THE RELATION OF PARTICLE SIZE TO CERTAIN FLOUR CHARACTERISTICS[1]

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ABSTRACT

A hard-wheat, 90% patent flour was air-classified in six particle size ranges and the separated fractions analyzed for particle size distribution, ash, protein, maltose value, gassing power, and viscosity as measured by the amylograph. The analysis of different samples of the same flour did not vary as greatly as does the analysis of the different size particles, themselves, that comprise the given sample of flour.

Both ash and protein content showed marked fluctuations with particle size ranges. At a very low micron size, the ash content was, roughly, double that of the original flour.

Ash decreased rapidly to about 15 microns where it was well below the original ash content. From 15 to 30 microns, the ash content increased, probably because the ratio of small endosperm cells and peripheral cells to more-or-less free starch granules increases. From 30 to 70 microns ash content again decreased, followed by an increase above 70 microns because there is a greater number of covered cells and aggregates in this size range.

Protein content followed the same general pattern, showing a wide range from 5.5% in the region around 15 to 30 microns (where free starch granules occurred in larger amounts) to well over 25.0% in the region under 5 microns.

The exact size at which these fluctuations in analysis occur and their extent depend on the wheat, the grade of flour milled from it, and the milling process used.

Maltose value and gassing power decreased with increasing particle size to approximately 70 microns where there was a definite increase.

Specific surface, which can be calculated from the particle size distribution curve, correlates very well with maltose value and gassing power for most flours — in fact, better than starch damage as it is presently measured. Starch damage is dependent on the type of grinding and does not necessarily parallel fineness of grind. Maltose values showed a log linear relationship with specific surface for a flour ground to varying degrees of fineness. The ratio of maltose value to gassing power increases as the particle size decreases.

Viscosity as measured by the amylograph showed an increase from the very small micron range to a peak around 20 to 30 microns, where there was the greatest concentration of free starch and the lowest protein content. There was then a drop in the curve, followed by an increase in viscosity in the coarsest size range.

Further work on the structure of the endosperm in relation to milling practices should lead to a better basis for assembling flour streams and to more realistic flour specifications.

Ash and protein content and some measure of malt response, such as maltose value, gassing power, or viscosity, are routinely used in

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the evaluation of flours. The relation of these factors to particle size and of particle size to the particular endosperm structure has not been sufficiently understood. Much excellent work on the structure of the wheat kernel is available and is beginning to receive the attention it deserves. As long ago as 1905, Cobb (10,11) published results on a comparative study of flour cells. He found a gradual decrease in the size of the starch granules from the center to the periphery of the endosperm. An exception is that part of the kernel near the crease, more particularly near the tip of the kernel where comparatively large starch granules occur, even near the outermost edge of the endosperm. Among the several descriptions of the general structure of wheat or its endosperm are those reported by Alexandrov and Alexandrova (1), Berliner and Rüter (3,4), Fairclough (14), Hayward (19), Percival (33), Vogel (37), and Winton and Winton (43). Greer and Hinton (15), Greer, Hinton, Jones, and Kent (16), Hinton (22,23), Hinton, Peers, and Shaw (24), and Jones (25), among others at the Cereals Research Station of the Research Association of British Flour-Millers, have made notable contributions to our knowledge of the structure of wheat and, in particular, the composition and distribution of certain constituents in the various dissected parts. In an outstanding series of papers, Bradbury, MacMasters, and Cull (5,6,7,8) reviewed earlier work and provided additional information on the gross anatomy and microscopic structure of various parts of the wheat kernel. Hess (20) and Hess and Mahl (21) have explored a new viewpoint of the structure of the endosperm and the formation of gluten by means of the electron microscope and X-ray and by ultraviolet fluorescent microscopic techniques. Two types of endosperm protein were separated by specific gravity using sedimentation in nonaqueous medium. Hess and co-workers termed these fractions "wedge protein" and "adhering protein" and reported them to be widely different in properties. According to Hess, only "wedge" protein forms gluten. Small amounts, a few percent or less, of wedge or "free" protein can be separated by sedimentation or air elutriation from a normal flour. More can be separated from a soft wheat flour than from a hard wheat flour and more from a finely ground flour than one milled conventionally. Elias and Scott (13), Hanssen and Niemann (18), and Wichser (42) have given some figures on the amounts and analyses of various fractions separated by air-classification of flour from hard and soft wheats. More recently Jones, Halton, and Stevens (26) have described flours obtained by the air-classification of hard and soft wheat flours.

For many years it has been recognized that the ash and protein

contents of flour are increased by small bran and germ particles that are occluded with the endosperm particles. It is less well known that cell-wall material from broken endosperm cells may contribute significantly to the ash content, particularly when it is present in higher than normal amounts. For example, when a fine, high-protein portion is air-separated from hard wheat flour, the ash is distinctly higher than the same particle size fraction of the same protein content separated from soft wheat flour. This is due to the greater amount of small broken pieces of cell-wall material in the hard wheat endosperm which, being small in size and light in density, are separated in the fine fraction. The cell-wall material has an important effect on viscosity, dough characteristics, color, and baking quality. About 65 to 70% of the endosperm cells are intact in a conventionally milled flour. This figure varies with the wheat variety, the tempering process, and the extent of grinding. Kent and Jones (27) gave an estimate of 65% intact cells in a straight-grade flour milled from Manitoba wheat, of which 13% were uncovered, 26% partly covered, and 26% covered; the balance of nonintact cells were given as 14% solitary and 21% aggregated. Flour is made up of peripheral, prismatic, and central endosperm cells which vary in size and shape. These cells contain large lenticular and small, more spherical starch granules, with some of intermediate size. The range in size of starch granules is from 1 to 50 microns. There are also present in flour very small percentages of free protein and endosperm cell-wall material from broken cells. The relative percentages of the different types of particles do not vary to any great extent from flour to flour of the same type, although marked variations occur in separate streams. The analysis of different samples of the same grade of flour does not vary as greatly as does the analysis of the different size particles, themselves, that make up the given sample of flour.

The uniformity of flour has assumed steadily greater importance with the continuing mechanization and control of the breadmaking process. The enzyme response of flour is a critical factor in maintaining this uniformity. Most bread flour milled from wheat grown in this country needs malt supplementation. Millers may add either wheat or barley malt flour. Bakers may use additional malt extract and various fungal enzymes. It has long been known that the response of flour to such enzymes depends on native starch susceptibility, the extent of starch damage, the level and balance of various enzymes of the flour and supplement, and the inactivation temperature of the enzymes. Sound, normal flours are considered by most investigators to contain largely beta-amylase with little, if any, alpha-amylase

except when milled from sprouted wheat.

There are several methods of measuring the malt response of wheat flour. These are the familiar maltose figure involving autolytic production of reducing sugars, gassing power in the 4th, 5th, or 6th hour, and the amylograph. In Europe where sprouted wheat is more of a problem, Molin's (30) method for the determination of sprout damage and its modification by Kent-Jones and Amos (28) as a dextrin figure are widely used. Each of these methods has certain advantages. The subject has been discussed by Dadswell and Gardner (12), Kent-Jones and Amos (28), and Sandstedt, Blish, Mecham, and Bode (35).

Any of these tests can be correlated with results of any baking test, but each method leaves much to be desired. While there is reasonable correlation between maltose, gassing power, and amylograph figures on the same grade of flour milled in one mill, correlations between any two of these measurements are not good in a comparison of flours milled from widely varying wheat mixes, of different grades, or with significantly different mill flows.

It has long been known that flours milled from certain wheats show poor malt response. Overgrinding of a flour, as for instance in a ball mill, will increase the response to malt because of smaller particle size, with consequent greater specific surface, and because of a large increase in damaged starch granules. However, the effect of particle size on malt response in a normal flour has not been clear; neither has the measurement of malt response to starch damage. Beta-amylase cannot act on raw, undamaged starch and it acts in flour only on those granules rendered susceptible to attack by other enzymes or by mechanical damage. The effect of excess grinding on the malt response and the baking quality of flour is usually attributed to starch damage, but our methods for measuring starch damage and consequent proof of this thesis leave much to be desired.

The studies reported in this paper were made to investigate the relationship of particle size and endosperm structure to ash, protein, maltose value, and gassing power as determined from air-classified fractions of a given flour. The effect of grinding on maltose value and gassing power and the dependence of these two measurements on the specific surface and starch damage will be discussed.

Materials and Methods

An untreated 90% patent flour milled from hard winter wheat, analyzing 0.42% ash and 11.2% protein on a 14% moisture basis, was used as a source material. It was air-classified in an Alpine 132-

MP Mikroplex Classifier nineteen times in order to make six fractions. A minimum of five classifications is necessary to make six fractions. The additional classifications may lead one to believe that excessive reduction of particles occurred. However, this was not the case; experience with this equipment has shown that most of the reduction is done during the first two or three classifications.

The aim in the present work was to resolve a flour completely into fractions of varying particle size by means of air-classification. In the coarser part of the range (above about 40 microns), this presented the difficulty that the range of separation is above that for

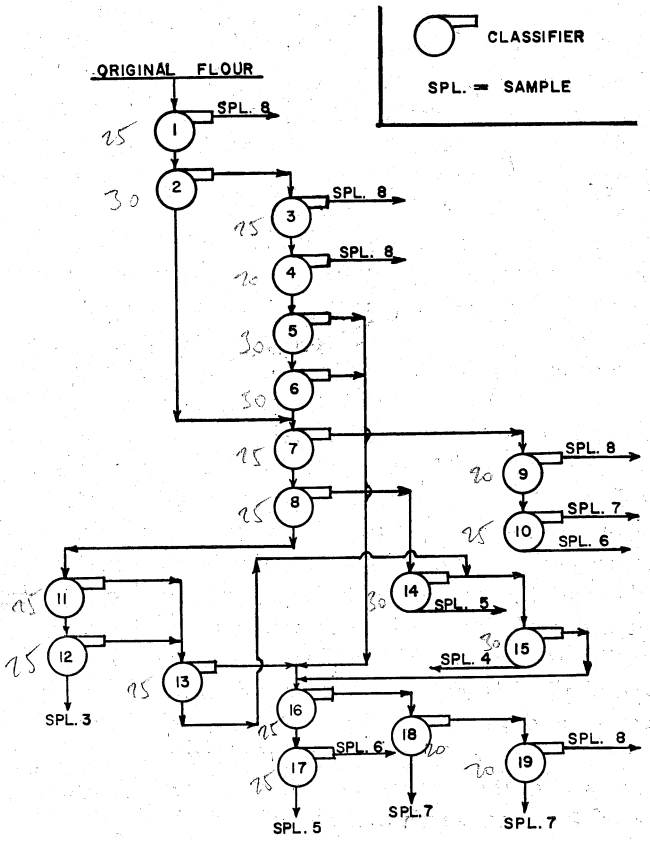

Fig. 1. Classification procedure. The vane setting is given in degrees and the feed setting in mm. They are as follows: 1) 20°, 25 mm.; 2) 50°, 30 mm.; 3) 20°, 25 mm.; 4) 25°, 20 mm.; 5) 50°, 30 mm.; 6) 30°, 30 mm.; 7) 40°, 25 mm.; 8) 45°, 25 mm.; 9) 25°, 20 mm.; 10) 50°, 25 mm.; 11) 50°, 25 mm.; 12) 50°, 25 mm.; 13) 50°, 25 mm.; 14) 50°, 30 mm.; 15) 50°, 30 mm.; 16) 50°, 25 mm.; 17) 50°, 25 mm.; 18) 50°, 20 mm.; 19) 50°, 20 mm. Feed rates varied between 80 lb. per hour and 400 lb. per hour.

which the Mikroplex Classifier is designed and, to obtain the desired cut size, it was necessary to feed the machine at relatively heavy rates in this range. With the Mikroplex, the actual cut size, obtained at any setting of the cut-size regulators, increases as the feed rate is increased. On the other hand, at the same time the sharpness of separation deteriorates. For this reason, a considerable number of classifications was necessary and, even so, the fractions finally obtained were not sharply defined in respect to particle size. Therefore, the chemical compositions of the particles theoretically present between various selected size limits were calculated from the data obtained on the experimental fractions.

The operation of the Alpine Mikroplex Centrifugal Air Classifier is described in detail by Rumpf and Kaiser (34). Briefly, the principle is as follows. A spiral air flow is induced toward the center of a shallow cylindrical chamber, the flat walls of which rotate at high speed to reduce drag effects. The sample to be classified is introduced into the chamber, whereupon each particle becomes subjected to two opposing forces: (a) a centrifugal force proportional to the cube of its size and (b) the air drag, proportional to the square of its size. For particles larger than the equilibrium or cut size (which is defined by the condition of operation), (a) will be greater than (b) and, for smaller particles, vice-versa. The coarse fraction thus accumulates in the peripheral region of the chamber, from where it is removed by a high-speed worm, whereas the fine fraction travels in the air stream to an exit at the center of the chamber and may be subsequently recovered by means of a cyclone or cloth filter. The operating cut size may be varied by changing the pitch of the spiral air stream by means of adjustable vanes through which the air passes on entering the separating chamber. The feed rate also affects cut size, but, at high feed rates, the sharpness of separation is reduced. A diagram of the classification procedure is shown in Fig. 1. The six samples of varying particle size ranges, from coarse to fine, are labeled samples 3 through 8.

The original flour was passed through the smooth rolls of an experimental Allis mill a total of five times in order to reduce the flour to a finer average granulation by roll pressure. This flour is labeled sample 1. The original flour was also ground in an Alpine 160-Z pin mill once at a speed of 17,500 r.p.m. This flour is labeled sample 2. Samples 1 and 2 were ground mainly for comparisons of maltose, gassing power, and amylograph data with the original flour.

The original flour, the ground samples, and the classified samples of varying particle size range were analyzed for ash, protein, maltose

value, and gassing power (6th hour) by conventional procedures as outlined in *Cereal Laboratory Methods* (2). Amylograph tests were made using 75 g. of flour at 14.0% moisture basis, 46 ml. of disodium phosphate citric acid buffer, and 414 ml. of distilled water (pH 5.35). The particular sample weight was chosen so all the determinations would be on the graph and as near as possible to the center. The particle size distribution was determined by the sedimentation method of Whitby (40,41). Whitby (40,41) and Cadle (9) have discussed the limitations of the sedimentation and other measurements of particle size distribution.

Microscopic examination of various fractions gave valuable information concerning types of cells. Starch damage was evaluated by staining with Congo Red (25) and also by the increase in maltose value on addition of 100 mg. of beta-amylase (Wallerstein) per 5 g. of flour.

Solution of Simultaneous Equations. A glance at the particle size distribution of the classified fractions, illustrated in Fig. 3, shows that there is a range in particle size in each of the fractions. It is apparent that the range in particle size overlaps from fraction to fraction, even on repeated air separations; i.e., particles of a given size may appear in more than one fraction. Arbitrary size ranges were selected and the proportion of particles in each interval was determined from the size distribution curves of each fraction. Equations were then set up for each fraction as follows:

$$\sum_{i=1}^{6} A_{ij} X_i = P_j$$

where A_{ij} = proportion by weight in the i^{th} size interval for the j^{th} sample;

X_i = the average $\begin{Bmatrix} \text{ash} \\ \text{protein} \\ \text{maltose value} \\ \text{gassing power} \end{Bmatrix}$ of the particles in the i^{th} size interval;

P_j = the chemical analysis for $\begin{Bmatrix} \text{ash} \\ \text{protein} \\ \text{maltose value} \\ \text{gassing power} \end{Bmatrix}$ of the j^{th} sample.

A system of six simultaneous equations with six unknowns was thus formed for ash, protein, maltose value, and gassing power.

One selection of intervals and the corresponding proportion in

the given range, as taken from Fig. 3, are shown in the following example.

Sample No.	Proportion in Range (Microns)						
	0–10	10–20	20–35	35–60	60–85	85–120	
3	0.0	0.0	0.0	0.08	0.46	0.46	
4	0.0	0.0	0.0	0.38	0.52	0.10	
5	0.0	0.0	0.07	0.57	0.36	0.0	
6	0.0	0.14	0.43	0.43	0.0	0.0	
7	0.0	0.32	0.62	0.06	0.0	0.0	
8	0.44 +	0.43 +	0.13 +	0.0 +	0.0 +	0.0	= 1.00

For the ash content, as shown in Table I, the equations are as follows:

$$0.08x_4 + 0.46x_5 + 0.46x_6 = 0.33$$
$$0.38x_4 + 0.52x_5 + 0.10x_6 = 0.33$$
$$0.07x_3 + 0.57x_4 + 0.36x_5 = 0.36$$
$$0.14x_2 + 0.43x_3 + 0.43x_4 = 0.43$$
$$0.32x_2 + 0.62x_3 + 0.06x_4 = 0.41$$
$$0.44x_1 + 0.43x_2 + 0.13x_3 = 0.59$$

The solution to this set of equations is:

$$x_1 = 0.88 \qquad x_4 = 0.41$$
$$x_2 = 0.33 \qquad x_5 = 0.26$$
$$x_3 = 0.48 \qquad x_6 = 0.38$$

The set of equations for protein, maltose value, and gassing power were solved similarly. Six points were determined for each curve in this manner. To improve the accuracy of the curves, numerical integration was used and the curves were adjusted accordingly. Figures 4 through 6 illustrate the results.

An assumption is made in the solution of these equations that a given x is constant for all samples. However, there is usually some deviation from this constant. This deviation can be minimized by selection of intervals where the slope of the curve is small; i.e., if, for a given x, $a - \Delta < x_i < a + \Delta$ for the set of equations, then as Δ becomes small, the equations will become more exact.

Results and Discussion

Table I gives the analytical data for the original flour, the ground samples, and the classified fractions.

Figure 2 gives the granulation of the original flour and of the same flour ground on rolls (sample 1) and by a pin mill (sample 2). Figure 3 shows the particle size distribution of the classified fractions (samples 3 through 8).

Ash. Figure 4 illustrates the ash content of flour in relation to particle size, expressed as Stokes equivalent spherical diameter in microns.

At a very low micron size (under 8 microns), the ash content is, roughly, double that of the parent flour. This is due partly to cell-

TABLE I

ANALYSIS OF AIR-SEPARATED FRACTIONS

SAMPLE	PERCENT OF ORIGINAL	RANGE OF PARTICLES [a]	MOISTURE	ASH [b]	PROTEIN [b]	MALTOSE VALUE [b]	GASSING POWER	AMYLOGRAPH
	%	μ	%	%	%	mg	mg Hg 6th hour	B.u.
Original flour	100.0	11 – 96	12.7	0.42	11.20	204	430	680
1	100.0	9.8– 76	11.2	.42	11.20	225	440	630
2	100.0	3.8– 60	7.3	.42	11.20	255	492	570
3	15.1	51 –115	9.6	.33	11.30	112	278	865
4	11.3	38 – 99	8.8	.33	12.30	106	271	835
5	15.8	30 – 83	9.0	.36	13.00	116	290	825
6	14.1	12 – 62	9.2	.43	10.80	180	400	770
7	23.4	11.5– 45	9.1	.41	7.30	237	472	860
8	20.3	3.3– 28	8.4	0.59	15.20	418	640	315

[a] The range is given as the mass median diameter ± two standard deviations.
[b] At 14% moisture.

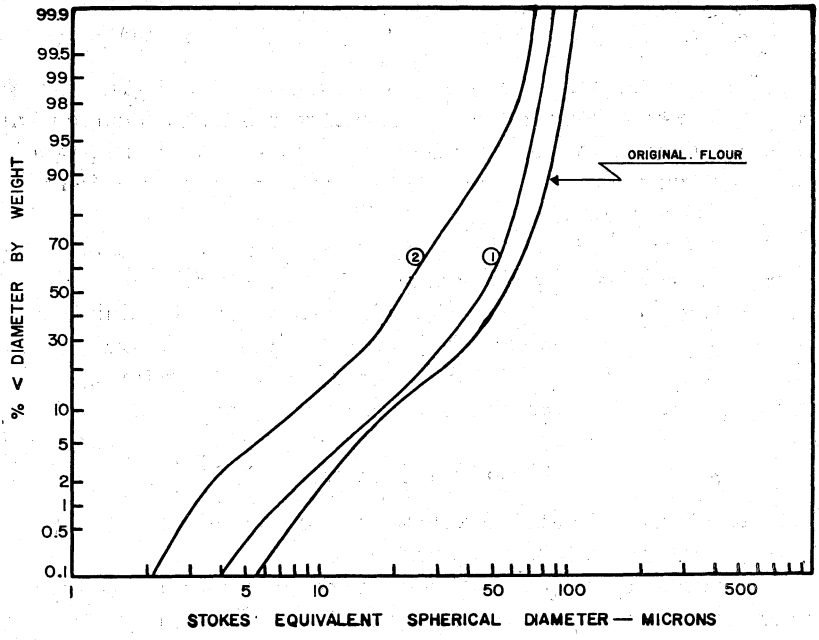

Fig. 2. Particle size distribution of original flour and of the same flour ground on rolls (sample 1) and by impact (sample 2).

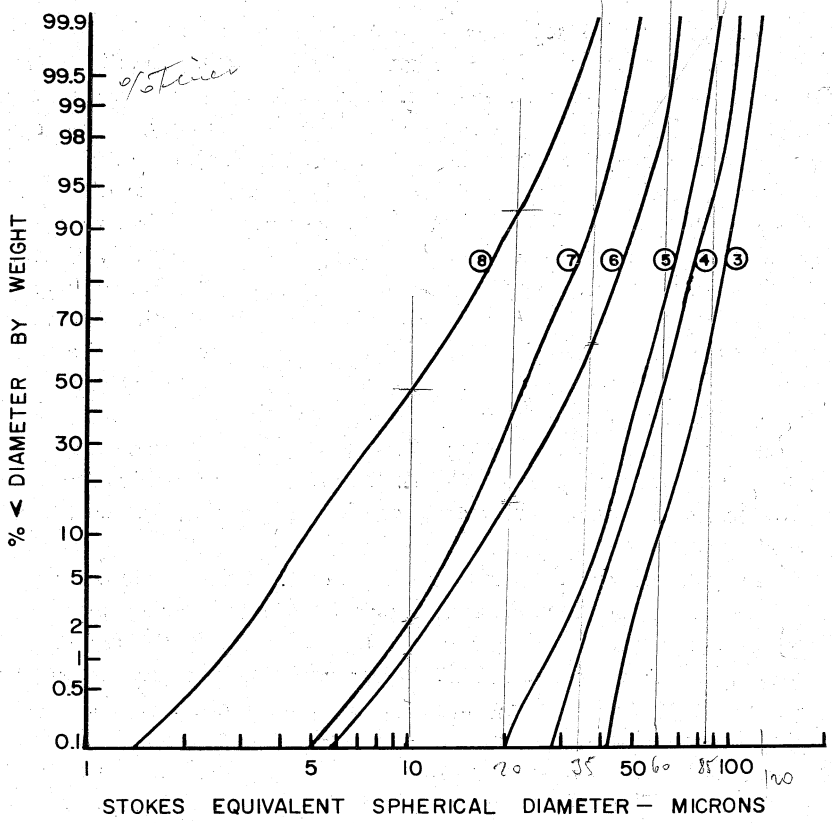

Fig. 3. Particle size distribution of classified fractions of flour.

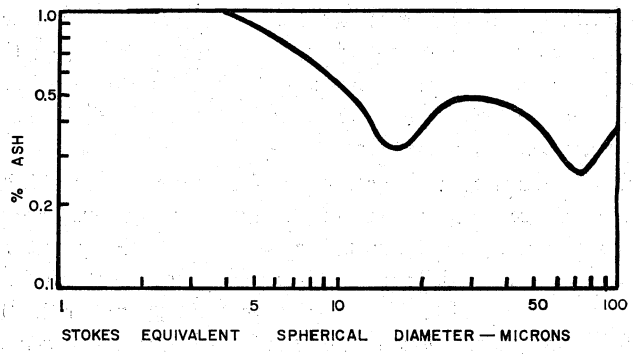

Fig. 4. Ash content of flour versus particle size.

wall material which separates in the finest fraction and also, to a lesser extent, to protein sheaths higher in ash than the smaller starch granules, to very small fragments of bran and germ, and to dust and crease dirt. The ash decreases precipitously to, roughly, 15 microns where it is well below the ash content of the original sample. This drop in ash content (from 0.42 to 0.30%) occurs because of the increase in the proportion of free starch granules in this size range. From 15 to 30 microns, the ash content increases, probably because the ratio of small endosperm cells and peripheral cells to starch granules increases. From approximately 30 to 70 microns, the ash again decreases; such a decrease may be related to an increase in the number of larger endosperm cells and a decrease of small, covered endosperm cells. From 70 microns to 100 microns and over, there is an increase in the number of covered and partly covered cells and aggregates containing higher-ash cell-wall material and probably also some aleurone cells; this probably accounts for the increase in ash in this particle size range.

The curve of ash content versus particle size varies in the maximum and minimum ash observed at varying micron sizes, depending on the type of wheat (hard spring, hard winter, or soft) and the percent extraction of the flour separated. Similar equations calculated for size separations made on spring wheat, short patent flour gave the same general curve, but a maximum ash is observed at about 50 microns instead of 30 microns as found with a longer extraction, hard winter wheat flour. The relative amounts of prismatic, central, peripheral, and aleurone cells vary with the grade of flour. Peripheral cells from winter wheat are reported to be smaller in size than from spring wheat. Endosperm cell-wall thickness and its relative ease of separation are important factors in the spectrum of ash versus particle size of flour. Larkin, MacMasters, and Rist (29), in examining Pacific Northwest wheats, found that the starchy endosperm cell walls near the aleurone layer were about one-half thicker (4 microns) than those near the center of the kernel (2.6 microns). The cell walls in the area next to the crease were from two to two and a half times thicker (7.3 microns) than those in the center.

Morris, Alexander, and Pascoe (31,32) have studied the distribution of ash and protein in the wheat kernel and, more recently, Hinton (23) measured the distribution of ash in the wheat kernel by means of hand-dissected parts of four different wheats. The aleurone layer accounted for 56.4 to 60.2% and the endosperm for 20.3 to 25.9% of the total ash. There was a gradient in ash content from the outer to the inner layers of the endosperm, except that the endosperm next

to the aleurone layer in the region of the crease was considerably higher. Hinton thought it probable that the gradient in ash content and in many other constituents throughout the endosperm is connected with the stage of development of the cells, increased concentration of ash, and decreased concentration of starch occurring in the less mature cells next to the aleurone layer.

Protein. The relation of particle size to protein distribution is shown in Fig. 5. As is well known, protein is highest in the smallest size range from 1 to 16 microns because more thin, light-density protein fragments are included in this fraction. The protein content decreases rapidly from 1 to 25 microns because a greater proportion of starch granules is included in the highest micron size. In fact, the fraction from about 15 to 35 microns is considerably below the protein content of the original flour, because this range includes an increased concentration of free starch granules.

The protein distribution curve rises steadily from 5.5 to 16.5% protein and from 25 to 45 microns as the ratio of more-or-less intact

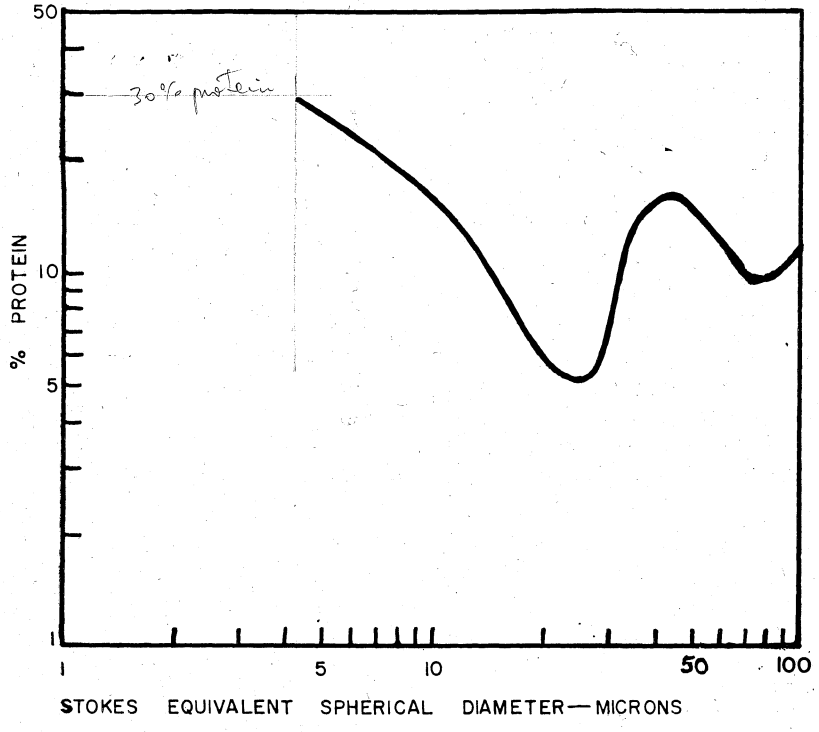

Fig. 5. Protein content of flour versus particle size.

endosperm cells to free starch granules increases. There is also an increase of prismatic and peripheral cells in this fraction. These cells are known to have a higher protein content than the central cells. From 45 to 70 microns, there is another, less sharp decline in protein percentage to somewhat below the protein content of the original flour. In this range, there are fewer peripheral cells and an increase in the number of central cells containing lower protein. More intact and aggregate cells appear in this range. Finally, from 70 to over 100 microns, there is another rise in protein content from, roughly, 9.0 to 12.0%. In this fraction, there is the highest concentration of covered and partly covered cells and double and multiple cells where no protein has been released which could account for the increase in protein content.

Maltose Value and Gassing Power. Figure 6 shows that the maltose value and gassing power of the particular flour used in these experiments are minimum at about 70 microns. Above and below this size,

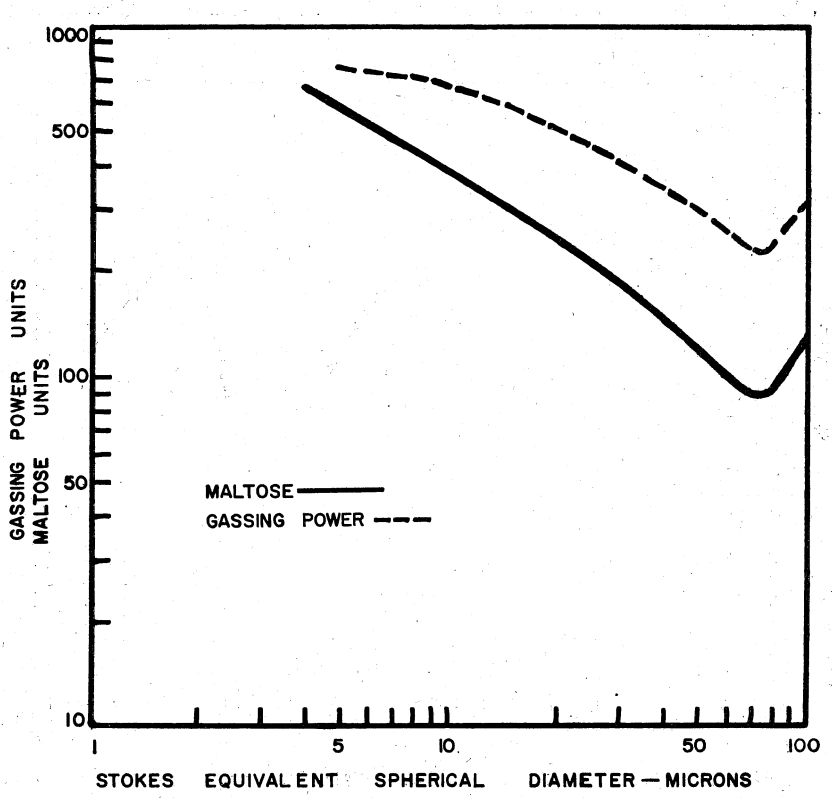

Fig. 6. Maltose value and gassing power of flour versus particle size.

maltose value and gassing power increase. For particles smaller than 70 microns, the maltose value and gassing power increase sharply with the decrease in particle size. It is difficult to account for the less marked, but decided, increase in maltose value and gassing power encountered in the size range coarser than 70 microns, since this fraction is made up of more intact endosperm cells and aggregates and has less specific surface and starch damage. A possible explanation might be that more amylolytic and/or cell-wall-splitting enzymes are present in these larger cells and aggregates. Some activity may be released during the course of the determination of maltose value and gassing power.

Similar calculations of simultaneous equations on the relationship of maltose value and gassing power to particle size on a short patent (80%) spring wheat flour gave a minimum point at 55 microns, instead of 70 microns as in the present study on a longer patent (90%) from winter wheat. The curves from both spring and winter wheat flours have the same general shape for both maltose value and gassing power.

For a given sample of flour ground to varying degrees of fineness, maltose value and gassing power show a log linear relationship with specific surface as calculated from particle size distribution. The formula is as follows:

$$A_t = 6 \sum \frac{f(d_i)_v}{d_i}$$

where A_t = total surface area per unit volume of particles; d_i = mean diameter of the particles in the i^{th} size interval; $f(d_i)_v$ = frequency by volume of the particles in the i^{th} size interval.

When flour is ground more finely, more endosperm cells are broken up, increasing the percentage of particles below 55 to 70 microns with consequent increase in specific surface. Normally, when ground by the same equipment, the finer the grind, the greater the starch damage. The shearing action and pressure of roll grinding, such as occur in conventional milling, produce more starch damage in achieving the same granulation than pin, stud, or fluid energy mills. Thus, in the hard winter wheat patent flour ground five times on smooth rolls (sample 1), there was more starch damage than in the same flour ground by impact in the Alpine 160-Z Pin Mill (sample 2). Yet the latter sample was considerably finer and showed a higher maltose value and gassing power. Microscopic examination of the ground flours, using 0.1% Congo Red solution, showed that, although "ghosts" were present in the pin-milled sample, there were virtually no cracked starch

granules; whereas, in the sample ground on smooth rolls, both radially damaged, cracked starch granules and more ghosts were present. Jones (25), in an excellent paper, stated that "granularity or particle size of flour and milling stocks is not for practical purposes a factor determining diastatic activity"; and further, that "in flours and intermediate stocks variously milled from a given wheat the maltose figure is a measure of the number of 'ghosts' present." Jones believed that the maltose figure is the result of the amount of damaged starch granules and the level of alpha- and beta-amylases. The amount of damaged starch is usually higher, the harder the wheat. When a given sample is ground in the same manner, as for example on rolls, the closer the roll setting and the greater the pressure, the finer the grind and the more starch-damaged granules, as Jones (25) has stated. However, in a comparison of stock ground by different actions, as for example rolls and impact or fluid energy, it is not valid to assume that starch damage necessarily parallels finer granulation or that particle size has no relation to maltose value.

Figure 7 illustrates the relationship of maltose value and gassing power with specific surface cm^2/cm^3. With any single conventionally

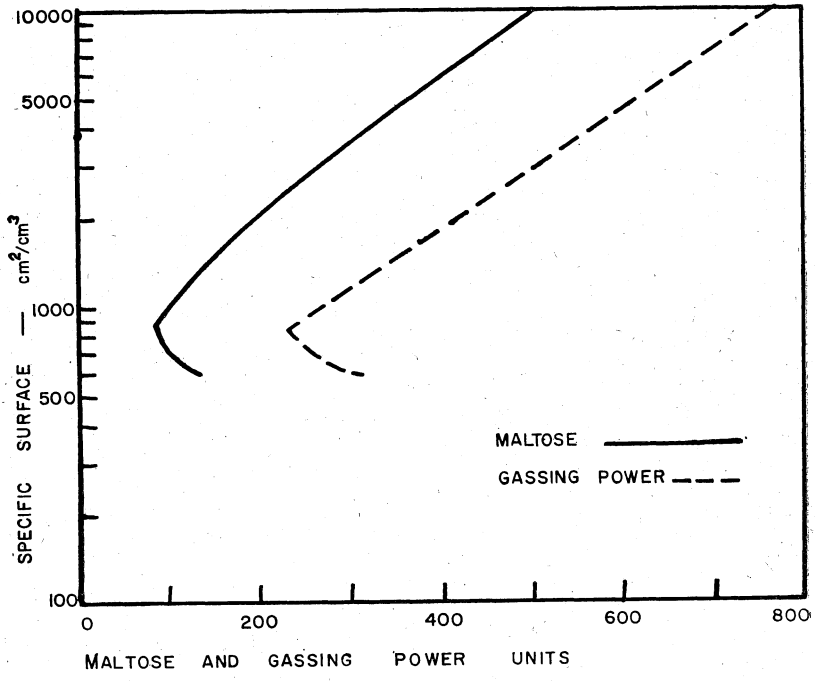

Fig. 7. Relation of specific surface of flour to maltose value and gassing power.

milled flour, there is a roughly linear relationship of maltose value and gassing power to specific surface, except in the region of lowest specific surface. For a given sample of flour ground to varying degrees of fineness, maltose value and gassing power show a high correlation with specific surface throughout the entire particle size range. This is because, in grinding more finely, more of the larger endosperm cells are broken open, thus increasing the percentage of smaller particles, the specific surface, and, consequently, the maltose value and gassing power.

Moreover, in our tests, it appears that both loaf volume and crumb resilience of bread flours are inversely correlated with specific surface.

The relation of starch damage to the specific surface and maltose value of flour needs further study. At present starch damage is usually measured by microscopic observation and counting of the damaged cells stained with Congo Red as originally proposed by Jones (25), by the amylose number advocated by Hampel (17), or by the increase in maltose value by the action of dialyzed malt extract (36). In our laboratory, we prefer to use the increase in maltose value with pure beta-amylase, together with microscopic observation of the stained cells. All of these methods leave much to be desired as quantitative procedures for starch damage. Measurements of increase in maltose value on addition of beta-amylase or dialyzed malt extract do not take into account how much damaged starch has been used as a substrate by the varying natural beta-amylases of flours.

It has been our experience that the larger starch cells (20 to 50 microns) are more subject to damage by roll pressure than the smaller cells that are present in the finest classified fraction. Yet the finest fraction is always very much higher in maltose value and gassing power than the coarser fractions. Since a damaged starch cell would be effectively lighter and its air drag increased, it would be found in a finer fraction than the normal starch granules of the same size. The relative influence on maltose value and gassing power of specific surface, of the concentration of damaged starch and of the amylases, themselves, in classified fractions remains to be determined.

Maltose value and gassing power increase in proportion to the specific surface only when the same type of grinding is employed. In an unclassified flour ground by different techniques, there is no significant change in total enzyme activity, but merely in specific surface and starch damage. The effect of two methods of grinding is illustrated in the following experiment.

A hard winter wheat patent flour, analyzing 0.39% ash and 11.5% protein (similar to but not identical with the flour that was classified),

was ground several times on closely set rolls and also on an Alpine 160-Z Impact Mill once at 17,500 r.p.m. and twice at 23,300 r.p.m. Maltose value was determined on each sample and on each sample plus 100 mg. beta-amylase. The difference in the two maltose values was taken as a rough measure of starch damage. Specific surface was calculated from the particle size distribution, as previously outlined.

TABLE II
EFFECT OF GRINDING ON MALTOSE VALUE

	Maltose Value	Difference in Maltose Value with Beta-Amylase	Specific Surface
			cm^2/cm^3
Original flour	158		
Original flour + beta-amylase	178	20	1,530
Roll-ground	586		
Roll-ground + beta-amylase	694	108	2,700
Impact-ground once, 17,500 r.p.m.	171		
Impact-ground + beta-amylase	196	25	3,170
Impact-ground twice, 23,300 r.p.m.	234		
Impact-ground + beta-amylase	290	56	5,320

Maltose value correlates with specific surface only when the same kind of grinding is used, as can be seen from the results in Table II. The flour severely ground on rolls showed more starch damage and gave a higher maltose value than the impact-ground samples of greater specific surface. The maltose value correlates with the specific surface on the two pin-milled samples as well as on flours ground on rolls.

There may be increased susceptibility to enzyme action by mechanical action of grinding in various ways that cannot be readily observed by presently used microscopic techniques. Reduction of particle size, by whatever means, is bound to result in stresses on the thin protein sheath surrounding the starch granules which would allow more ready access to enzymes. Moreover, internal stresses within the starch granule may cause rupture and cavitation on the granule surface, as Whistler, Goatley, and Spencer (38,39) have shown to result on the air-drying of corn starch. All of these points need further study.

Maltose Value Versus Gassing Power. There is reasonably good correlation between maltose value and gassing power. Many laboratories prepare curves showing a linear correlation of these two factors. But it is general experience that, with widely different mill mixes and with various flows and percentage extractions, decided departures from a straight-line relationship are common. Within a single milling or baking organization, the same chart cannot be used for all mills even when comparing the same grade of flour. The reason for this situation

is found in studying Fig. 6 on the relation of particle size to maltose value and gassing power. It is apparent that there is not a linear relationship and that the ratio of maltose value to gassing power increases as particle size decreases. Even for a given particle size, this ratio is not constant, but varies with the particular wheat mix, the milling practices, and the starch susceptibility.

Amylograph. No curve is shown for amylograph results versus particle size, since the relationship is more complicated than with the other analytical data. A few important points that have not had sufficient attention in considering amylograph data may be worthy of mention.

It is obvious that the higher the protein content of a flour, the less starch there is to gelatinize. Other factors being equal, the higher the protein content of a flour, the lower the amylograph viscosity. Beta-amylase has little effect on the amylograph figure of a normal flour. Table I shows that, on the unclassified samples, the finer the granulation, the lower the viscosity. The original flour showed 680 Brabender units as compared with 630 B.u. for roll-ground sample 1 and 570 B.u. for the more finely impact-ground sample 2. On the air-separated fractions which varied in protein content, the very fine fraction with the highest protein content (sample 8) showed only 315 Brabender units and the coarsest fraction (sample 3) gave 865 B.u. The intermediate classified samples followed no definite trend because of a number of factors, such as granulation and protein content, influencing the hot viscosity measurement. Viscosity figures do not lend themselves to treatment by simultaneous equations. The effect of particle size, protein content, and starch damage on amylograph figures will be discussed in another paper.

Further studies of the effect of milling practices on the structures of the endosperm and the relation of particle size and specific surface to various analytical specifications will lead to a sounder basis for the evaluation of flours.

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