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Dr. Norman R. Goetze

Studies of some components of test weight in Soft White wheat revealed distinct subclass differences. Wheat kernels of Soft White more completely occupied a given volume than did kernels of White Club. The Soft White kernels were larger and had a higher density than the White Club kernels. Because of their larger size, fewer Soft White kernels were retained in a given volume.

Due to their higher percent volume occupancy and their greater kernel density, Soft White wheats had a significantly higher test weight than White Club wheats.

Studies with wheats which had been sized by maximum cross-sectional diameter showed that the larger kernels had the highest test weight. They also had a higher percent volume occupancy than smaller kernels. However, it was concluded that size, per se, was not the reason for the higher percent occupancy. The general shape and condition of the bran coat of large kernels is generally more

conducive to close packing than that of smaller kernels. Generally, kernel density did not differ significantly between the larger sizes.

The smallest kernels had a lower average test weight, kernel density and occupied less of the volume than the larger kernels. Often the smallest kernels had wrinkled bran coats or distorted contours which may have caused the low packing density.

The general shape of White Club kernels is less favorable to close packing than the longer more cylindrical shape of Soft White kernels. Therefore, test weight is a measurement of unequal quantities of wheat when Soft White and White Club wheats are compared.

Some Components of Test Weight of Soft White Wheat

by

Myron Daniel Shenk

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[redacted]

Head of Farm Crops

[redacted]

Dean of Graduate School

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SOME COMPONENTS OF TEST WEIGHT OF SOFT WHITE WHEAT

INTRODUCTION

The purpose of the Grain Standards Act of 1916 was to provide guidelines by which the different qualities and condition of grain could be measured and the results expressed in terms mutually understood by all parties in the grain trade (44). Certain standards were established to measure and regulate adulteration by material other than the grain being described. The weight of a given volume of grain was supposedly related to the "soundness" of the grain.

The principal consideration in establishing the minimum weight of No. 1 wheat at 60 pounds per Winchester bushel was the amount of flour obtained during milling. Holmberg (30) states that wheat of low bushel weight produces low flour yields and that extra quantities of wheat would be required to produce equivalent amounts of flour. Much research has been reported substantiating this relationship between bushel weight and flour yield (3, 11, 28, 31, 41, 58).

However, considerable dissatisfaction has arisen to the minimum limits established for No. 1 wheat. The relationship between bushel weight and flour yield has been studied by numerous workers. Many of these researchers concluded that bushel weight was not a precise measure of the flour yielding potential of wheat, but instead was only a very general indicator (3, 4, 5, 8, 31, 50, 53, 58). In a very real sense, the United States Department of Agriculture gave official recognization to this failure of test weight as a measure of potential flour yield when it established the minimum test weight for No. 1 Red Spring Wheat at 58 pounds per bushel instead of 60, as are all other wheats.

Much effort has been devoted to developing methods which would more accurately predict flour yield. These techniques include weight of 1,000 kernels, number of kernels per given weight, cell wall thickness of bran and or aleuron layers, extraction of certain constituents with chemicals, and various sizing techniques.

Test weight is an inadequate measure of potential flour yield from white club wheats. These wheats have a very compact head and the kernels have characteristically distorted contours (8). When grown in the Pacific Northwest, white club varieties commonly have lower test weights than varieties of common soft white wheat (8, 51).

Despite this fact, Barmore and Bequette (8) have shown that over a 15-year period the flour yields of white club wheats have averaged 4 to 5 percent more than higher-test weight soft white varieties from the same region.

Thus, the purpose of this investigation is to study various components of test weight in an effort to better understand what factors may be influencing bushel weight significantly. Hopefully, such information will enhance the precision of test weight as an indicator of potential flour yield.

LITERATURE REVIEW

Bushel weight is a volume-mass relationship, greatly complicated by the fact that the mass consists of highly heterogenous particles packing in a random fashion (28). The cause of the heterogeneity can be either: 1) physiological properties of individual kernels such as density and relative amounts of various constituents, and 2) physical properties such as kernel size, kernel shape and bran condition. Many of these factors are interrelated and interdependent (3-6, 12-14, 45, 55).

The volume contained in a Winchester bushel is 2150.42 cubic inches. Since this volume is fixed, any variation in the weight of the granular material contained therein must be attributed to the nature of that material. The following discussion will consider the most pertinent factors of the apparent bushel weight of wheat.

Volume-Void Relationships

Since the basic consideration in bushel weight is weight per unit volume, the various mechanical factors are of primary interest. The granular mass of wheat filling a bushel consists of the grains and the air spaces between the grains. With a given sample of wheat, the greater the proportion of the volume which is filled with wheat the more the mass in that volume will weigh (28, 39, 54).

Soil scientists designate the total volume of a container as (V); the portion of the volume occupied by solids as (Vs), and the volume of the void spaces as (Ve). The void ratio (e) is the ratio of the volume of void spaces to the volume of solids ($e = \frac{Ve}{Vs}$), and percent porosity (n) is the ratio of the volume of void spaces to the total volume, multiplied by 100. ($n = \frac{Ve}{V} \times 100$), (54). It follows that the greater the (Vs), the smaller will be: (Ve); (e) and (n), for a given volume, and the greater will be the bulk density of the mass in that volume, assuming homogenity of density of the individual particles.

Physical Properties

Particle Size

To visualize some of the principles involved, one may construct a model to deal with the weight per unit volume relationships of a granular material. If a cubical container one foot on each side were filled with steel spheres two inches in diameter, they could be arranged in six layers of 36 spheres per layer with a total of 216 spheres. This can be represented diagramatically as seen in Figure I. The same volume could be filled by using spheres one inch in diameter. In this case the spheres could be arranged in 12 layers of 144 spheres per layer, giving a total of 1, 728 spheres, as represented by Figure II.

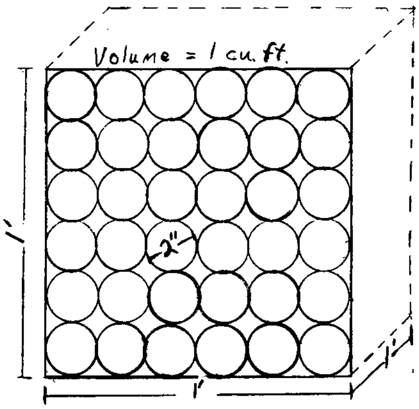

Figure I. 216 Two Inch Spheres in One Cu. Ft.

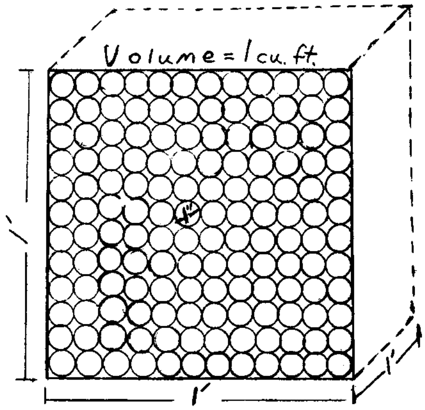

Figure II. 1728 One Inch Spheres in One Cu. Ft.

If the formula for determining the volume of a sphere is applied to the above cases, the total volume of the 216 two inch diameter spheres is 0.524 cu. ft. The total volume of the 1728 one inch diameter spheres is also 0.524 cu. ft. Thus, when packed in discrete layers, the total volume occupied by solids in a given container is independent of the size of the spheres, as long as the spheres are of uniform diameter. The implications of the above model would suggest that kernel size in itself is of little importance in determining bushel weight of grain.

Further support for this idea is gained from an examination of official grade standards for various agricultural products as listed by Leonard and Martin (37). They show that the average test weight for six products of vastly differing sizes is the same; 60 pounds per bushel. The products are: 1) clover seed with 1,500 seeds per gram; 2) alfalfa seed with 500 seeds per gram; 3) common wheat, 25 kernels per gram; 4) soy beans, 6-13 seeds per gram; 5) field beans, 4 seeds per gram; and 6) potatoes which may weigh several hundred grams per tuber.

Packing

In the theoretical models above, a specified system of packing was utilized. Since the total volume of the solid mass was unchanged in the two cases, the weight of the mass and the void ratio (assuming the same density for all spheres) would remain equal. The void ratio would be 0.908, $(\frac{.476}{.524})$. The same spheres could be packed into a smaller volume by shifting each tier of spheres a half diameter to the right as illustrated in Figure III.

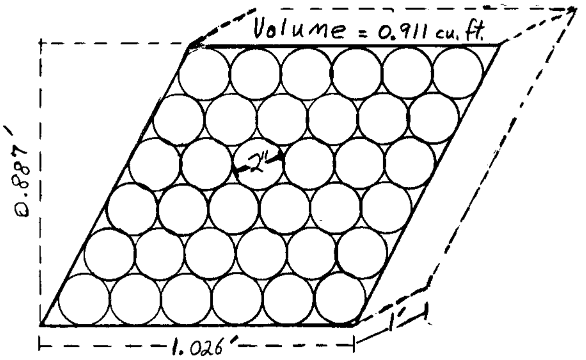

Figure III. 216 Two Inch Spheres in 0.911 Cu. Ft.

The same number of spheres would fit in a container with a volume of 0.911 cu. ft. The void ratio would be reduced from 0.908 to 0.739. The void ratio could be further reduced if each layer of spheres was now shifted one-half diameter in a direction at a right angle to the prior shift. Thus, while it has been shown that uniform particle size does not affect the void ratio of a container, it is evident that the arrangement of the particles in the container is very significant.

Grading of Particle Size

Although it has been shown that the void ratio is not affected by uniform particle size, it will be shown that the void ratio could be reduced with the admixture of varying-sized spheres.

In a geometrical study with spheres of uniform size Furnas (23) concluded that in the most loosly packed condition, a pile of spheres will have a void of 52.36 percent, and in the most closely packed conditions the void space will be reduced to 25.95 percent. He also stated that when two different sized materials are uniformly mixed, the percentage of voids is less than when a single sized material is used. This is due to the "nesting" of the smaller particles between the larger ones. If the air spaces between the spheres in Figure III were filled with smaller spheres, as illustrated in Figure IV, it is clear that the void ratio would be reduced considerably.

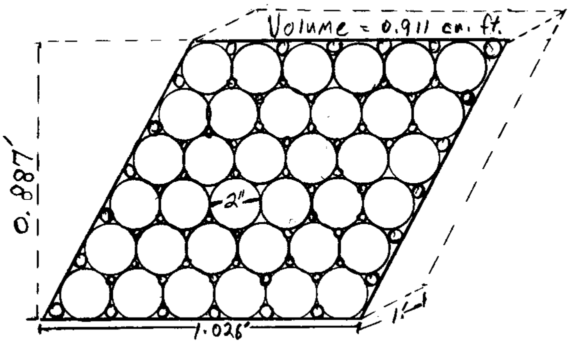

Figure IV. Nesting Effect With Varying Particle Size

This principle is well illustrated in the making of concrete. One common mix (61, p. 226) calls for .89 cubic yard gravel, .44 cubic yard sand, and .22 cubic yard of cement plus 30 gallons of water. The individual components, excluding the water, have a volume of approximately 1.55 cubic yards, but when combined they occupy a volume of only one cubic yard. The small sand particles fill in the voids between the larger particles of gravel, and the finely ground cement fills in the spaces around the sand particles.

Whether there is sufficient range in gradation of kernel size in wheat to effectively implement the nesting effect, which would decrease the void space, is a pertinent question. It is evident in Figure IV that small particles must be fractionally smaller than the large particles in order to occupy the voids. As will be discussed later, the relationships of particle size, void, and mass is greatly complicated in grain because variation in kernel density is often a concomitant factor of reduced size. Also, one could raise the question as to what is the optimum gradation of size which would give the highest possible test weight.

Particle Shape

The above models have been based on spheres. However, few wheat kernels are spheres. There may be particle shapes which could pack more tightly (leave less void spaces) than spheres. Spangler (54, p. 65) reported that minimum percent voids could be obtained only if the particles were "true cubes or parallelepipeds similar to a child's building blocks". Since most wheat kernels are neither perfect spheres nor perfect parallelepipeds they may not respond in a manner similar to the above models. However, the basic principles should apply. Hlynka (28, p. 239) concludes:

> Random packing of round plump kernels may give a different overall bulk density from that given by random packing of long thin kernels. If small and large kernels were mixed together in the same sample, the bulk density might be different than that of either of the two sizes when packed alone. The small kernels would, for instance, occupy inter-kernel spaces that were too small for kernels of normal size.

This does not, however, shed light upon the question of what is the ideal kernel shape to achieve maximum packing density. One might consider the case of the popular Soft White Wheat variety, Gaines, so widely grown in Oregon and Washington and a formerly popular White Club Wheat variety, Omar. In a three-state survey conducted in 1966 (51), the average test weight of Gaines was 1.1 pounds higher than Omar. Gaines generally has a long, rather cylindrical kernel while Omar has a distorted shape, as is common to club wheats. Club wheats have a characteristic "humped back".

Based on Spangler's observation that to obtain maximum occupancy of a volume, the granular material would have to be parallelepiped in nature, those wheat varieties approaching this shape would result in higher packing densities than those having cylindrical or spherical-like kernels.

A rough bran coat results in a lower test weight since the kernels do not pack as tightly as when the bran coat is smooth. When wheats are handled in elevators, the bran coat becomes polished and test weight generally increases. The same phenomenon is observed with the removal of the brush from the kernels as a result of handling (8, 21, 52, 53, 58, 59). In the study conducted by the Tri-State Grain Standards Committee (51) this polishing effect was demonstrated as the average increase in test weight from passing grain through an elevator was 0.67 pounds per bushel.

Kernel Density

It has been stated that test weight is dependent upon packing characteristics (as discussed above) and the density of the kernels

(8, 28, 38, 50, 58). Spangler illustrates this principle by suggesting that half of the two-inch diameter steel spheres in Figure I be replaced with two-inch diameter wooden spheres. The volume of the contents of the container remains equal, but the total weight would be reduced greatly (54).

Often small shriveled kernels are the result of adverse weather or soil conditions during kernel maturation. When this is the case, the small shriveled kernels have a considerably lower density and as these kernels of low density are added to the volume, the test weight decreases (3, 8, 50, 63). Normal well-filled kernels having low densities would have the same affect (3, 52).

Physiological Properties

Swanson (58, 59) and Sharp (50) list the major chemical components of wheat in the following average proportions for 858 samples taken from across the United States:

Moisture 10.20%
Ash 1.90%
Fat 2.10%
Crude fiber 2.20%
Protein 12.40%
Nitrogen free extract 71.20%

The protein content varies more within the same class of wheat than any other organic constituent. The nitrogen free extract is important as an indicator of starch content. The relative proportion of these constituents, especially protein and nitrogen free extract, will vary greatly between classes and varieties. Variation in edaphic and climatic conditions may cause wide variations in these relative proportions within a class also (8, 21, 52, 53, 58, 59).

The protein content of wheat probably influences kernel density and milling performance more than any other single constituent. Since the density of starch is approximately 1.45 and protein 1.25, one would expect that the lower protein wheats should have the highest density. However, this does not appear to be the case. Bailey (3) and Sharp (50) report that high kernel density is correlated with high protein content. Sharp (50) shows that the interstitial air space in a kernel is closely related to protein content, and consequently, to kernel density. His microscopic studies revealed that in low protein wheats, there are relatively large air spaces surrounding the starch granules, while in high protein wheats, the spaces between starch grains tend to be filled with proteinacous materials. He concluded, as did Bailey (3), that the air spaces between the starch grains in low protein wheat are responsible for their chalky (opaque) appearance. When the air spaces are filled with protein, the kernels are darker, harder, and more vitreous.

The relationship of protein content to interstitial air spaces is clearly seen in the wetting and redrying of low moisture wheat. In wheats of low protein, the kernel never shrinks back to the original size possessed before wetting, even though the same weight is maintained. Thus, the density of the kernel will be lower than before wetting. Sharp states that wheat which has been wetted and redried is opaque or starchy in appearance due to the formation of air spaces between starch granules. The endosperm cells are unable to decrease in size as the moisture is removed. He says, (50, p. 27)

> The ability to increase in size and return to the original volume is related to the connective network of the endosperm, that is, the protein material which fills in the interstitial air spaces around the starch granules. The greater gluten content of high protein allows for greater elasticity.

Milner and Shellenberger also show that the reduction in density from wetting and redrying of low moisture wheat is due to the formation of internal fissures (42). When swollen grain is dried, stresses are created in the kernel. However, when immature grain of high moisture content is dried rapidly, these fissures are not formed in the endosperm.

Thus, within a given class of wheat one would expect kernels of high protein content to have a greater density than the kernels of lower protein. Shollenberger (52) divided hard red wheat into three divisions; vitreous, mottled, and starchy. He determined test weight, protein content, density, weight of 1, 000 kernels, and flour yield for each of the divisions. The vitreous kernels were highest in protein content, density, and flour yield, and intermediate in test weight and weight of 1, 000 kernels. The mottled kernels were highest in test weight, and weight of 1, 000 kernels, and intermediate in protein content, density, and flour yield. The starchy kernels were lowest in all of the above factors. It should be emphasized that these relationships were true within samples, not across samples (52).

Within a given variety of sound wheat there is a general, although not always significant, correlation between test weight and protein content, and between protein content and flour yield (4-6, 18, 24, 26, 29, 30).

It has been shown that the position of a wheat kernel on the spike will greatly influence such factors as size, shape, and protein content (40). There are two primary environmental factors which determine the protein content of wheat; climatic conditions, and available soil nitrogen. If the climatic conditions are favorable to a long growing season, large plump kernels are formed which have a relatively lower protein content. However, if the growing season is shortened by adverse weather, the kernels tend to be smaller with a lower test weight, but the relative protein content will be higher (2, 9, 29, 34, 48, 57, 65). The availability of soil nitrogen has only limited influence on protein content, while the time when soil nitrogen is most readily available can affect protein content greatly. For maximum protein content of sound wheat it is important that the plant have an ample supply of nitrogen at heading time (17, 19, 38, 40, 53).

Moisture

Moisture content of grain can also affect kernel size and density, and consequently, test weight. Many studies have shown that as moisture content of grain decreases, test weight and density increase over an effective range of approximately 9-19 percent (10, 12, 13, 19, 28, 47, 50, 58). Lorenzen (39, p. 58) reported that between 10 and 19 percent moisture, there is an increase in test weight of approximately 0.8 pounds per bushel for each one-percent decrease in moisture content. Stanfield and Cook (22) reported that wheat gained three pounds in test weight when the moisture content was lowered from 18 percent down to 13 percent.

Peters and Katz (46, p. 490) emphatically state that, "to speak of density differences of wheat varieties without regard to moisture content is meaningless." Jones (32) reports that over the useful range, density is linearly related to moisture content, the gradient being 0.0041 grams per cubic centimeter for each one-percent difference in moisture. As grain absorbs moisture it increases in size at a greater proportion than the resulting increase in weight, causing a decrease in density. Bushuk and Hlynka (10) reported that when the moisture content of wheat was increased from 7 to 17 percent and redried to 7 percent, the test weight fell 0.5 pounds. The degree of swelling is seen in the packing of stored grain in bins, or even the

the bursting of bins when sufficient moisture enters (1, 15). Moisture content should be specified when giving test weight.

Factors in Flour Yield

From the standpoint of milling the three major anatomical divisions of a wheat kernel are the endosperm, the bran coat, and the germ. Milling of wheat is a physical or mechanical process of separating the outside bran coat and germ from the endosperm and converting the latter into fine flour. Swanson (59, p. 61) states; "complete separation is never obtained but the sharpness or degree of completeness of this separation is one measure of the efficiency of the milling process....The milling processes then depend on the physical characteristics inherent in the wheat kernel."

The average percent of endosperm, bran, and germ is given by Bailey (3), Swanson (59, and Swanson and Kroeker (60) as 84, 14.5, and 1.5 percent respectively. With the average flour yield ranging from 70-75 percent (4, 5, 6, 8, 53, 59, 60) it is evident that 25-30 percent of the endosperm is not converted into flour. This is influenced by milling efficiency and kernel characteristics.

Test Weight

Numerous workers have reported that large plump kernels have a greater percent endosperm than small kernels, and consequently, have higher potential flour yields (3, 14, 25, 29, 58, 59). Many of these same workers claim that wheat with a high test weight can be related to plump well filled kernels.

However, there is considerable evidence suggesting that high test weight is not synonomous with high milling yields nor that plump kernels will not necessarily result in greater flour yields. Hlynka and Bushuk (29) and Bailey (5) show there is very little correlation between test weight and flour yield with test weights above 58 pounds per bushel. Barmore and Bequette (8), Willard and Swanson (63) and others (25, 49, 52, 60) present data showing that small sound kernels may yield as much, or more, flour as large plump kernels when compared across classes. Bailey (5), and Bailey and Sherwood (6) show that wheats of equal test weight, in the same class, varied in flour yield by as much as 2.5 percent. In a study by Shuey (53), wheats having test weights differing by nine pounds yielded the same percent of flour when milled. Thus, it becomes evident that potential flour yields can only be approximated from test weights.

Swanson (60) reports that some wheat varieties give low flour yields due to a thick bran layer. He cited one hard red winter wheat variety which consistently had a test weight of 60 pounds or more, but did not surpass the flour yield of a companion variety which had a test weight at least three pounds lower.

Barmore (8), and Hlynka and Bushuk (29), and others (3, 50, 58) call attention to the critical role of the ratio of endosperm to bran in flour yield. The larger the ratio, the higher the potential flour yield. A reduced ratio is always experienced in small shriveled grain.

Alternative Measures of Flour Yield

Several alternatives to test weight as a measure of potential flour yield have been developed. However, none of these alternatives have been accepted in the wheat industry. This can be attributed in part to their lack of simplicity of operation. The two most promising alternatives, kernel count and sizing techniques should be considered in detail.

A number of workers have shown that the weight of 1,000 kernels often correlates more closely with flour yield than does test weight. Johnson and Hartsing (31) counted the number of kernels in 30 grams. Kernel count gave a higher correlation with flour yield than test weight.

There are claims that kernel count really measures kernel size and/or kernel plumpness (11, 29). It is reasoned that the greater the weight of a given number of kernels the larger and more dense those kernels must be. Consequently they should have a greater potential flour yield. Hlynka (28) and Hlynka and Bushuk (29) state that 1,000-kernel weight is a function of kernel size and density and that large kernels generally have a higher ratio of endosperm to nonendosperm components than do smaller kernels. Therefore, one would expect 1,000-kernel count to be a more reliable indicator of flour yield than test weight. However, in their experimentation a significant advantage in kernel count was not evident. Fisher and Halton (20) conclude that 1,000-kernel count is generally unreliable unless a specific method of sampling is adopted with the probable error for that sampling method specified.

In general, it seems that kernel count is a better indicator of flour yield than is test weight, but it lacks the convenience of test weight. Electronic seed counters are being developed with great accuracy and speed, but they are rather costly.

Shuey (53) has employed a method which sizes wheat kernels according to their cross-sectional area. Potential flour yields are then calculated for the percentage of the sample remaining on each of three different sized sieves. A correlation of 0.957 was obtained between yields calculated from sizing data and actual yields obtained on commercial flour mills for 287 samples. A correlation of only 0.744 was obtained between test weight and flour yields for these same samples. This would support the idea that plumpness is a good indicator of flour yield.

Callaghan and Millington (11) have shown that when wheat was sieved, the grain held by the large sieves had a higher test weight than the wheat retained by the small sieves. The malting barley industry has also found that plumpness is more accurately measured by sieving than by test weight. A high correlation has been found in barley between test weight and kernel weight when measured after sieving (16, 22).

Some additional methods which have been studied to predict flour yield and milling responses are the thickness of cell walls of the bran layer and endosperm, and the extraction of pentosans with dilute acid (14, 35, 36, 62, 64). Generally it is doubtful that cell wall thickness of the bran can be used to predict milling behavior. However, a correlation has been found between endosperm cell wall thickness and millability. This is also generally true for the amount of pentosans which can be extracted with acid solutions. But these methods are impractical for use in commercial trade channels.

Katz _et_ _al_. (33) and Milner, Farrell and Katz (43) graded grain with a machine which separates kernels on a mass/radius basis. Rapidly moving belts project the grain into still air. The kernels with a greater mass/radius ratio would be projected further than lighter kernels. They were able to achieve a considerable gradation of test weight by collecting grain at ten different distances from the moving belt. They achieved a high correlation between test weight and 500-kernel count, and a moderate to high correlation between test weight and protein content. This principle seems to offer considerable promise as a means of grading grain.

Thus it can be seen that test weight is influenced by numerous factors. While it is not a precise measurement of potential flour yield, its simplicity makes it more desirable than alternative indicators of potential flour yield. Perhaps, if more is learned about many of the variables influencing test weight, its precision can be increased.

METHODS AND MATERIALS

This investigation was designed to study the two basic components of test weight in wheat of packing characteristics, and kernel density. These two factors were studied for field run wheat, and for wheat which had been graded by maximum cross-sectional diameter into four different sizes.

Field Run Wheat

During the 1966 harvest season, samples of four varieties of white wheat were collected at four locations in Washington and Idaho. The varieties Gaines and Nugaines were of the subclass Soft White, and Omar and Moro were of the subclass White Club. Of the four locations, two were from the dryland nurseries of Washington State University located at Pomeroy and Walla Walla, Washington, and two were from the Aberdeen and Tetonia dryland nurseries of the University of Idaho. In each case, the wheat had been fertilized at the same rate that farmers in the respective areas normally use. Foreign material and dockage were removed from all samples prior to experimentation.

The relationship of packing characteristics to test weight was divided into two facets; 1) The number of kernels retained in the test weight kettle and, 2) the percent of the total volume of the test weight kettle which was actually occupied by wheat. The former will be called kernel count and the latter percent Vs in this work. In the kernel density measurements, only limited attention was given to the protein content of the wheat. The density values were not corrected to zero-moisture content since moisture content of samples in each comparative series fell within a range of 10.2-11.5 percent.

Triplicate determinations were made of test weight, kernel count, percent Vs, and kernel density for all samples. A single protein analysis was obtained for each sample.

Test weight was determined using the micro-technique developed by Harris and Sibbit (27). A 100 ml graduated cylinder was cut down to exactly 16 ml to serve as a test weight kettle. A funnel with a diameter of 1/2 inch at the spout tip was fixed at a height of one inch above the top edge of the test weight measure.

A shutter was placed in the funnel neck by means of a thin wooden slat which could be quickly removed, allowing wheat to flow from the funnel into the kettle below. The test weight kettle was over-filled and leveled off with three zig-zag strokes as prescribed by the U.S.D.A. Grain Inspection manual. The striker was a round glass rod 3/8 inch in diameter, seven inches long. (See Figure V for a photograph of this apparatus.)

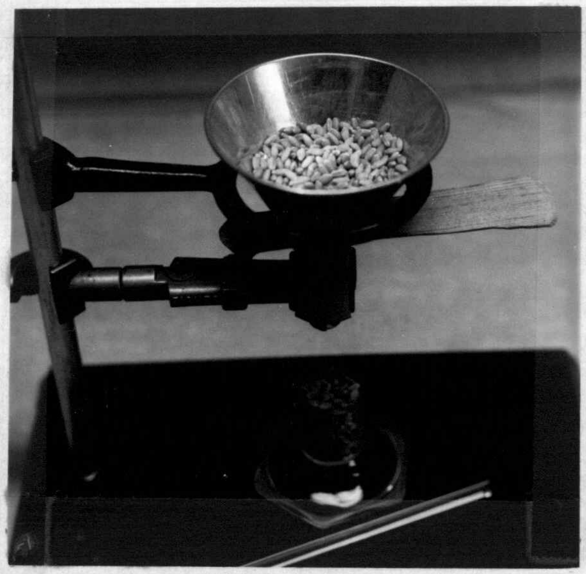

Figure V. Micro Test Weight Apparatus

The weight of wheat remaining in the test weight kettle after being leveled off, was recorded in grams, and will be referred to as test weight hereafter. (A simple factor of five converts grams per 16 ml directly to pounds per bushel if the conventional measure is desired).

After the test weight had been determined the number of kernels retained in the 16 ml test weight kettle (kernel count) was ascertained, using a vacuum-head counter.

The true density of these same kernels was then determined using the liquid-volume displacement method described by Bailey and Thomas (7). The amount of toluene displaced by a known weight of wheat was measured. A 50 ml Gay Lussac-type pycnometor was used, with all determinations being made at a constant temperature of

24.8°C. All samples were placed in a vacuum respirator at 3-5 pounds vacuum to ensure the removal of air bubbles entrapped between wheat kernels before weighing the pycnometor and its contents.

Soil scientists differentiate between the apparent (or bulk) density and the true density of a granular mass. The apparent density of a granular mass is the ratio of the weight of the granular particles and their void spaces, per unit volume. The true density is the ratio of the weight of the particles per unit area, exclusive of the void spaces (54).

Thus, the apparent density of wheat in this study would be the weight of wheat retained in the 16 ml test weight kettle divided by 16 ml. The true density would be the value obtained in the liquid-volume displacement method described earlier.

Percent Vs was calculated by dividing the apparent density by the true density and multiplying by 100.

Sized Samples

The relationship of packing characteristics and kernel density to kernel size were studied on previously sized wheat samples. The same four varieties of wheat were used. However, only wheat from the two Washington locations was employed.

The wheat was sized according to maximum cross-sectional diameter in a manner similar to that described by Shuey (53). Sieve boxes 9" x 12" x 1" were constructed so that each screen just fit within the frame of the smaller-sized sieve beneath it. In this manner the desired number of sizes could be obtained simultaneously.

The screen boxes were placed on a Syntron Jogger, Model J1 A. (See Figure VI). The vibrating action of the "Jogger Board" upended the kernels, allowing them to pass through the sieve if small enough, thus, grading them by maximum cross-sectional diameter. Approximately 350 grams could be handled efficiently with this equipment. Each "batch" was allowed to vibrate for three minutes.

Figure VI. Sizing Screens and Jogger Board

Four round-holed screen sizes were used, the hole diameters expressed in 64ths of an inch as follows: 8 1/2, 8, 7 1/2, and 7. Wheat retained by each screen was designated according to the respective screen size.

Test weight, kernel count, percent Vs, and kernel density were determined in duplicate for each size in each sample, in the same manner as outlined in field run trials above.

Analysis of Variance

In the field run experiment, an analysis of variance was calculated for the five factors of test weight, kernel count, percent Vs, kernel density, and protein content in a randomized block design. Simple correlation coefficients were also determined for each factor, correlated with all other factors, with data from both subclasses being combined. Correlation coefficients were also calculated for each factor correlated with all other factors within each subclass.

In the experiments with sized samples, an analysis of variance was calculated for the four factors of test weight, kernel count, percent Vs, and kernel density for each size in a randomized block design. Simple correlation coefficients were also determined for each factor correlated with all other factors combining data from both subclasses. These same correlations were determined within each subclass also.

RESULTS AND DISCUSSION

Field Run Wheat

Test Weight

Varietal means for test weight ranged from a high of 12.60 g/16 ml for Nugaines, to a low of 12.16 for Moro. The average test weight of Gaines was second highest at 12.49, followed by Omar with an average of 12.22, as shown in Table I.

Table I. Varietal and subclass means and levels of significance for test weight, kernel count, kernel density, percent Vs and protein content of field run wheat.+

Variety	Test Weight g/16 ml	Kernel Count #/16 ml	Kernel Density g/ ml	Percent Vs	Protein Content %
Gaines	12.49b	336a	1.398ab	55.84b	11.14a
Nugaines	12.60a	331a	1.401a	56.21a	11.08a
Omar	12.22c	382b	1.392b	54.92c	12.26a
Moro	12.16c	379b	1.390b	54.69d	11.44a
Subclass					
Soft White	12.55	333	1.400	56.03	11.11
White Club	12.19	381	1.391	54.80	11.85

+Any two varietal means not followed by the same letter differ significantly at the one percent level.

The analysis of variance indicated a significant variation in test weight between varieties (Appendix Table I). The variety means were consequently subjected to Duncan's multiple range test (56). Test weight means for the varieties Gaines and Nugaines differed significantly at the one percent level, while the difference between the test weight means of Omar and Moro was insignificant at the one percent level.

The average test weight of wheat was unusually high throughout the Pacific Northwest in 1966. Soil moisture was limited during the winter months. But timely spring rains and unusually cool weather for several weeks prior to harvest allowed excellent filling of wheat kernels. Barmore and Bequette present data for the period from 1959 - 1963 showing that the average test weight of Gaines wheat was 60.9 pounds per bushel (8). In contrast, Gaines averaged 62.5 pounds per bushel in this study.

The significantly higher test weight of the subclass Soft White, observed in this investigation, is also common in this region. In the same work by Barmore and Bequette it was reported that the average test weight of Soft White wheat exceeded White Club wheat by 1.3 pounds per bushel. During this five year period, an average of 13.1 percent of the Gaines samples had a test weight below 60 pounds per bushel. In contrast, 44 percent of the Omar samples tested below 60 pounds per bushel.

Some varietal test weight means differed significantly at each location (Table II). It will also be noted that there was an interaction within the subclass White Club between the Washington and the Idaho locations. The test weight of Omar exceeded Moro in Washington but was less than Omar in Idaho.

Table II. Varietal and subclass means for test weight of field run wheat at four locations.[+]

	Location			
Variety	Pomeroy g/ml	Walla W. g/ml	Aberdeen g/ml	Tetonia g/ml
Gaines	12.56a	12.65a	12.26a	12.51a
Nugaines	12.69a	12.69a	12.40a	12.62a
Omar	12.34b	12.60a	11.65b	12.31c
Moro	12.14c	12.44b	11.73b	12.33c
Subclass				
Soft White	12.63	12.67	12.33	12.57
White Club	12.24	12.52	11.69	12.32

[+] Any two varietal means not followed by the same letter differ significantly at the one percent level.

The interaction of Omar and Moro between the Washington and the Idaho locations can not be definitely explained. There may have been a difference in maturity dates and environmental patterns affecting individual varieties. The elevation is 1, 170, 2, 600, 4, 405, and 5, 895 feet above sea level at Pomeroy, Walla Walla, Aberdeen, and Tetonia. The precipitation was 15.1, 15.0, 12.1 and 5.6 inches for the respective locations in 1966.

It has been shown earlier that test weight is dependent upon packing characteristics and the density of the kernels. Packing characteristics depend in turn upon kernel shape, bran condition, presence of brush and moisture content. Thus, the values for kernel count, kernel density, percent Vs and protein content were examined to better understand these variations in test weight.

Kernel Count

The data presented in Table I show that the mean kernel counts did not differ significantly within the two subclasses. However, the mean kernel counts for the subclasses differed significantly. The mean kernel count for Soft White wheat was 333 as compared to 381 for White Club wheat.

At each location, there was a wide variation in kernel count between varieties. Within the subclass Soft White, there was an interaction in kernel count at the Tetonia location (Table III). In the subclass White Club, there was an interaction between the Washington and Idaho locations. The latter case coincides with the interaction noted in test weight. No definite explanation can be given for these interactions. Perhaps it is due to varietal responses to differences in weather patterns and elevation between the locations.

Table III. Varietal and subclass means for kernel count of field run wheat at four locations.+

	Location			
Variety	Pomeroy #/16 ml	Walla W. #/16 ml	Aberdeen #/16 ml	Tetonia #/16 ml
Gaines	373c	337c	311c	324b
Nugaines	356d	333c	303c	331b
Omar	387b	354b	405a	384a
Moro	413a	362a	363b	377a
Subclass				
Soft White	364	335[	307	328
White Club	400	358	384	381

+Any two varietal means not followed by the same letter differ significantly at the one percent level.

The greater kernel count of the White Club varieties indicates that White Club kernels are smaller than Soft White kernels and/or that a greater number were retained in the 16 ml test weight kettle due to a more complete filling of the volume. The values for percent Vs (Table I) show that the percent Vs for Soft White wheat exceeds the percent Vs for White Club wheat by a significant margin, 56.03 to 54.80.

Dividing test weight and the volume occupied by wheat (in ml), by the kernel count, shows that the average Soft White kernel weighed 0.0376 gr. and occupied approximately 0.0269 ml, while the respective figures for the average White Club kernel are 0.0320 gr. and 0.0230 ml. Thus, the average Soft White kernel is heavier and occupies a larger volume than the average White Club kernel. Does the larger size of the Soft White kernel result in the greater percent Vs, or is it some other factor such as kernel shape?

Percent Vs

Some varietal means for percent Vs differed significantly at the one percent level (Table I). The average percent Vs was also significantly greater for Soft White wheat than for White Club wheat at all locations (Table IV).

Table IV. Varietal and subclass means for percent Vs of field run wheat at four locations.+

	Location			
Variety	Pomeroy Percent Vs	Walla W. Percent Vs	Aberdeen Percent Vs	Tetonia Percent Vs
Gaines	55.89b	56.14a	55.56a	55.69a
Nugaines	56.77a	56.09a	55.97a	55.99a
Omar	55.65b	56.09a	53.07b	54.85c
Moro	55.17b	55.23b	53.21b	55.13b
Subclass				
Soft White	56.33	56.12	55.77	55.84
White Club	55.41	55.66	53.14	54.99

+Any two varietal means not followed by the same letter differ significantly at the one percent level.

There was an interaction within the subclass White Club between the Washington and Idaho nurseries. This interaction is in the same direction as the interaction in test weight at these locations. The percent Vs within both subclasses follows the same order or ranking as the test weight means for each location. This suggests that test weight is closely associated with the packing characteristics of wheat.

The interaction between the various localities for percent Vs is the inverse of the kernel count interaction within the White Club varieties. Kernel count of Moro exceeded Omar at Pomeroy and Walla Walla, but percent Vs of Moro was less than that of Omar at these locations. This suggests that percent Vs is negatively associated with kernel count.

Kernel Density

Wheat of the subclass Soft White had a significantly heavier kernel density than White Club wheats. The variety Nugaines had the highest varietal average followed closely by Gaines (Table I). The average kernel density of Moro was slightly lower (insignificant at the one percent level) than Omar.

Wheat grown at Walla Walla had a higher average kernel density than wheat grown at the other locations. The average kernel density was 1.409, 1.404, 1.390 and 1.383 g/ml for Walla Walla, Tetonia, Pomeroy and Aberdeen respectively. The varietal means demonstrate wide variability of kernel density at each location (Table V).

Table V. Varietal and subclass means for kernel density of field run wheat at four locations.+

Variety	Location Pomeroy g/ml	 Walla W. g/ml	 Aberdeen g/ml	 Tetonia g/ml
Gaines	1.402a	1.408ab	1.397a	1.404ab
Nugaines	1.397a	1.414a	1.384b	1.408a
Omar	1.386b	1.404b	1.372c	1.405a
Moro	1.375c	1.408ab	1.378c	1.398c
Mean	1.390	1.409	1.383	1.404
Subclass				
Soft White	1.400	1.411	1.391	1.406
White Club	1.381	1.406	1.375	1.402

+Any two varietal means not followed by the same letter differ signigicantly at the one percent level.

All varieties except Moro had their lowest average density at Aberdeen. The lowest average test weight was also obtained here. It appears that an environmental stress was experienced at Aberdeen which affected all varieties adversely.

Within the subclass Soft White there was an interaction for kernel density between the Pomeroy and Aberdeen, and the Walla Walla and Aberdeen locations. These interactions differ from the interactions displayed for test weight, kernel count and percent Vs. These variations in kernel density reflect the response of individual varieties to diverse soil and climatic conditions.

Protein Content

In the analysis of variance for protein content, the error mean square was zero (Appendix Table I). The variety-location interaction was used to test for significance of differences between varieties, locations and subclasses. The average percent protein content was highest for the variety Omar (Table I). The average percent protein of all varieties was highest at the Aberdeen location (Table VI).

Table VI. Varietal and subclass means for percent protein of field run wheat at four locations.

	Location			
Variety	Pomeroy Percent	Walla W. Percent	Aberdeen Percent	Tetonia Percent
Gaines	9.90	11.25	11.20	12.20
Nugaines	9.90	12.60	11.15	10.65
Omar	10.90	9.55	14.90	13.70
Moro	9.30	11.90	12.05	12.50
Subclass				
Soft White	9.90	11.93	11.18	11.43
White Club	10.10	10.73	13.48	13.10
Locational Avg.	10.00	11.33	12.33	12.27

The unusually high protein content in the Club wheats at Aberdeen and Tetonia are accompanied by low test weights which suggest that certain environmental conditions induced premature cessation of kernel development. Consequently, an increase in the percent protein resulted. This is a common phenomenon as has been reported in other studies (9, 29, 32, 48, 57, 65). Generally, if high protein percentages are the results of shriveled kernels test weight could be expected to be low. However, in the case of sound wheat, a higher protein content is usually associated with an increased density and test weight (52). This appears to be the case with the Soft White varieties at the Washington and Tetonia locations.

From Table I it is seen that White Club wheats had the lowest average test weight, kernel density and percent Vs, but had the highest kernel count. This would suggest that there are some important relationships between kernel count and percent Vs and between kernel density and test weight.

Table VII presents correlation coefficients for all factors with data for both subclasses being combined. The correlation between kernel count and percent Vs shows an inverse relationship, significant at the one percent level ($r = -.465$). This might suggest that the increased voids are associated with more kernels. Perhaps this could be due, not so much to an increase in numbers, as to an increase in the number of kernels of a particular shape which packs less tightly than some other shape.

Table VII. Simple correlation coefficients for test weight, kernel count, kernel density, percent Vs and protein content. Data combined from all varieties. Field run wheat

Factor	Test Weight	Kernel Count	Kernel Density	Percent Vs	Protein Content
Test Weight	---	-.468**	.776**	.943**	-.486**
Kernel Count		---	-.312*	-.465**	.133
Kernel Density			---	.525**	-.616**
Percent Vs				---	-.617**
Protein Content					---

n, = 48 paired observations
*, ** Significant at the five and one percent level respectively

The latter hypothesis is strengthened when the correlation coefficients are determined by individual subclass (Table VIII). For Soft White wheat, the correlation coefficient between kernel count and percent Vs is positive at the five percent level (r = .441). In contrast, the same relationship within the subclass White Club is negative (r = -.230). Apparently something other than kernel numbers is influencing the packing characteristics of these two subclasses.

The simple correlation coefficients for factors in individual subclasses reveals that the relationship of kernel count to test weight differed between subclasses. In Soft White wheat, there was a positive significant correlation between kernel count and test weight, (r = .585). In the White Club varieties, this association between test weight and kernel count was negative (r = -.408).

Table VIII. Simple correlation coefficients for test weight, kernel count, kernel density, percent Vs and protein content, for the subclasses Soft White and White Club wheat. Field run wheat

Factor	Test Weight	Kernel Count	Kernel Density	Percent Vs	Protein Content
Soft White					
Test Weight	---	.585**	.785**	.735**	-.572**
Kernel Count		---	.447*	.441*	-.563**
Kernel Density			---	.157	.248
Percent Vs				---	-.360
Protein Content					---
White Club					
Test Weight	---	-.480*	.792**	.952**	-.521**
Kernel Count		---	-.625**	-.230	.155
Kernel Density			---	.572**	-.774**
Percent Vs				---	-.654**
Protein Content					---

n, = 24 paired observations
*, ** Significant at one and five percent levels respectively

One additional subclass distinction in kernel count relationships is seen in the kernel count-kernel density correlations. The simple correlation coefficient for Soft White wheat is positive at the five percent level of probability (r = .447), while in the White Club wheats this correlation is negative, being significant at the one percent level (r = -.625). This suggests that the smaller kernels in Soft White wheat have a higher density, while in the White Club wheats the smaller kernels have a lower density than the larger ones.

It would appear that for the Soft White wheats, the high degree of association between test weight and kernel count can be attributed in part to several indirect effects. As the kernel size decreased there was an increase in the percent of the volume occupied by wheat, as well as an increase in the density of the kernels occupying that volume.

In a like manner, the negative association between test weight and kernel count in White Club wheat may be attributed to several indirect effects. There was an inverse relationship between kernel number and percent Vs. Of greater importance was the highly negative relationship between kernel count and kernel density, significant at the one percent level ($r = -.625$). As White Club kernel size decreased there was a slight increase in void space, a significant decrease in kernel density, and a significant decrease in test weight.

The correlation coefficients in Table VIII show a high degree of association between test weight and kernel density for wheat of both subclasses. As discussed above, kernel density is also positively correlated with kernel count and percent Vs in Soft White wheat. However, in White Club wheat, kernel count is negatively associated with both test weight and kernel density. These differences are quite contradictory.

Visual examination of kernels and a careful study of Tables II, III, IV and V may explain these unexpected associations in Soft White wheats. At Aberdeen, kernel count, kernel density and percent Vs were low for both Gaines and Nugaines. Thus, it appears that despite large-sized kernels (indicated by the low kernel count), test weight was low. Close examination of samples of both varieties showed that the kernels in the samples from Aberdeen were long and thin with unusually large ridges along the dorsal side of the kernels. Some of the kernels appeared to be pinched at the brush end also. Thus, with the distorted contours, fewer kernels were retained in the test weight kettle and the percent Vs was reduced. The low percent Vs and low kernel density may have resulted in the low test weight.

The penultimate test weights and kernel counts of these two varieties were obtained at Tetonia. Again, the percent Vs was lower than for the two Washington locations, which apparently accounts for the lower test weights. In contrast to the smooth seed coats of these two varieties evidenced at the Washington locations, the seed coats were quite wrinkled at Tetonia, reducing the packing density.

The variety Gaines had a higher kernel count at Pomeroy than at any other location. The kernels were very smooth with a large length to diameter ratio similar to Gaines from the Walla Walla location. Kernel density, percent Vs and test weight were higher at this location than at Aberdeen and Tetonia.

Thus, it appears that the low percent Vs associated with the large distorted kernels, and the higher percent Vs associated with the small uniform kernels, caused this unexpected positive relationship between kernel count and percent Vs. Consequently, there was an unexpectedly high relationship between kernel count and test weight in Soft White wheats.

These data reveal that large kernels do not necessarily pack more tightly in the test weight kettle than small kernels. For the variety Gaines the highest percent Vs was obtained at Walla Walla. The kernel count was second highest here. The kernel count at Tetonia was less than at Walla Walla, but the percent Vs was considerably lower. Again, the bran coat of kernels appeared to be less smooth at Tetonia than at Walla Walla.

The example of the variety Nugaines best illustrates the fact that kernel size, per se, is not important in determining density. The kernel count at Pomeroy was 356 as compared to only 333 at Walla Walla. However, the percent Vs was 56.77 at Pomeroy and only 56.09 at Walla Walla. The bran coats were quite smooth in both cases, but the sample from Pomeroy appeared to have a smaller diameter to length ratio than the Walla Walla sample. Thus, it appears that kernel shape may be closely related to packing density.

The above facts suggest that percent Vs is of prime importance in test weight, and that kernel number is less important than kernel shape or the condition of the bran. These observations are supported by data from the subclass White Club.

The highest average test weight, kernel density and percent Vs for White Club wheat was obtained at Walla Walla. The average kernel count was lowest at this location. The conclusion might be drawn that the low kernel count resulted in the larger percent Vs. But the data indicate this was not the case.

Kernel count of White Club wheat was higher at Pomeroy than at Aberdeen (400 as compared to 384). But, percent Vs was much lower at Aberdeen than at Pomeroy (53.14 vs 55.41). Likewise, the kernel count and percent Vs were both lower at Tetonia than at Pomeroy.

Despite having a significantly higher percent Vs, test weight was slightly lower at Pomeroy than at Tetonia for White Club. It can be explained by examining the respective kernel densities. The average density was much greater at Tetonia than at Pomeroy (1.402 vs 1.381).

From these experiments with field run wheat it has been shown that Soft White wheat has a higher average test weight than White Club wheat. This can be attributed to the fact that kernels of Soft White wheat pack more tightly into the test weight kettle and also have a higher average kernel density. The Soft White kernels are also larger. However, it was shown that within a subclass large kernels do not necessarily pack more tightly than smaller kernels. It appears that the shape of Soft White kernels is more favorable to a high packing density than the shape of White Club kernels. More information is needed concerning the packing characteristics of specific kernel shapes.

Sizing Study

The relationships of kernel size to: test weight, kernel count, kernel density and percent Vs were studied for kernels of various size groupings. The corresponding mean squares and their levels of significance are shown in Appendix Table II. The analyses of variance indicate a significant variation in the test weight for: sizes, varieties, locations and the variety-location interaction.

Test Weight

Size means displayed a decrease in the average test weight from the two largest to the two smallest seed sizes. The average test weight was 12.53, 12.50, 12.43 and 12.34 g/16 ml. for size 8 1/2, 8, 7 1/2 and 7 respectively (Table IX).

The means of Table IX show that the average test weight of each respective size was considerably higher at Walla Walla than at Pomeroy. These higher average test weights at Walla Walla apparently reflect soil and climatic differences between the two locations. The dryland nursery at Walla Walla is 1430 feet lower in elevation than Pomeroy (2600 vs 1170 feet above sea level). The total precipitation was nearly equal at the locations in 1966, but the soil at Walla Walla has a much greater moisture storage capacity.

Table IX. Varietal and location means for test weight of four kernel sizes at two locations in sizing study.[+]

		Size (64ths of an Inch)			
		8 1/2	8	7 1/2	7
Location	Variety	g/16ml	g/16ml	g/16ml	g/16ml
Pomeroy	Gaines	12.59	12.56	12.48	12.40
	Nugaines	12.73	12.73	12.71	12.55
	Omar	12.07	11.99	11.84	11.90
	Moro	12.33	12.38	12.16	12.10
	Mean	12.43d	12.41de	12.30fe	12.23g
Walla Walla	Gaines	12.69	12.71	12.63	12.60
	Nugaines	12.74	12.78	12.77	12.76
	Omar	12.42	12.35	12.30	12.13
	Moro	12.71	12.55	12.55	12.33
	Mean	12.64a	12.60b	12.56cd	12.46cd
Size Mean		12.43	12.50	12.43	12.34

[+] Any two size-location means not followed by the same letter differ significantly at the one percent level.

The higher available soil moisture at Walla Walla permits the use of higher rates of nitrogen fertilizer. The rate was 70 pounds per acre at Walla Walla and 40 pounds per acre at Pomeroy. If available at the proper time, abundant quantities of nitrogen fertilizer may raise the protein content of wheat. Sound wheat with a high protein content often has a higher density and consequently higher test weight than lower protein wheat of the same class (17, 19, 38, 52). As shown in Table VI, the average percent protein was considerably higher at Walla Walla than at Pomeroy.

The higher test weight of the larger-sized kernels suggests that there is a positive relation between seed size and test weight.

Kernel Count

Kernel count (kernels/16 ml) shows the opposite pattern of test weight (Table X). Kernels of size 8 1/2 had the lowest average number of kernels. There was a substantial increase in kernel number with each successively smaller size. The average kernel count was 305, 352, 416 and 480 for size 8 1/2, 8, 7 1/2 and 7 respectively. The difference between the means of the four sizes is significant at the one percent level. The means show that the average kernel count of each respective size was lower at Walla Walla than at Pomeroy, the difference being significant at the one percent level in each case.

As was shown in Table IX, the average test weight followed a descending order from a high at size 8 1/2 to a low for size 7. The average test weight was also higher for each size at Walla Walla. The average kernel count follows an ascending order from size 8 1/2 to size 7. The average kernel count for each size was also lower at Walla than at Pomeroy. One might conclude from these data that the larger kernels (lower kernel count) have a higher test weight, and that smaller kernels cause a reduction in test weight.

Table X. Varietal means for kernel count of four sizes at two locations. Sizing study.[+]

		Size (64ths of an Inch)			
		8 1/2	8	7 1/2	7
Location	Variety	#/16ml	#/16ml	#/16ml	#/16ml
Pomeroy	Gaines	293	337	398	468
	Nugaines	293	343	415	477
	Omar	337	389	445	508
	Moro	326	381	443	513
	Mean	312g	363e	425c	492a
Walla Walla	Gaines	281	325	383	443
	Nugaines	283	326	394	457
	Omar	310	364	426	482
	Moro	318	356	425	490
	Mean	297h	343f	407d	468b
Size Mean		305	352	416	480

[+] Any two size-location means not followed by the same letter differ significantly at the one percent level.

However, based on the earlier discussion of environmental and cultural differences, care should be exercised in comparing the various factors across locations or subclasses. The following example will poignantly illustrate this fact.

Table IX shows that the average test weight of kernel size 7 at Walla Walla is equal to the average test weight of size 8 1/2 at Pomeroy. But the average kernel count of size 7 at Walla Walla exceeds the average kernel count of size 8 1/2 at Pomeroy 468 to 312. This comparison sharply contradicts the above suggestion concerning the relationship of kernel size and test weight. It also reinterates the need for logical interpretation of data.

The above comparisons have been made by combining all varieties. When considered by individual varieties or by subclasses, several different patterns develop (Table XI).

Table XI. Subclass means for test weight, kernel count, kernel density and percent Vs of four kernel sizes in sizing study.+

Subclass	Factor	Size (64ths of an Inch)			
		8 1/2	8	7 1/2	7
Soft White	Test Weight	12.68a	12.69a	12.63a	12.58a
White Club		12.38b	12.32b	12.21c	12.11c
Soft White	Kernel Count	287h	333f	397d	461b
White Club		323g	372e	435c	498a
Soft White	Kernel Density	1.408a	1.413a	1.409a	1.406ab
White Club		1.397cd	1.400bc	1.394cd	1.392d
Soft White	Percent Vs	56.32a	56.13ab	56.11ab	55.90ab
White Club		55.40b	54.99bc	54.71c	54.40c

+Any values within each factor not followed by the same letter differ at the one percent level.

For the subclass Soft White, the average test weight of the four sizes did not differ significantly. In contrast, the two smaller sizes differ significantly from the two larger sizes for White Club wheat. It is also seen that for each respective size, Soft White wheat had a significantly higher test weight than White Club. Kernel count for all sizes follows the same order as when summed across subclasses.

A careful examination of the data in Tables X and XI shows that the average test weight of size 8 1/2 does not differ significantly from the average test weight of size 8 at either location. But the test weight means for sizes 7 1/2 and 7 generally differ at the one percent level from the two largest sizes. At Walla Walla, the variety Nugaines had high test weights for the smaller sizes. This resulted in the insignificant difference between the large and small sizes for Soft White wheat.

Kernel Density

The average kernel density also shows some variation in the ranking of size means (Table XII). The values were 1.407, 1.402, 1.401, and 1.399 for size 8, 8 1/2, 7 1/2 and 7 respectively. The only significant difference at the one percent level is between sizes 8 1/2 and 7. However, the average kernel density of each respective size was significantly higher at Walla Walla than at Pomeroy.

The higher average kernel densities at Walla Walla can not be definitely explained other than the explanation given for the locational differences for test weight. The higher rates of nitrogen fertilizer used at Walla Walla may have resulted in the increase in protein content and thus a higher density.

Table XII. Varietal and location means for kernel density of four kernel sizes in sizing study.+

		Size (64th of an Inch)			
		8 1/2	8	6 1/2	7
Location	Variety	g/ml	g/ml	g/ml	g/ml
Pomeroy	Gaines	1.397	1.409	1.402	1.401
	Nugaines	1.405	1.407	1.399	1.399
	Omar	1.376	1.382	1.383	1.381
	Moro	1.389	1.392	1.390	1.381
	Moro	1.392d	1.398d	1.393d	1.391d
Walla Walla	Gaines	1.419	1.419	1.416	1.414
	Nugaines	1.409	1.418	1.417	1.410
	Omar	1.415	1.417	1.407	1.408
	Moro	1.407	1.408	1.400	1.396
	Moro	1.413ab	1.416a	1.410ab	1.407b
Size Mean		1.402	1.407	1.402	1.399

+Any size-location means not followed by the same letter differ significantly at the one percent level.

Percent Vs

The size means for percent Vs followed the same ranking as with test weight (Table XIII). Kernel size 8 1/2 had the highest percent Vs and was followed in order by size 8, 7 1/2 and 7. The largest kernels occupied an average of 55.86 percent of the volume of the test weight kettle. The smaller sizes had values of 55.56, 55.41 and 55.15 percent respectively (Table XIII). This suggests that the percent Vs may be positively associated with test weight.

Table XIII. Varietal and location means for percent Vs of four kernel sizes in sizing study.

		Size (64th of an Inch)			
		8 1/2	8	7 1/2	7
Location	Variety	Percent	Percent	Percent	Percent
Pomeroy	Gaines	56.29	55.72	55.62	55.32
	Nugaines	56.63	56.52	56.80	56.03
	Omar	54.80	54.21	53.52	53.82
	Moro	55.48	55.57	54.65	54.72
	Mean+	55.80a	55.50a	55.15b	54.97b
Walla Walla	Gaines	55.89	55.97	55.72	55.69
	Nugaines	56.47	56.32	56.32	56.55
	Omar	54.86	54.48	54.65	53.87
	Moro	56.46	55.72	56.04	55.21
	Mean+	55.92a	55.62a	55.68a	55.33b
Size Mean		55.86	55.56	55.41	55.15

+Any size-location means not followed by the same letter differ significantly at the one percent level.

Data in Table XI show that percent Vs is significantly greater for Soft White than for White Club wheat for each respective size. These data suggest that the percent Vs may be one of the key factors which influences test weight.

Simple correlation coefficients for all factors are presented in Tables XIV and XV. Table XIV represents the combined data for both subclasses while Table XV presents the correlation by subclasses. These data show the strong correlation between test weight and percent Vs. They also show subclass differences in packing characteristics.

Table XIV. Simple correlation coefficients for test weight, kernel count, kernel density and percent Vs. Data combined from all varieties for sizing study.

Factor	Test Weight	Kernel Count	Kernel Density	Percent Vs
Test Weight	---	-.490**	.735**	.932**
Kernel Count		---	-.382**	-.444**
Kernel Density			---	.438**
Percent Vs				---

n = 64 paired observations

** significant at the one percent level.

Table XV. Simple correlation coefficients for test weight, kernel count, kernel density and percent Vs for the subclasses Soft White and White Club Wheat in all possible comparisons for sizing study.

Factor	Test Weight	Kernel Count	Kernel Density	Percent Vs
Soft White				
Test Weight	---	-.409*	.496**	.771**
Kernel Count		---	-.259	-.272
Kernel Density			---	-.171
Percent Vs				---
White Club				
Test Weight	---	-.499**	.645**	.898**
Kernel Count		---	-.328	-.445*
Kernel Density			---	.243
Percent Vs				---

n = 32 paired observations

*, ** significant at the one and five percent level respectively.

The difference in packing characteristics of the two subclasses may explain why White Club Wheats consistently have a lower test weight than Soft White varieties.

The size means in Tables XI and XIII for percent Vs and kernel count appear to give evidence that large kernels fill a greater percent of a given volume (have a higher packing density) than do small kernels. However, as was noted earlier, erroneous conclusions may be drawn when comparing values across sizes, varieties and locations.

Table XV represents the correlation coefficients for test weight, kernel count, kernel density and percent Vs, by individual subclasses. The correlation coefficients are quite similar for both subclasses. There is a significant negative correlation between test weight and kernel count and between kernel count and percent Vs. But the negative correlation between kernel count and percent Vs is much larger in White Club than in Soft White wheats. This again suggests that there are some aspects of White Club kernels which are less favorable to close packing than are Soft White kernels.

Swanson states that plump kernels with a small diameter to length ratio have a greater potential flour yield because they have less surface in proportion to mass, and hence, a greater proportion of endosperm. He continues that such kernels also pack more tightly into a given volume (58).

This idea is supported by the case of Gaines wheat at Pomeroy and Aberdeen, in the study with field run wheat. Both samples were rather long and thin, but the samples from Aberdeen lacked the plumpness of the Pomeroy samples. Plumpness should not be construed to signify a large diameter. Rather, it should mean a kernel which is well filled and uniform in contour. In the discussion of field run wheat from Tetonia it was stated that kernels which were pinched at the brush end had a reduced percent Vs, despite being quite large. Thus, they lacked uniformity of contour.

The case of the variety Nugaines well illustrates the importance of kernel shape to packing. At Walla Walla, the test weight of size 7 kernels exceeded that of the largest size, 8 1/2. The reason for this lies in the fact that percent Vs was greater for the smaller kernels. Why was the percent Vs so high for these small kernels? Visual examination showed that the diameter to length ratio was very small, and the kernels were quite uniformly cylindrical. Despite their small diameter they could be considered to be well filled in the sense that there was little evidence of shriveling. The bran coat was also quite smooth which aided in close packing.

This example emphasizes the fact that kernel size, per se, is not an important factor in packing characteristics. The kernel count for size 7 was 457 as compared to 283 for size 8 1/2. Nevertheless, the percent Vs was equal (56.55 for the smaller size in comparison to 56.47 for the larger kernels).

The role of bran condition and certain general shapes is further illustrated with the White Club varieties. Moro wheat from Walla Walla had a surprisingly high test weight (12.71), for size 8 1/2 (Table IX). The average test weight of the three smaller sizes was less, but nevertheless they exceeded the test weights of the respective sizes for Omar at this location, and for both varieties at Pomeroy.

The kernel density was quite high at Walla Walla. Although the density of Moro was lower than the density of Omar at Walla Walla, the test weight was higher due to the greater percent Vs. The values for this factor were 56.46 and 54.86 for Moro and Omar respectively for size 8 1/2.

Examination of the kernels shows that the kernels of Moro from Walla Walla resembled Soft White kernels to a remarkable degree. The kernels were longer and thinner and quite smooth, with less distortion than White Club kernels characteristically display. The short "humped" Omar kernels had rather deep creases which probably contributed to the increased void space and consequently to the low test weight at this location.

Based on the results of the sizing study, some general relationships and conclusions can be stated. Wheat of the subclass Soft White had a significanlty higher test weight, kernel density and percent Vs than White Club wheat. Soft White wheat had a lower kernel count than the White Club wheats, for each respective size.

The kernels from the two larger-sized groupings had a higher average test weight than the two smaller-sized partitions. The percent Vs followed the same pattern as kernel count. However, it was shown that kernel size, per se, seems to be less of a factor in this relationship than does kernel shape. The greater percent Vs for the larger kernels resulted in their higher average test weight. Plump well filled kernels with a small diameter to length ratio appear to pack more closely. The smallest-sized kernels had significantly lower densities than the two largest sizes. Perhaps the smallest kernels often reflect some shriveling which would account for both the low densities and the low percent Vs.

It has been shown that percent Vs is of primary importance in determining test weight. Kernel density is also important, but less so than percent Vs.

SUMMARY AND CONCLUSIONS

The average test weight was greater for Soft White than for White Club wheats collected from four locations throughout the Pacific Northwest in 1966. The average Soft White kernel was considerably heavier and occupied a greater volume than the average White Club kernel. The Soft White kernels also filled a given volume more completely than White Club kernels.

The average kernel density was greater for Soft White than for White Club kernels. Highly shriveled kernels generally had low densities. Kernels with highly wrinkled bran coats packed rather loosely (had greater void spaces) which caused a reduction in test weight.

When sized, the largest kernels had a higher percent occupancy and also had a higher test weight. The ability of the larger kernels to more completely fill a given volume can be attributed not so much to size, per se, but rather to the fact that their shape and bran condition generally favor higher packing densities. Kernels of the smallest partition had a high percent occupancy if the kernels were well filled, smooth and quite uniformly cylindrical in shape.

The general shape of Soft White kernels is more favorable to close packing than are White Club kernels. Packing density was shown to be of primary importance in determining test weight. The correlation between test weight and the percent occupancy was .938.

The significantly higher test weight of Soft White wheat can be attributed to the fact that it had a higher packing density and the average kernel density was greater than that of White Club wheat.

It should be recognized that White Club wheats have a lower average kernel density and pack less tightly than Soft White wheats. Because of this, White Club wheats weigh less for a given volume. Therefore, when comparing test weights of Soft White and White Club wheats, the weights of unequal volumes of wheat are being compared.

In conclusion, one can say that test weight of wheat is a volume-mass relationship which is greatly complicated by the fact that a given volume is being filled with highly heterogenous particles. Future investigations in this area should include the study of individual kernel shapes and their packing characteristics.

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APPENDIX

APPENDIX

Table I. Summary of mean squares from the factorial analysis of variance for test weight, kernel count, kernel density, percent Vs, and protein content in Field run wheat.

Source of Variation	df	Mean Squares and Level of Significance				
		Test Weight	Kernel Count	Kernel Density	Percent Vs	Protein Content
Variety	3	.53030**	8989.89**	.00033**	5.35600**	3.58172
Location	3	.76328**	3537.50**	.00320**	5.53615**	14.16297
Variety x Location	9	.05529**	1005.24**	.00009*	1.12319**	5.64339
Error	32	.00477	32.02	.00001	.11999	0.0

*, ** Significant at the five and one percent level respectively.

APPENDIX

Table II. Summary of mean squares from the factorial analysis of variance for test weight, kernel count, kernel density, percent Vs. Sizing study.

Source of Variation	df	Mean Squares and Level of Significance			
		Test Weight	Kernel Count	Kernel Density	Percent Vs
Variety	3	1.067221**	7570.807**	.000940**	13.286715**
Location	1	.783225**	5757.016**	.005150**	1.262817**
Size	3	.114542**	92599.141**	.000160**	1.400290**
Variety x Location	3	.061054**	53.349*	.000308**	.536954**
Variety x Size	9	.008951	50.474*	.000012	.120422
Location x Size	3	.004467	61.432	.000017	.161003
Variety x Location x Size	9	.008262	25.043	.000032	.231925
Error	32	.006669	14.547	.000015	.152286

*, ** Significant at the five and one percent level respectively.