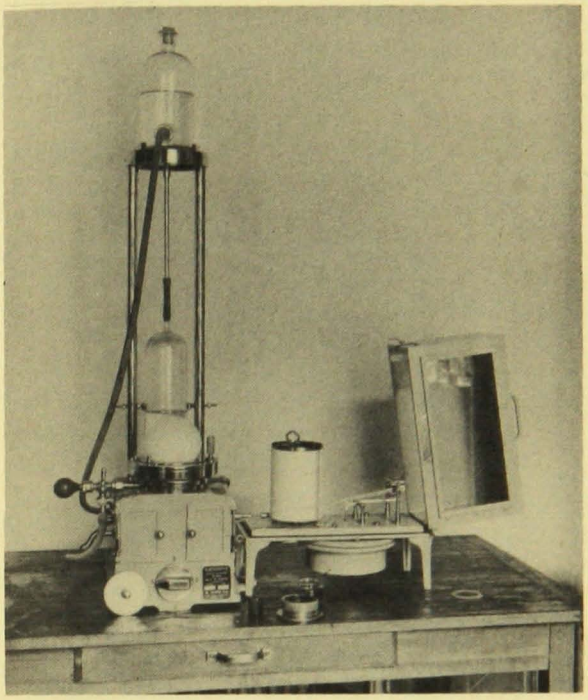

FIG. 22.—Chopin alveographe

and the effect of milling (93); the comparison of the results obtained by the extensimeter and the alveographe reported by Alexinsky (94); and many other published papers in which the results of such studies are recorded.

Undoubtedly the extensimeter has been used extensively in Europe in recent years in detecting and determining the extent of damage to wheat effected by insects belonging to certain species of the genera *Aelia* and *Eurygaster,* and possibly others, which puncture immature wheat kernels in the head before harvest in the manner described by Nuret (95) and others. The result is *"blés punaises"* in the French vernacular, *"Wanzenweizen"* in the German. Ougrimoff (96) summarized his studies with the extensimeter, and presented a graph showing that the value for *W* fell off sharply as the percentage of *"farine punaisée"* or flour from "buggy" wheat was increased. This was particularly true after the dough had been allowed to stand for several hours. Since there have been seasons when such buggy wheat was much in evidence in the crop from certain sections of Europe and northern Africa, the cereal technologists of western European mills have been much concerned with the task of sorting out the wheat thus damaged, and have used the extensimeter largely to this end.

Naszalyi (97) described a dough-testing device called the "alphitograph," which appears to have many features in common with the extensimeter and the alveographe. His process is less highly automatic than Chopin's, and certain points of difference should be mentioned. Evidently the dough from the mixer is flattened into a thin sheet which is then rolled into cylindrical form, and sections are cut off the end of this roll for testing. After 20 minutes' rest these are pressed thin, and then inflated by air pressure provided by a simple pump, the piston of which is moved forward by means of a hand crank. This mechanism is geared to the drum on which the recording chart is fastened. Accordingly, the rate of flow of air is fixed in relation to the horizontal movement of the stylus on the graduated chart, and does not have to be independently calibrated as in the Chopin extensimeter.

In his series of six papers cited above, Naszalyi (97) details the results of an extensive study of this system of dough testing. Among the variables studied are ratio of flour to water, mechanical mixing treatment, time of rest allowed the dough between mixing and testing, mechanical formation of the dough

91. A. Ougrimoff, "Contribution à l'étude des propriétés plastiques des pâtes I, II," *ibid.*, September–October 1937, No. 62, pp. 222–32; November 1937, No. 63, pp. 273–79.

92. *Ibid.*, March 1938, No. 67, pp. 67–78.

93. *Ibid.*, May 1938, No. 69, pp. 136–41.

94. V. Alexinsky, "Étude comparative des résultats obtenus à l'extensimètre et à l'alveographe," *ibid.*, April 1939, No. 78, pp. 109–16; May 1939, No. 79, pp. 144–47.

95. H. Nuret, "Blés punaises," *ibid.*, July–August 1936, No. 51, pp. 177–78, 208–17.

96. A. Ougrimoff, "Essais sur blés punaisés," *ibid.*, December 1936, No. 54.

97. N. Naszalyi, "Étude sur les qualités plastiques des pâtes," *ibid.*, January 1935, No. 35, pp. 4–12; February 1935, No. 36, pp. 40–44; March 1935, No. 37, pp. 72–76; April 1935, No. 38, pp. 99–101; May 1935, No. 39, pp. 122–23; November 1935, No. 43, pp. 221–22.

after mixing, influence of salt in the dough solution, comparisons of flours milled experimentally and industrially, the behavior of flour and wheat mixtures, and a discussion of the permeability of inflated doughs to gases.

From certain portions of these studies one would conclude that small variations in the preparation and treatment of doughs before testing may register substantially in the results of such physical tests, in addition to the contribution made by the flour itself.

The Buhler comparator, invented by Mr. Bouvier of Buhler Brothers, Uzwil, Switzerland, and patented in England in 1924 by L. Baumann (British Patent 232,585) has not been widely discussed in the literature, although the author has been informed that several hundred instruments were distributed. Wolf (98) published an illustration, as did the manufacturers, Buhler Brothers (99). The ensemble included three machines or instruments: (1) a hand-operated double-blade mechanical dough mixer, (2) a hand-operated screw press for forming the thin sheet of dough, and (3) the comparator itself. The latter provided a platform on which the thin sheet of dough formed by the press was securely mounted. This platform could be caused to move steadily downward, by means of a motor-propelled worm gear, until the sheet of dough came into contact with a rounded wooden cone with its apex directed vertically upward. As the sheet of dough continued its movement downward, it began to form around the cone which thus extended its surface. Also, an appreciable pressure was exerted against this cone. This pressure was measured by a balance system and recorded by an inked stylus on a chart. This chart also moved laterally in synchrony with the downward movement of the dough sheet over the cone. Consequently the horizontal length of a curve drawn to the point where the film of dough ruptured, and the pressure began suddenly to approach zero, was an approximate measure of extensibility. Curves thus drawn were not exactly like the extensimeter records, in that the pressure continued to rise in the former to the instant of rupture of the dough film, instead of early passing through a maximum and then receding as in extensimeter curves.

The ensemble lacked certain refinements in its original design, especially temperature and possibly humidity control. Before these were supplied it was apparently decided to withdraw the instrument in favor of other devices which supplied these controls.

Borasio and de Rege (100, 101) described their pneumodynamometer, which functions much like the extensimeter except that, instead of blowing a dough bubble outward from the chamber by applying air pressure from within, the bubble was drawn downward into a chamber under atmospheric pressure by reducing the pressure within the chamber. For convenience in operation, a fairly large air tank was provided in which the pressure could be reduced to the desired level of a partial vacuum by means of a simple pump.

As with the extensimeter, provision was made for recording the force applied in extending the dough from the inception of the process to the point of rupture of the inverted bubble. The relative extension of surface of the latter was also indicated. Apparently the same general mathematical analyses of the curves were made by Borasio and de Rege, as were previously described in the instance of the Chopin extensimeter curves.

De Rege (102) later presented a discussion of the mathematical treatment of the pneumodynamometer data and their relation to viscosity and other fundamental physical properties of dough.

Geoffroy (103) substantially amplified the

98. Wolf (Dippoldiswalde), "Der Mehlprufapparat Komparator," *Die Mühle*, Jan. 2, 1930, pp. 1–4.

99. Buhler Brothers, "Flour Tester 'Comparator,' Buhler's Patent" (pamphlet, undated).

100. L. Borasio and F. de Rege, "A pneumodynamometer for the determination of flour and gluten quality" [translated title], *Giornale di risicoltura*, 1932, XXII, 197–211. (Abstract in *Das Mühlenlaboratorium*, January 1933, III, 29; original not seen.)

101. L. Borasio and F. de Rege, "Das Pneumodynamometer, ein Apparat zur Qualitätsbestimmung der Mehle," *Das Mühlenlaboratorium*, June 1934, IV, 77–82.

102. F. de Rege, "Studio sulla natura colloidale e methodo di determinazion del coefficente di viscosità plastica del glutine a mezzo dei dati extensimetrici," *Giornale di risicoltura*, May and June 1939, XVII.

103. R. Geoffroy, "Examen de quelques farines avec le Dilatomètre," *Bulletin des anciens élèves de l'école française de meunerie*, January 1939, No. 75, pp. 3–4.

extensimeter techniques in one detail by arranging to employ heated air at a temperature of 180° C. to inflate the bubble of expanding dough produced in the device which he called the "dilatomètre." In consequence the doughs were baked at the end of the process, and their height and diameter constitute convenient indices of their volume. In most instances these two measures were closely related.

Geoffroy suggests that the physical conditions imposed in this system of testing more closely resemble those involved in bread baking than has hitherto been the case, when doughs were tested at 20° to 25° C. In a series of 20 flours milled from American, French, and Russian wheats of widely varying gluten content, there does not appear to be a substantial correlation between Geoffroy's "dilatomètre" values and those obtained by normal application of the extensimeter. From his data one cannot judge which type of measurement is in best agreement with actual baking behavior of these flours. It does appear, from scanning the data, that the dilatometer values are less highly correlated with the dry gluten content of the flours than is true of the extensimeter measurements.

Issoglio's (104) ergometer provided a simple means for extending a sheet of dough clamped between two plates. The lower plate had an aperture through which air under pressure was forced, and the sheet of dough was stretched upward through a 6 cm. opening in the upper plate. Three characteristics—(1) resistance to extension, (2) "elasticity,"* and (3) work expended—were recorded, and Issoglio compared these with the gluten content of a series of 6 flour types ranging downward from 42¼ to less than 29 per cent wet gluten. With decreasing gluten content, resistance or tenacity decreased progressively from 99 to 36, "elasticity" from 33.9 to 21.7, and "work" from 442 to 96.

Engledow's (105) system of dough testing involved the use of simple equipment that could be found or constructed in practically any chemical laboratory. Disks of dough made from 62 g. of standard flour, and a like quantity of the flour under observation, respectively, were each placed over the end of a glass tube 0.8 inch in diameter. These two glass tubes were mounted in a heavy wooden board so that their upper ends, on which the dough rested, were flush with the upper surface of the board. The doughs were held firmly in position by means of another board resting on them, and weighted with a 100 g. balance weight. The lower ends of the glass tubes were connected by pressure tubing to a large bottle in which the gas pressure could be reduced by a suitable vacuum or suction pump. With the doughs in place, suction was applied, each dough drawn down into its respective tube, and an observation made as to which dough bubble burst first.

In these simple tests it was possible to determine only from replicated tests which of the two doughs represented the weaker flour. In certain types of plant-breeding studies, and particularly in the early stages when the quantity of wheat available is still very small, such comparisons might be useful in indicating trends in the matter of flour strength.

The Engledow "distensometer" was employed by Frankel and Donald (106) in the New Zealand Wheat Research Institute in classifying wheat varieties into five classes on the basis of such tests.

Kosutány's "Belastungsprobe" or load test is briefly described by Neumann (107). A sphere of known weight, presumably of metal, was allowed to produce a depression in the dough, and the extent of this depression was measured. A "Strudelteigprobe," also originated by Kosutány is described in the same section of Neumann's book, and supplemented by notes communicated by Dr. Karacsonyi. A

* Here "elasticity" is enclosed in quotation marks because it is probably not identical with modulus of elasticity as that expression is employed later elsewhere in this monograph.

104. Giovanni Issoglio, "L'ergometro delle farine del cereali," *Atti del I° Congresso Internazionale di Panificazione*, Rome, 1932, pp. 308–11.

105. F. L. Engledow, "An Aid in the Determination of Flour Strength," *Cereal Chemistry*, January 1928, V, 1–9.

106. O. H. Frankel and H. P. Donald, "Some Critical Observations on Quality Testing in Wheat Breeding," *Proceedings of the World's Grain Exhibition and Conference, Regina, Canada* (2 vols., Ottawa, 1933), II, 400–07.

107. Thomas Kosutány, "Belastungsprobe," "Strudelteigprobe," cited by M. P. Neumann, *Brotgetreide und Brot* (3d ed., Berlin, 1929), pp. 281–82.

well-mixed dough comprising 70 g. flour, 5 g. of lard, and 40 cc. of water at 36° C. was molded into a ball and allowed to rest for 30 minutes. It was then placed upon a linen cloth drawn over a round table 50 cm. in diameter. The cloth and dough were lightly dusted with flour and the dough rolled until it was uniformly 1 (or 2) cm. thick. The stretching was then continued by hand, starting at the middle and working radially. The operation was continued over the edge of the table until the thin central sheet began to tear because of its thinness. All the dough then over the edge of the table was cut off, and the 50 cm. disk was gathered up and weighed. The lower the weight, the higher the quality possessed by the dough for producing "Strudelteig" or Hungarian "Retes."

Lucente (108) described a dough-testing apparatus consisting of a special burette in the upper part of which an exact quantity of dough was placed. The burette was then filled with water, and the upper end was closed. Water was then allowed to run out at the bottom, and the volume was assumed to be an index of the expansion of the dough, which, in turn, depended upon the elasticity of the dough.

A major contribution to sound and constructive thinking in the field of dough physics has been made by Schofield and Scott Blair (109, 110, 111, 112). Extensive use was made, in Section I of this monograph, of their emphasis upon the application of appropriate physical terms and formulas to such discussions. In the early stages of their studies they applied the "pachimeter," as previously designed by them for measuring plastic strength under rolling in terms of the stress (W) required just to start plastic flow in a deformable material. In their early paper (113) they report the "pachimetry" of twelve flour samples ranging from $W = 22.5$ g. with Manitoba, to $W = 11.6$ g. for English-grown Yeoman. With one exception, the W values appear to be in order of baking strength, although the basis upon which strength was appraised is not disclosed. In another paper (109) they mention one deficiency in applying such pachimeter tests to doughs, namely, that the stress is then applied for only a fraction of a second, whereas in actual baking the stresses set up by gases generated in a leavened dough operate over several hours.

A second testing machine, called a "rack," was accordingly designed by Schofield and Scott Blair (109) which permitted applying the stress over extended periods of time. Early in such studies it was found that elastic recovery (see Section I for definition of terms) increased with the percentage of extension of a long cylindrical piece of dough, up to 100 per cent; but no further increase was registered up to 200 per cent. Elastic recovery was also an inverse exponential function of the time under stress in seconds. *Relaxation time* $\left(\frac{-dt}{d(\log_e x)}\right.$, where t is time, and x is elastic recovery) decreased as an exponential function of stress, although it later developed that the actual magnitude of these ratios was determined also by the percentage of extension effected by the applied stress; the greater the percentage of extension, the higher the stress equivalent to a unit of relaxation time.

At this stage of their researches Schofield and Scott Blair devised the scheme of floating the strand of dough under observation in a bath of mercury, elsewhere (114) illustrated in more detail. A convenient schematic diagram was presented by Halton and Scott Blair (115) and is here presented as Figure 23.

108. Giacomo Lucente, "Determination of the Plastic Properties of Flours by Use of a Simplified Apparatus," *Annali di chimica applicata*, 1935, XXV, 677–79. (Abstract in *Chemical Abstracts*, XXX, 6461; original not seen.)

109. R. K. Schofield and G. W. Scott Blair, "The Relationship between Viscosity, Elasticity and Plastic Strength of Soft Materials as Illustrated by Some Mechanical Properties of Flour Doughs" (I), *Proceedings of the Royal Society*, Series A, 1932, CXXXVIII, 707–19.

110. *Ibid.* (II), 1933, CXXXIX, 557–66.

111. *Ibid.* (III), 1933, CXLI, 72–85.

112. *Ibid.* (IV), 1937, CLX, 87–94.

113. G. W. Scott Blair and R. K. Schofield, "The Pachimeter as an Instrument for Testing Materials, with Special Reference to Clays, Soils, and Flours," *Journal of Rheology*, July 1932, III, 318–25.

114. R. K. Schofield and G. W. Scott Blair, "Apparatur zur Bestimmung der mechanischen Eigenschaften von Mehlteigen in absoluten Einheiten," *Das Mühlenlaboratorium*, April 1934, IV, 41–46.

115. P. Halton and G. W. Scott Blair, "A Study of Some Physical Properties of Flour Doughs in Relation to Their Bread-making Qualities," *Cereal Chemistry*, March 1937, XIV, 201–19.

Evidently extensive use was made of this device by Scott Blair and associates. It is essentially a research instrument, however, and has not been produced commercially for industrial or technological applications.

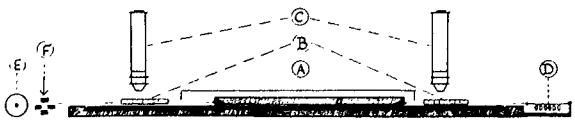

FIG. 23.—Diagram of the extensimeter employed by Schofield and Scott Blair, and by Halton and Scott Blair

In these studies it also became apparent that dough viscosity, as measured in terms of rate of flow of a strand of dough, was dependent not only upon the shearing stress but also the *amount of shear* that had taken place. There is some parallelism here with the "work-hardening" of metals. Accordingly there can be agreement in the replicated determinations of η only when the dough treatments are uniform, and any value of η recorded must be determined in the light of the history of the dough specimen.

Elastic after-effect in doughs was also demonstrated by use of the instrument illustrated in Figure 23, using a solid cylinder or strand of dough 0.7 cm. in diameter and about 10 cm. long, prepared by forcing properly aged doughs through the aperture of a dough gun not unlike an extrusion plastometer. Two small graduated scales designated as B, and to which we will refer as B_r and B_l (i.e., right and left scales respectively), were attached at the ends of the dough, and situated under the microscopes (C). At the right of scale B_r was a resilient member (marked D), originally a rubber strand and later a small coiled spring, anchored at the extreme right. At the left is a winch on which the cord attached to the dough and scale B_l could be wound. Then the position of the scale at the right, B_r, could be used as a direct indication of the stress, since the resilient member, D, had already been calibrated by hanging weights on it. Thus if it took k grams to stretch it one scale unit, and it was then stretched x scale units, the tensile stress on the dough per unit cross section was $\frac{gxk}{\pi r^2}$ dynes, where r = radius of the dough strand and g = acceleration of gravity = 981 c.g.s. units. Therefore shearing stress

$$S = \frac{981\,xk}{3\pi r^2}$$

On progressively increasing the tensile stress, a point was ultimately reached at which the plastic strength was exceeded, and nonrecoverable or plastic extension occurred. In a certain case the plastic limit was about 5,000 dynes per cm.^{2} Below that point an extension due to a small increase in stress appeared to be wholly recoverable on restoring the stress to its former value, provided sufficient time was allowed. This was demonstrated by a direct experiment. If the applied stress exceeded the plastic strength, plastic flow resulted, but here the elastic aftereffect was superimposed, and accordingly was added as a negative contribution to the Maxwellian equation for expressing the rate of fractional elongation de/dt. Then $\Delta e = \frac{l}{n}\,\Delta S - \Delta\alpha$, where e = elongation, n = modulus, S = stress, and α = elastic after-effect. As a steady condition is approached where the system is left undisturbed, it may be assumed that α approaches zero.

Viscosity (η) can be determined by the device illustrated in Figure 23, as in the following typical case (Schofield and Scott Blair, 111). A dough strand was extended at a steady rate of 0.0154 cm. per second until its length was 25.3 cm. At that point

$$\frac{de}{dt} = \frac{0.0154}{25.3} = 6.1 \times 10^{-4}\ \text{sec.}^{-1}$$

During this elongation the cross section of the dough strand was decreasing. S, the shearing stress, which is 1/3 tensile stress per unit area of cross section, was determined from the scale readings and the dimensions of the dough strand, and found to be 2.7×10^3 dynes per cm.^{2} While the value for the modulus, n, was not known exactly, it was low and probably not more than 1×10^4. The elastic part of the elongation $\frac{l}{n}\frac{dS}{dt}$ then equaled $1.6 \times 10^{-4} \times 10^{-4}$ sec.$^{-1}$ Since the stress was applied steadily

and slowly the elastic after-effect was negligible and could be disregarded. The rate of plastic flow then becomes

$$(6.1 - 1.6) \times 10^{-4} = 4.5 \times 10^{-4} \text{ sec.}^{-1}$$

Dividing into S,

$$\eta = \frac{2.7 \times 10^{3}}{4.5 \times 10^{-4}} = 0.6 \times 10^{7} \text{ dynes cm.}^{-2} \text{ secs.}$$

That some attention to temperature control is essential in such measurements is indicated by Halton and Scott Blair's (115) observation that the viscosity of dough falls by about 10 per cent per 1° C. rise in temperature, while the modulus falls about 5 per cent.

A relaxation time of $tr = 100$ seconds was computed for the experiment.

Elastic hysteresis in doughs caused the modulus, n, to decrease steadily whenever dS/dt preserved the same sign for an appreciable time, and increased abruptly when the sign of dS/dt was changed.

Before the fourth paper (112) in the Schofield and Scott Blair series appeared, Halton and Scott Blair (116) published the results of studies conducted by them with the mercury bath extensimeter (illustrated here in Fig. 23). Extending the time of mixing from 3 minutes to 12 minutes effected a reduction in η from 6.38×10^{6} to 2.92×10^{6}. While the dough mixed 3 minutes decreased in η on standing, reaching 4.92×10^{6} in 30 minutes, the dough mixed 12 minutes increased somewhat on standing 30 minutes, reaching $\eta = 3.55 \times 10^{6}$. Modulus ($n$) was 4.29×10^{4} in the dough mixed 3 minutes and decreased somewhat on standing, reaching 3.94×10^{4}, and 3.73×10^{4} in 30 and 60 minutes respectively. The modulus of the dough mixed 12 minutes was 3.02×10^{4} and increased to 3.50×10^{4} on standing 60 minutes. It is evident, therefore, that the history of the physical treatment accorded a dough, as well as time intervals involved in the several rest periods, are reflected in these, as well as other physical properties. Much the same general conclusions respecting a partial recovery of overmixed doughs upon resting have been reached in other types of testing procedures.

Halton and Scott Blair expanded this phase of the study to include fermented doughs held for 7 hours, and using flours of graduated strength. Certain of the data indicating the trends are included in Table 5. It is evident that the weak Australian flour dough changed more in these physical properties than did the strong No. 1 Manitoba. Also there was a greater relative change in viscosity than in modulus, which altered the ratio of these two properties with the lapse of time.

Although bakers have reported a "toughening" of strong flour doughs during fermentation, no flours thus classified have failed to register an actual decrease in viscosity and modulus during fermentation when tested by Halton and Scott Blair.

TABLE 5.—EFFECT OF FERMENTATION ON VISCOSITY (η), MODULUS (n), AND THE η/n RATIO, AS REPORTED BY HALTON AND SCOTT BLAIR, 1936

Flour	Time in hours	Viscosity $\eta \times 10^{6}$	Modulus $n \times 10^{4}$	η/n ratio
No. 1 Manitoba.....	1.2	3.97	3.16	126
	6.9	3.25	3.09	105
No. 3 Manitoba.....	1.1	3.25	2.61	124
	7.0	1.83	3.09	90
Barusso Plate (Argentina)	1.1	3.33	3.53	94
	7.1	2.07	2.39	89
Australian	1.1	2.52	3.21	78
	7.0	0.76	1.58	48

While Halton and Scott Blair do not find in these studies a basis for quantitatively expressing the approach of optimum fermentation in terms of η or n, they do observe that these constants are of major importance. Viscosity must be high enough to prevent undesirable flowing-out of the dough; on the other hand, modulus must be low, to permit of a substantial elastic expansion under the relatively low gas pressure within the vesicles of an expanding leavened dough. Since both η and n are influenced by the water content of dough, considerations involving these variables must take cognizance of the role of the water present. They also recognize that tensile strength of dough determines its extensibility and gas-holding properties, and accordingly is a factor of major importance.

116. P. Halton and G. W. Scott Blair, "A Study of Some Physical Properties of Flour Doughs in Relation to Their Bread-Making Qualities," *Journal of Physical Chemistry*, May 1936, XL, 561–80.

In a continuation of these studies Halton and Scott Blair (117) extended their discussion of "shortness," or the tendency to tear, in bread doughs. The baker's concept of bread-dough shortness appears to be a complex one which depends both on ductility and tensile strength. The relationship between the rate at which η falls with increasing stress (structural viscosity) and the brittleness of materials may constitute a measurement of shortness. If dough were a true highly viscous fluid, it could be extended until the test piece was a fine thread before rupturing; if it were a solid, it would scarcely deform at all up to a limiting stress (tensile strength), and at this stress it would fracture squarely. This suggests that the more nearly a dough approaches the characteristics of a true fluid, the less "short" it is likely to be.

A relatively short dough that had been extended until it broke evidenced a mechanical anisotropy* that simulated a "fibrous" structure. Rupture occurred as a result of tearing apart of the fibers. In the process of deforming or extending the dough, there was a tendency toward the production of coarse fibers, which produced a heterogeneity of structure. This, in turn, resulted in a progressive slipping of fibers as the stress increased, which evidenced itself in high structural viscosity. When the juncture between two fibers slipped and broke, a rent was formed, and the subsequent contraction of the fibers made the rent worse.

Schofield and Scott Blair (112) developed this general concept further by means of a mechanical model to demonstrate work-hardening in dough. This model consisted of the system of six springs shown in Figure 24. Three of these springs are securely linked at *P*, the other three at *Q*, while they are insecurely linked in pairs at *R*, *S*, and *T*. Also the two springs linked at *S* are represented as only half the length of the other four. Now, if each insecure link at *R*, *S*, and *T* will stand the same maximum strain, the link between the short springs at *S* will break before those at *R* and *T*.

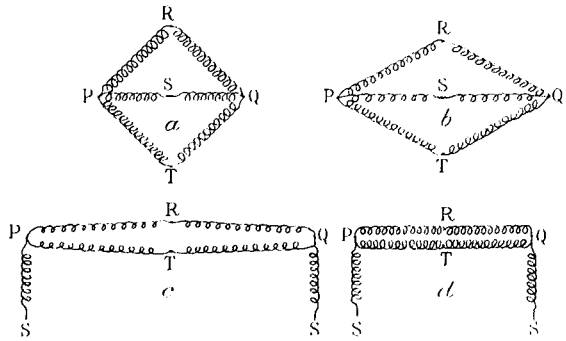

FIG. 24.—Model of a system of springs designed by Schofield and Scott Blair to illustrate certain dough properties.

The application of a small horizontal stress will produce the situation indicated at *b*, with all the links holding, and, on releasing the strain, it will return to the original condition represented at *a*. A strain sufficient to break the link at *S*, as indicated at *c*, will result in failure of the system to recover its unstrained length (as at *a*) when the stress is released; it can return only to the condition shown at *d*. The system has then undergone a permanent elongation, and has "flowed."

To be sure, a dough is not as simple as this, but comprises many such systems. Not all of these behave exactly the same when subjected to a stress. Moreover, as the progressive breaking of these links or junctions proceeds under stress, the greater must be the next increment of stress to effect the breaking of more junctions. Schofield and Scott Blair believe that the gluten contributed by wheat flour to a bread dough is actually responsible for these properties, since in these particulars washed crude gluten preparations behaved about the same as dough. Accordingly, they assumed that the gluten in dough forms an elastic network which dominates the mechanical behavior.

Additional emphasis upon the "spring" of dough was laid by Halton and Scott Blair (115), as that term was used by them to describe the recovery of dough after deforma-

* A specialized term presumably implying that a material exhibits different mechanical properties when tested in different directions.

117. P. Halton and G. W. Scott Blair, "The Relationship between Conditions Governing Rupture and Flow in Flour Doughs," *Journal of Physical Chemistry*, June 1936, XL, 811–19.

tion.* They considered this characteristic of dough to be associated with relaxation time, or the ratio η/n. Attention was also called to the fact that by adjustment of water content it was possible to make doughs from each of three flours of widely different baking quality which had either the same modulus (n) or the same viscosity (η), but by no such adjustment could the η/n ratio be made the same for the three flours without making very wide differences in viscosity itself. When η was adjusted to the same value, the strong Manitoba wheat flour dough had the lowest, and the weak Australian wheat flour dough the highest modulus; conversely, when they were brought to the same n, the Manitoba dough had the highest and the Australian dough the lowest η. This indicates the significance of the η/n ratio or relaxation time, which they regard as of fundamental importance in determining the baking quality of flour. For convenience they uniformly determined the relaxation time at constant values of n, namely 1×10^4 c.g.s. units, presumably by adjustment of the water content of the dough.

In standardizing certain of their testing techniques with the "extensimeter" diagrammed in Figure 23, they found that stresses of 1,000 and 2,000 dynes/cm.^{2} applied for one minute were the most satisfactory. The ratio between these two values of η for a series of flours, recorded in Table 6 as "structural viscosity" (shortness), appears to increase generally with decreasing flour strength. When the modulus was measured, the dough was allowed a relaxation period of three minutes, by which time the elastic after-effect appeared to be completed.

Under the testing conditions here described the data recorded in Table 6 were reported by Halton and Scott Blair. While no bakers' marks are recorded for these flours, certain comments were made as follows:

The two No. 1 Manitoba flours were unsatisfactory samples, and in the bakehouse were very slightly inferior to the samples of No. 2 Manitoba. The No. 3 Manitoba was also a poor sample of its type and its much lower spring figure of 58 compared with about 90 for the No. 2 Manitoba samples is in keeping with its much poorer quality in the bakehouse. The No. 4 Manitoba was one of a batch of Nos. 4, 5, and 6 Manitobas which were all badly frosted. The flours were all poor in the bakehouse, the doughs being gummy and short. With none of these flours did the structural viscosity figure agree with the excessive shortness.

TABLE 6.—RELATION BETWEEN VISCOSITY η AND MODULUS n FOR A SERIES OF FLOURS OF VARYING BAKING QUALITIES, AS REPORTED BY HALTON AND SCOTT BLAIR, 1937*

Laboratory number	Flour type	Relaxation time, spring η/n	Structural viscosity (shortness) $\left(\frac{\eta\ 1000}{\eta\ 2000}\right)$
S424.....	Imported Canadian...	102	1.3
NC946....	No. 1 Manitoba.....	85	1.3
NC1011...	No. 1 Manitoba.....	84	1.3
NC958....	No. 2 Manitoba.....	91	1.4
NC1013...	No. 2 Manitoba.....	89	1.2
NC1005...	No. 3 Manitoba.....	58	1.3
NC1010...	No. 4 Manitoba.....	52	1.2
NC995....	South Australian.....	55	1.5
NC997....	South Australian.....	50	1.9
NC998....	Western Australian...	50	1.9
NC1012...	South Australian.....	38	1.6
W152/8...	English	79	1.4
W151/7...	English	56	1.6
W167/8...	English	28	2.0

* Reference 115, p. 216.

Of the four Australian flours No. 997 and No. 998 were both very short while the other two were only slightly short and yielded much better bread.

The three English samples were interesting in that they were special experimental wheats. W152/8 was an extraordinarily good sample and quite unlike ordinary English. Its high spring figure and low shortness figure are quite in keeping with its quality. W151/7 was quite good for all-English wheat flour and showed only slight shortness. W167/8, however, was a typical poor English sample and was very short.

Their data, in the light of these general comments on baking qualities of the samples involved, indicated to them the close connection between baking quality and the two physical properties of relaxation time and structural viscosity.

Issoglio (118) employed an "isterometer"

* American bakers often use the term "spring" in an entirely different sense, to refer to the increase in volume of dough during the first few minutes of oven baking.

118. Giovanni Issoglio, "La mineralizzazione delle acque e gli imposti da pane," *Annali della r. accademia d'agricoltura di Torino,* 1937, LXXX, 35–49.

having some characteristics in common with the "extensimeter" used by Scott Blair *et al.* As shown in Figure 25 it included a glass tube 4 cm. in diameter containing a mercury trough on which the test piece of dough was floated. Humid air at 20° C. was passed through the tube. The test piece of dough was prepared by mixing 75 g. of flour with an average of 32 g. of water, and allowing it to rest for 20

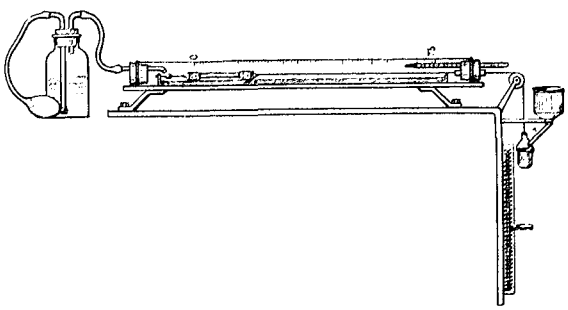

FIG. 25.—Issoglio's isterometer

minutes at 20° C. A special die was employed in cutting out a piece of dough 10 cm. long and 1 cm. in section, with enlarged ends 2.4 cm. long and 1.5 cm. in diameter. These bulbous ends were grasped by jaws, one of which was secured by a cord to the hook at the left end of the tube as shown in Figure 25, while the other was attached to a cord which passed over the pulley at the right, and terminated with a small bucket. Shot could be poured through the funnel into this bucket, thus applying to the test piece an increased force or stress, or what Issoglio terms "the force of traction."

By means of the ergometer described elsewhere by Issoglio (104) he measured the plasticity, consistency, elasticity, and work done in extending dough; with his sclerometer he measured the "hardness"; and with this "isterometer" he measured the percentage elongation with relation to time, and the reduction in diameter or percentage constriction between the initial section and the section near the point of breakage where compactness is at a minimum. From the several data he then computed the modulus of elasticity and the mechanical viscosity of the flour dough. While he does not indicate the mathematics of his calculations, one would assume that they are analogous to those detailed by Scott Blair and associates, and recorded elsewhere in this monograph. In general, the mechanics of his system are not as complete and convenient as the stressmeter of Bohn and Bailey (119), or the Schofield and Scott Blair (114) extensimeter shown above in Figure 23.

Issoglio then applied these several physical methods to a study of the effect of the constituents of natural waters, and of added minerals including sea salt, upon dough properties. Two flours were employed, one of low strength, the other of medium strength. Common salt (NaCl) appeared to affect dough properties favorably with both flours, increasing the elasticity, plasticity, and consistency, and favoring dough expansion in baking. Calcium ions in the dough solution beneficially modified dough properties if not used in excess, the optimum being equivalent to 0.15 g. Ca^{++} per liter. The effect of the latter was essentially independent of the negative ion, at least in so far as sulfate, chloride, phosphate, and bicarbonate ions are concerned. Magnesium ions did not have a like beneficial effect.

Wolarowitsch and Samarina (120) find that Schofield and Scott Blair's (109–111) η values for dough are too high, and call attention to the inapplicability of Newton's viscosity equation $\frac{F}{S} = \eta \frac{dv}{dr}$ to colloidal solutions and disperse systems, the η of which is not stable or steady. Bingham had previously inserted the yield value ϑ in the equation thus: $\frac{F}{S} - \vartheta = \eta \frac{dv}{dr}$. Wolarowitsch and Tolstoi in an earlier paper (120, p. 165) had described a coaxial cylinder plastometer by means of which they confirmed Bingham's theory represented conveniently by the equation $\frac{dv}{dr} = \varphi(\tau - \vartheta)$ in which $\frac{dv}{dr}$ is the velocity gradient, φ the fluidity (mobility), τ the shearing

119. L. J. Bohn and C. H. Bailey, "Elasticity of Wheat Flour Dough," *Cereal Chemistry*, July 1936, XIII, 389–409.

120. M. P. Wolarowitsch and K. I. Samarina, "Über Viskosität und Plastizität disperser Systeme. II. Untersuchungen der plastischen Eigenschaften des Mehlteigs nach der Methode eines rotierenden Zylinders," *Kolloid-Zeitschrift*, 1935, LXX, 280–85.

stress (or $\frac{F}{S}$ where F = tangential force and S = shearing surface), and ϑ the yield value or force required to institute flow.

Wolarowitsch and Samarina applied this method to the study of doughs. The device itself comprised an inner stationary cylinder, and an outer cylinder to which force could be applied. The yield value ϑ could be determined from the force (weight) applied in just instituting motion in the outer cylinder. Means was provided for measuring the velocity of the inner cylinder when the force applied (P) exceeded the force equivalent to ϑ (P_o).

Wolarowitsch and Samarina noted that when the weight, P, was large there was a linear relation between it and the velocity of rotation (Ω) of the inner cylinder, but when the weight, P, was reduced considerably the curve assumed a logarithmic form.

In their studies of dough, 100 g. of absolutely dry flour was mixed with varying amounts of water ranging from 90 to 150 g. It required one hour for the preparation to reach a stable state where constant values resulted. Thereafter all the preparations were mixed in a mortar for 30 minutes and then rotated in the apparatus for 10 minutes, when constant rotation values were reached.

A correlation was observed between the capacity of flour to bind water, as determined by Dumansky's refractometric method, and the plasticity constant of the flour when converted into dough.

In an effort to simplify the rather intricate "extensimeter" described and used by Scott Blair and associates (Fig. 23), Bohn and Bailey (119) designed an apparatus for measuring stress-strain relations in flour dough which is illustrated in Figure 26. The strand of dough to be tested was extruded through the circular 5 mm. orifice of the dough "gun." After a suitable rest period, this was floated on the mercury in the trough at the lower right. This bath could be placed in a thermostat for temperature control, and the humidity under the cover was maintained at a high level by moistened blotting paper. One end of the test piece was attached to a cord which passed over the windlass at the right. The other end was attached to the stress balance at the left. The latter registered the stress on the test piece, measured directly in grams. The stress balance scale was calibrated by passing the cord over the pulley shown near the center of the ensemble, attaching metric weight, and marking the readings on the scale. It will be noted that it was provided with three counterweights which permitted of a wide range of adjustment, particularly in the early stages of the experiments.

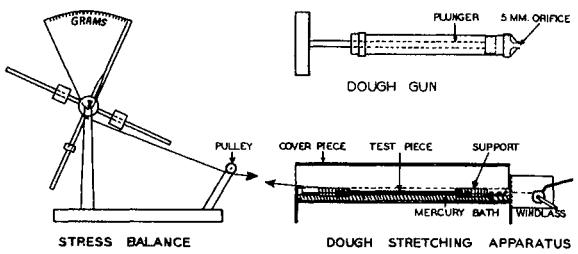

FIG. 26.—Bohn and Bailey's stressmeter assembly

As in all such studies of dough, it early became apparent that great care must be taken to accord uniform treatment to the dough in preparing the test pieces. A standard procedure commonly followed involved mixing the dough in a mechanical kneading machine to a consistency equivalent to 540 farinograph units with a 2 per cent NaCl solution, removing it immediately from the mixer bowl, rolling out a cylinder just small enough to enter the large end of the dough gun, allowing it to stand 7 minutes in the gun, extruding the test piece through the 5 mm. aperture and transferring it to the mercury trough, clamping the supports to the two ends about 16 to 20 mm. apart, and then proceeding to apply the tests. These manipulations required about 10 minutes. Other tests were also made involving total elapsed times of 15 and 20 minutes.

Since a dough in the process of fermentation extends to about five times its original size, it was arbitrarily decided to extend these dough strands to five times their original length. Thus if the latter was 18.5 mm., it was extended at a steady rate to 92.5 mm. by means of the windlass, and held there for exactly 10 seconds; 5 seconds later the first reading was recorded, or 15 seconds after ap-

plying the stress; and again after a total of 30, 60, and 120 seconds, and otherwise as necessary to the tests in progress. Duplicated tests agreed fairly well, 18 per cent of the tests having a mean difference of 1.0 g. or less with an average of 17.6 g. All tests were made at 26° C.

The recorded readings in grams were reduced to the equivalent of g./cm.^{2} and assume a constant area of cross section of the test pieces. This is an arbitrary assumption probably not in accordance with the facts, since the stronger, more elastic doughs tend to contract lengthwise and stretch in cross section, on being extruded from the dough gun, more than do the weak flour doughs. It is a convenient assumption, however, and may be quite justified in view of other empiricisms of the test, especially since it tends to set the strong and weak flour doughs even farther apart than would be the case if corrections were applied for the exact diameters. Moreover, the diameter of the test piece changes upon extension to a degree not known in these studies.

Three flours of varying baking strength, and containing (*A*) 13.2, (*B*) 11.8, and (*C*) 8.1 per cent of crude protein respectively were used in Bohn and Bailey's studies. The stressmeter readings were highest with the strong flour at all times after the stress was applied; thus, 15 seconds after applying the stress, the values were (*A*) 25.3, (*B*) 20.0, and (*C*) 12.4 g. respectively. Dying out of the stressmeter readings could be expressed graphically as a straight line when the logarithm of the reading was plotted against the logarithm of time. Moreover, the slope of this line was about the same with all three flours.

Confining comparisons to the 15-second stressmeter readings, a high correlation with the baking-quality score of loaves baked from leavened doughs mixed for 5 minutes (a rather heavy mixing treatment for the machine that was employed) was computed in a series of 36 comparisons made with hard wheat flours, $r = +0.90$. The correlation was significant, but lower, between the same stressmeter readings and the baking-quality score when doughs were mixed only 3 minutes, viz., $r = +0.54$. In general, the stressmeter readings were somewhat more highly correlated with the baking tests than was the crude protein content.

These studies were extended by Bohn and Bailey (121) to include other variables. When time of mixing in the farinograph mixer of either strong (*D*) or medium-strength flour (*E*) was the variable, the 15-second stressmeter readings decreased substantially during the progress of mixing. Thus the reading for the strong flour dough (*E*) was 16.4 g. after 3 minutes, 10.7 g. after 15 minutes, and 3.2 g. after 30 minutes mixing. With the medium-strength flour (*E*) the equivalent readings were 13.5, 7.7, and 3.9 g. respectively. Effects of overmixing in terms of diminished stressmeter readings were evident from similar studies with the Swanson-Hobart dough mixer.

The thermal coefficient of these stressmeter readings was large, varying from 1.3 g./cm.^{2} to 2.0 g./cm.^{2} per degree C. as the temperature was decreased progressively from 35° C. to 20° C. Effect of water used in the dough upon stressmeter readings has been discussed in Section I.

Bohn and Bailey (122) traced the effect of fermentation, and of salt, fats or shortening, dry milk solids, papain, malt extract, and malted wheat flour upon these stressmeter readings, but these details of baking technology are somewhat beyond the scope of this monograph and will not be discussed here. One general suggestion may well be made, however, namely, that the appropriate degree of "softening" or "mellowing" in fermenting bread doughs merits more study than has been accorded it. The author suspects that the right combination of physical properties and gassing rate* results in optimum bread quality, and that this combination may ultimately be identified and maintained, not alone

* Gassing rate defines the rate of production of gaseous CO_2 in dough as a consequence of alcoholic fermentation and involves an adequate concentration of fermentable sugars.

121. L. J. Bohn and C. H. Bailey, "Effect of Mixing on the Physical Properties of Dough," *Cereal Chemistry*, September 1936, XIII, 560–75.

122. L. J. Bohn and C. H. Bailey, "Effect of Fermentation, Certain Dough Ingredients, and Proteases upon the Physical Properties of Flour Doughs," *ibid.*, May 1937, XIV, 335–48.

through the selection of suitable flours and other dough ingredients, but also in terms of the progressive change in physical properties which occurs in baking. Too much attention has been given to the properties of freshly mixed dough, and not enough to the properties of the same material after it has fermented for a time.

Neumann and Mohs (123) devised a machine for measuring the stretching abilities or ductility of dough. A 200 g. portion of dough was fitted and locked into two clamps supported on a track in such a manner that they could be moved horizontally away from each other. By means of cords, these clamps were steadily drawn apart and the strand of dough thus elongated until it ruptured. The distance through which it had been extended was then read on a graduated scale. These investigators noted that the extensibility thus measured tended to increase through the first hour after mixing, and in certain instances for even a longer time. Using the mean values recorded at half-hour intervals over 3 hours, the measurements ranged from 7.9 to 36.2 cm. When yeast was included in the dough, the values were reduced in all cases. While this crude machine possessed certain features found in several of the new and more refined instruments, it apparently was not extensively applied, either in the laboratory where it originated or elsewhere.

Extensograph

Munz and Brabender (124) call attention to certain inadequacies in farinograph tests of doughs, particularly in the instance of doughs at rest, and in studying the effect of oxidizing agents upon dough extensibility. For the latter purposes the Brabender extensograph previously described by Kuhlmann (125) and others has been found to be more adequate. A schematic diagram of the extensograph is shown in Figure 27. The solid cylinder of

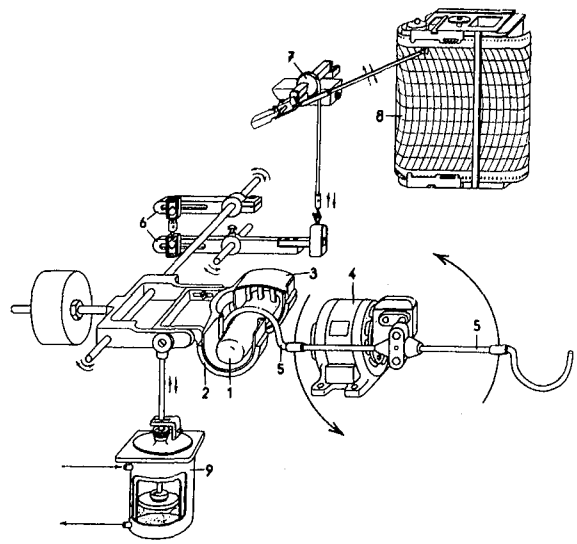

Fig. 27.—Schematic diagram of the Brabender extensograph

dough to be tested is shown at 1, supported by an arm, 2. The dough is held by clips, the farther one being shown at 3, while the one at the near end of the dough cylinder has been removed to expose the dough. A motor at 4 drives the arm at 5 which engages and extends the dough. In later models this has been changed to provide an arm which moves vertically, instead of rotating in a circular manner as illustrated here. As the dough is extended by motion of this arm, force is exerted which works against the counterweight at the left and registers through the lever system, 6 and 7, to the stylus running on the face of the chart at 8. The greater the force, F, the farther down the chart does the stylus move. The horizontal motion of this chart is synchronized with the motion of the motor, 4, and accordingly registers the distance that the arm, 5, moves in extending the dough.

While either leavened or unleavened dough can be tested with the extensograph, the former appears to introduce a higher variability into the procedure and may well be avoided unless the effect of fermentation is involved. Preparation of the doughs by the farinograph

123. M. P. Neumann and K. Mohs, "Studien über den Brotteig; Zähigkeitsmessungen," *Zeitschrift für das gesamte Getreidewesen*, 1912, IV, 247–49.

124. Emil Munz and C. W. Brabender, "Prediction of Baking Value from Measurements of Plasticity and Extensibility of Dough. I. Influence of Mixing and Molding Treatments upon Physical Dough Properties of Typical American Wheat Varieties," *Cereal Chemistry*, January 1940, XVII, 78–100.

125. W. Kuhlmann, "Der Extensograph, ein neues Hilfsmittel der Mehlphysik zur Ermittlung der günstigsten Chemikaliendosierung," *Die Mühle*, Sept. 18, 1936, p. 1213.

has been proposed, to facilitate control of consistency and degree of mixing (or overmixing). In the extensograph ensemble is included not only the actual device as diagrammed in Figure 27, but also (1) a "rounding up" machine for preliminary forming of the round dough masses; (2) a dough-molding machine for mechanically preparing the solid cylinders; (3) a thermostat in which the doughs are incubated during rest periods and prior to testing. This feature insures constant temperature of the test pieces.

The result of such a dough test is recorded in the type of chart shown in Figure 28. From

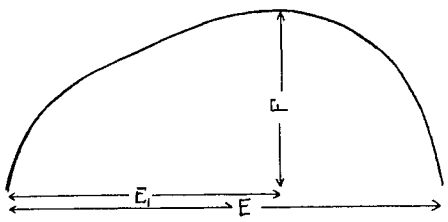

FIG. 28.—Type extensogram

such a graphic record Munz and Brabender take the following constants:

F = the force applied to extend the dough at constant speed of extension.

E = extensibility, measured on the horizontal axis.

E_1 = extension to optimum point of resistance to extension.

A = area under the extensogram.

Early in their studies Munz and Brabender found that dough properties disclosed by this system of testing changed steadily with time, and as a function of mixing treatment, fermentation, dough ingredients, and other variables. The ratio of F/E was not uncommonly profoundly altered by these variables, and accordingly this ratio constituted a convenient analysis of curve characteristics. The area under the curve was also changed, though usually to a smaller degree, since F commonly increased while E was decreasing.

Dough made from strong American spring-wheat flour and molded 4 hours after mixing exhibited less decrease in the F/E ratio on subsequent standing than did doughs molded immediately after mixing. A weak European wheat flour dough behaved quite differently, the F/E ratios being not materially different after a 4-hour rest period following mixing.

On extended overmixing, doughs tended to lose extensibility (E), and increased in resistance to extension (F), but their relative alteration appeared to be correlated with the relative "developing time" (Brabender's *Konstanz in Minuten* discussed under the farinograph) as recorded with the farinograph. Flours were quite variable in their deportment when doughs made from them were overmixed, and then allowed to rest before testing them. In general those flours which were most sensitive to overmixing, in terms of their test properties immediately after mixing, also exhibited the greatest tendency to recover the properties of a normally mixed dough when permitted to rest for a time. Munz and Brabender point out that there may be some inadequacies in the use of the slope of the farinogram as a measure of mixing tolerance, being acceptable only when dealing with the weaker flours of generally similar character.

Munz and Brabender (126) emphasized that while the farinograph does not adequately register the effect of oxidizing agents, such as potassium bromate, upon the properties of flour doughs, properly conducted tests with the extensograph are very useful and significant. Certain properties of untreated flour doughs can be used in predicting their response to oxidizing agents, and the "oxy-number" can be estimated from the formula $\frac{Area}{F/E \times 10}$. A low value approaching zero and ranging up to 20 indicates a strongly negative reaction to bromate, i.e., an impairment of baking qualities when bromate is included in such a dough; 20–30 implies moderately negative behavior, 30–40 is generally neutral, 40–50 moderately positive, and over 50 very positive. The values are not absolute criteria, however, since the position of the "neutral" or nonreactive value is contingent in part upon bakeshop practices where the dough is being converted into bread. The effect of bromate in controlling or restraining the action

126. Emil Munz and C. W. Brabender, 1939. (Unpublished manuscript, which will probably appear during 1940 in *Cereal Chemistry*.)

of proteolytic enzymes of the papain type in dough, and of protease activators such as cysteine, was demonstrated from the extensograms. Thermal or heat conditioning of soft European wheats could be standardized conveniently in terms of extensograph tests.

Area under the extensograms appeared to furnish a basis for prediction of bread-baking qualities of wheat flour doughs. Values in excess of 1,200 (arbitrary units as measured in terms of 0.1 cm.^{2} under the conditions of the experiments) indicated large loaves representing "strong" flours, and areas below 400 very small loaves, with gradations between these extremes.

An artificial manipulation of the gluten content of dough, as effected by addition of crude gluten or by dilution with starch, also resulted in altering the *Area* under the extensogram. The role of gluten was further emphasized by experiences with natural flours having a varying gluten content. Assuming flours to have been accorded a proper conditioning, or treatment with oxidizing agents, the tentative relations between *Area* and gluten content are: *Area* = 600± for 8 per cent crude protein in the flour; *Area* = 1500± for 16 per cent crude protein, with equivalent areas at intermediate levels of protein content.

Munz and Brabender also suggest that the adaptability of soft wheat flours to special baking purposes, such as making soft cakes, cookies, pastry, and crackers, can be determined from attributes of the extensograms. The following ranges in *Area* are proposed:

Type of baked product	Area under extensograms
Angel food and layer cake	300–450
Cookies and pastry	350–500
Cracker sponges	600–700
Cracker dough	500–600

Moreover, in bread-baking practices, certain details of formula and shop program can be brought under more definite control, in the judgment of these investigators, by analysis of the extensograms resulting from appropriate variation in dough treatments.

A device having some characteristics in common with the extensograph, at least in so far as the dough characteristics to be measured are concerned, but differing substantially in its purely mechanical features, is described in the British patent issued to Halton and Fisher (127). Viscosity and tearing properties of dough are measured and recorded by impaling a ball of dough (generally following appropriate fermentation) upon two separate horizontal arms. The upper arm is attached to a weighted lever which functions as a balance in measuring the force applied in extending the dough. The lower arm is attached to a worm gear in such wise that as the worm is rotated the arm steadily moves downward, and extends the dough impaled on it.

When the test is started, these two arms or pins are in juxtaposition. A motor is then set into motion which moves the lower arm downward. The same gear which moves it also rotates a cylindrical drum on which a paper chart is mounted. As in the extensograph just described, a stylus records vertically the force applied throughout the test until the dough strand fractures and the force returns to zero. Also the extension is indicated along the horizontal axis.

Concerning the data resulting from such tests, no extended reference has yet been made in the literature. The author has seen the device in action in the laboratories where it was designed, and representatives of certain British milling firms have expressed satisfaction with it, based upon their experience or observations.

Discussion

The formation of a normal bread dough is a gradual rather than an instantaneous process in which time, mechanical treatment, and dough ingredients are most prominent in determining its properties at the instant of measurement. Such dough possesses several physical properties that are of significance, including viscosity or plasticity, elasticity, ductility or extensibility, tensile strength (particularly significant when extended under stress), stickiness or adhesiveness, and possibly others, or unique combinations in complex

127. Philip Halton and Ernest A. Fisher, "An Improved Process for Determining the Baking Qualities of Wheaten Flour Dough and Apparatus Therefor" (British Patent 492,049, Sept. 14, 1938).

properties. It has not proved to be simple or easy to devise testing machines that would measure these properties singly. Moreover, it is not yet clearly evident how each of these properties should be weighted in introducing them into an equation for the prediction of baking quality. Schofield and Scott Blair proposed the *relaxation* time (*tr*), or ratio of viscosity (η) to the rigidity modulus (n), as a compound factor which they found to be related to baking behavior of dough. This equation is probably not complete, however, and they refer to the probable significance of work-hardening and tensile strength.

Of the types of mechanical devices which have had the largest application in dough testing, two have been outstanding: (1) the recording dough mixer, and (2) some sort of extensimeter. Several commercial instruments have been offered for both purposes.

The recording dough mixer has been proposed particularly for (*a*) affording a measure of relative viscosity or mobility ("consistency") of dough as a function of the proportion of water used, (*b*) tracing the relative rate of dough formation, and (*c*) indicating dough-mixing stability in terms of the rate of softening or increase in mobility with extended mixing. It has been proposed that when *a* is standardized at a constant value, *b* and *c* singly or combined afford an index of flour strength. With natural or untreated flours, there may be a correlation between *a* and *b* on the one hand, and baking strength of flour, although the measurements in question do not directly reveal those physical properties which are really responsible for the satisfactory behavior of dough in baking.

Data have been presented from time to time which appear to justify certain general observations relative to the interpretation of recording dough-mixing data. Dough has an appreciable temperature coefficient in terms of mobility or consistency, and accordingly such measurements should be made at constant temperature. "Strong" flours generally require a more extended mixing than weak flours. Optimum mixing time is an exponential function of mixing speed, i.e., the rate of rotation (within reasonable limits) of the arms of a dough mixer. The work input to bring dough to the optimum state in mixing is relatively constant when speed of mixing is the variable. Optimum mixing time is somewhat short of the time required for doughs to reach maximum consistency or minimum mobility.

Sensitivity to overmixing, as evidenced by a high rate of decrease in consistency after the maximum is reached, appears to be a function of several variables, including mechanical degradation of the gluten structure, proteolytic action, action of α-amylase, and presence of protease accelerants such as cysteine or glutathione—which may be contributed by wheat-germ tissue and by dough ingredients other than flour such as milk solids, salt, and other materials. Oxidizing agents commonly used as dough improvers, such as bromates, do not evidence their effect as emphatically when tests are made by recording dough mixers as when dough extensibility is determined.

Using the dough-development time, or time in minutes for the dough to register maximum consistency in a recording dough mixer, it was observed by Markley (128) that at least 7 per cent of gluten must be present to insure a continuous gluten matrix. Above 8 per cent of gluten the dough properties are related to the properties of the gluten, while below 7 per cent the dough properties are determined largely by the starch component. Stamberg (129) computed that the film of protein at this 7 per cent gluten level would be 3700 Å thick* in an anhydrous state; but of course it is thicker, and to an unknown degree, in the wetted or hydrated state. Also it was calculated that each milligram of gluten, when most highly attenuated, would cover 20.9 cm.^{2} of starch granule surface in the dough.

When an overmixed dough is removed from the mixer and allowed to stand for a time, it tends somewhat to regain the properties of a normally mixed dough. Evidently some rearrangement of the disturbed structure formed

* Å or Ångstrom unit = 0.1 millimicron (mμ) or 1×10^{-7} mm.

128. Max C. Markley, "The Colloidal Behavior of Flour Doughs. III. Studies upon the Properties of Flour-Starch-Water Systems," *Cereal Chemistry*, July 1938, XV, 438–44.

129. Olof E. Stamberg, "Starch as a Factor in Dough Formation," *ibid.*, November 1939, XVI, 769–80.

by the gluten micelles occurs with the lapse of time.

Extensimeters can be devised which will afford measures of (1) dough viscosity or plasticity, (2) elasticity or rigidity modulus, and (3) extensibility. Chopin computes and records the first in terms of pressure (P) required to inflate a thin dough bubble, the third in terms of increased surface area (G), and also attaches significance to the total work (W) done in inflating the bubble to the point of bursting. The same general principles of analysis of inflated dough bubble tests were accepted by Borasio and de Rege.

Records of dough tests made with Brabender's extensograph, where a strand of dough is extended as a U by applying force at the lower center until it ruptures, are analyzed in terms of (1) force applied as an index of resistance to extension (F), (2) extensibility (linear) to the point of rupture (E), and the relative area (A) under a curve or extensogram expressing F vertically and E horizontally. The ratio of F to E becomes quite significant in characterizing a flour or a dough. Thus with certain types of flours it may often be appreciably increased by appropriate thermal treatments or heat conditioning, or by addition of certain oxidizing agents such as bromates.

A simple mathematical treatment of the extensogram was proposed by Munz and Brabender for predicting response to oxidizing reagents such as bromates, viz., "oxynumber" $= \frac{Area}{F/E \times 10}$. Values below 30–40 generally implied a negative or unfavorable response to such reagents, and values above that level were encountered in flours responding positively.

Area (A) under the extensogram was observed by Munz and Brabender to afford a basis for prediction of baking quality. They also observed that A tended to increase regularly with increasing gluten content under conditions where gluten properties did not become predominant factors. They also decided that extensograms might prove more useful in adjusting bakeshop practices to varying flour qualities or dough formulas than through the use of a recording dough mixer.

In a normal bread dough it appears that a sustained stress may result in a permanent disarrangement of the gluten micelles, to the extent that they are drawn out of their original "brush heap" pattern into a more orderly pattern with the micelles more nearly parallel along their longest axis. In the latter state their polar groups become more definitely involved in attaching micelle to micelle, with a resulting loss in elasticity. This pattern is not normal, however, and if the stress is promptly removed the dough tends to regain its normal pattern. Time is a factor, however, and if the stress continues for an extended period, work-hardening results, and the dough loses its "spring" or resiliency. Accordingly, in a scientifically conducted bakeshop program, the optimum quality of bread should be the consequence of (1) selection of flour of adequate strength, (2) dough-mixing treatment adjusted to the flour and to the fermentation treatment to follow, (3) a fermentation practice adjusted to take the fullest possible advantage of the progressive changes in dough properties as a function of time and biochemical reactions, to include (4) an adequate rate of CO_2 gas production so as to complete the desired inflation of the dough mass before the latter loses the necessary tensile strength, extensibility, and elasticity. *Time* is a very important factor.

Substantial progress has been made within the past decade in studying dough properties, and in designing instruments and machines for measuring them. Certain of the latter have been overrated by their inventors, and frequently because they provided means for only an indirect approach to, or did not include means for observing all of, the significant dough properties. Gradually these inadequacies are becoming recognized, and proper allowance made for them. It would be almost a miracle if, in these early stages of working our way through this complex problem, we should be provided at once with an instrument which not only measured but integrated all these variables, and introduced them into a completed numerical score with the variables weighted just as they are in the baker's appraisal of dough quality.

Moreover, it seems highly unlikely that such

a testing mechanism should be expected to indicate an optimum program for the bakeshop on the basis of a single test. Rather must we expect, for some time to come, that several tests must be applied, notably through the progress of a fermentation period, to determine how a dough is responding with the lapse of time, and in the face of the ensuing biochemical events. Thus we may gradually evolve a sound approach to the study of doughs, devoid of the conjecture and inadequately supported claims that have created some confusion well confounded in recent years.

This study was kindly prepared at the request of the Food Research Institute. The author is professor of agricultural biochemistry in the University of Minnesota and was editor-in-chief of Cereal Chemistry *1924–30.*

INDEX