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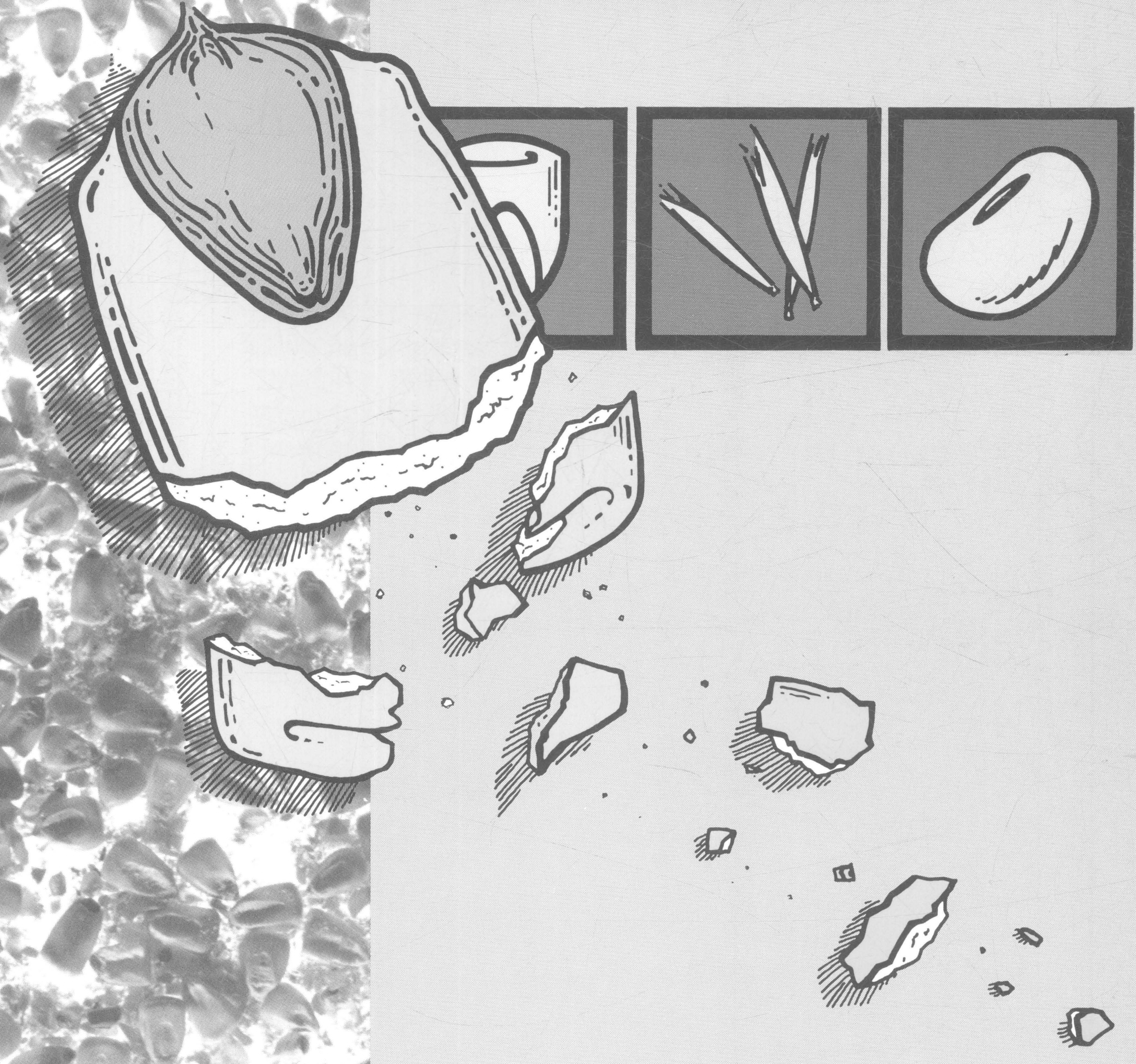
Fine Material in Grain



Ohio Agricultural Research and Development Center
Wooster, Ohio
OARDC Special Circular 141

FINE MATERIAL IN GRAIN

North Central Regional Research Publication 332

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The Ohio State University
Wooster, Ohio
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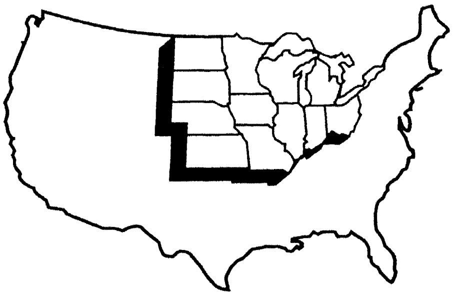
Prepared by Members of the North Central Regional Committee NC-151,
Richard Stroshine, ed.



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Contents

Preface

In 1988, the NC-151 USDA regional research committee on "Marketing and Delivery of Quality Cereals and Oilseeds" decided to sponsor several symposiums in conjunction with their annual meetings. Each symposium was to focus on a topic of critical importance to grain quality. For its first symposium, the committee selected what it considered to be one of the most important aspects of grain quality—fine material. The symposium was held on February 15, 1989 in St. Louis, Missouri. NC-151 recognized that the grain industry would benefit from a comprehensive publication on this topic. Therefore, those who gave presentations were invited to submit written papers, which would be edited and published as a regional research bulletin.

This publication is the compilation of papers from the Fine Material in Grain Symposium. It reflects the committee's heterogeneous composition. NC-151 is comprised of scientists from a variety of disciplines, including cereal chemistry, agricultural economics, entomology, agricultural engineering, and plant pathology. Industry representatives also attend NC-151's annual meetings and workshops. The group discussions are therefore generally broader than discussions at meetings of professional societies yet more technical than those at gatherings of grain industry representatives. A variety of viewpoints are represented. The involvement of industry encourages researchers to address practical concerns and to evaluate the implications of their results.

The papers in this publication were written by experienced researchers who attempted to synthesize results of key research. Papers discuss basic principles and practical implications. They also include valuable results which have not been previously published. For example, the paper "Effects of Fine Material on Mold Growth in Grain" includes information from several interesting yet previously unpublished research reports. Similarly, the chapter on "Genotypic Differences in Breakage Susceptibility of Corn and Soybeans" contains previously unpublished data on damage susceptibility of soybean varieties. Several of the papers point out "gaps" in our current knowledge and give recommendations for additional research. A considerable amount of effort was put forth to ensure the quality of this publication. Each paper was evaluated by two or more peer reviewers. The authors were then asked to respond to the reviewer comments and to make appropriate changes in their manuscripts. Subsequently, a draft of the publication was sent to each of the participating experiment stations for evaluation. Additional comments were received, and these suggestions were also incorporated.

This publication benefited from the technical editing of Mr. Robert Furbee, Associate Head and Editor, Section of Information and Applied Communications, Ohio Agricultural Research and Development Center, Wooster, Ohio. He gave valuable guidance on format and layout, found typographical errors in the text, and coordinated the printing and distribution of the publication. Ms. Marilyn Haas, secretary in the Department of Agricultural Engineering at Purdue University, used her skills in word processing to transform the original papers, which were received on computer discs in a variety of formats, to a single consistent format in an attractive layout. She also incorporated a significant number of changes in the manuscripts, which were necessitated by the editor's attempts to reconcile reviewer comments and the perspectives of individual authors.

Richard Stroshine
Editor

Fine Material in Grain: An Overview

Richard Stroshine[a]

Definition of Fine Material

Fine material consists of pieces and small particles of kernels mixed with the grain that can be removed from the grain using screens of specified sizes. This definition distinguishes the fine material from foreign material, which includes material other than grain such as weed seeds, dirt, chaff or hulls, pieces of plant stems, and other types of grain. In the past, fine material and foreign material were not distinguished in marketing channels. The grades defined by the U.S. Grain Standards (Federal Register, 1987) have been the primary measure of relative value. When grain is graded, a representative subsample of approximately 1000 g (2.20 lbs) is weighed and sieved. The weight of the material passing through the sieve is determined and added to the weight of non-grain material remaining on top of the sieve. This total is divided by the original weight of the sample and converted to a percentage. This is designated as the percent broken corn and foreign material (BCFM) in corn (*Zea mays* L.), percent foreign material in soybeans (*Glycine max* L.), and percent dockage in wheat (*Triticum aestivum* L.). For corn and soybeans the standards specify metal sieves 0.813 *mm* (0.032 *in*) thick with round perforations of diameters 4.76 *mm* (12/64 *in*) and 3.175 *mm* (8/64 *in*), respectively. Perforations are 6.35 *mm* (16/64 *in*) from center to center and each row is staggered in relation to the adjacent row. For wheat the screen has oblong perforations 1.626 *mm* (0.064 *in*) wide and 9.525 *mm* (3/8 *in*) long. Sieves for barley, rye, sunflower and triticale also have oblong perforations. The sieve used for sorghum has triangular perforations while determinations for oats use one sieve with triangular perforations and another with oblong perforations.

The grain industry recognizes that the distinction between foreign material and fine material is important. Although broken pieces of grain (fine material) are less valuable than whole grain, fine material is more valuable than foreign material because it has more nutritional value. This awareness is reflected in recent changes to definitions in the U.S. Standards for shelled corn. As of 30 June 1987, the standards included separate definitions for "broken corn" and "foreign material." Broken corn consists of the material which passes through the 4.76 *mm* (12/64 *in*) sieve and is retained on top of a 3.175 *mm* (8/64 *in*) sieve. Foreign matter is defined as the material which passes through the 3.175 *mm* (1/8 *in*) sieve along with material other than corn remaining on the top of the 4.76 *mm* (12/64 *in*) sieve. Using specially designed two-tiered sieves, Federal Grain Inspection Service (FGIS) personnel can determine both "broken corn" and "foreign material." They record the values on the inspection log of export shipments and the remarks section of certificates for domestic shipments. However, BCFM, the sum of the values for broken corn and foreign material, continues to be used when determining grade.

The two-sieve method has been used for many years in the grading of sorghum. Broken kernels, foreign material, and other grains (commonly called BNFM) are defined as material which passes through a 1.98 *mm* (5/64 *in*) triangular sieve and remains on top of a 0.993 *mm* (2.5/64 *in*) round-hole sieve. In the June 1987 changes, FGIS amended the definitions to distinguish between foreign material and broken kernels. Percentage broken kernels is determined from the material passing through the 1.98 *mm* (5/64 *in*) sieve and staying on top of the 0.992 *mm* (2.5/64 *in*) sieve. Foreign material is the material removed by the no. 6 riddle* on the dockage tester along with

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[a] Agricultural Engineering Department, Purdue University

* The riddle on the dockage tester is made of a series of molded plastic strips arranged in pairs inside a wooden plastic frame. Grain can pass between a pair of strips by making a 90° turn. Large pieces of stem and other foreign material cannot pass through.

the material remaining on top of the 0.992 mm (2.5/64 *in*) sieve. Foreign material also includes other grains mixed with the sorghum. FGIS is evaluating whether the dockage should also be included as foreign material. However, the grade determining factor remains BNFM, the sum of foreign material and broken kernels.

Factors Affecting the Production of Fine Material

Fine material is generated by impacts which occur during harvesting and handling. Free fall tests (Fiscus et al., 1971b) have demonstrated that corn will break up more readily than soybeans and that wheat is the least susceptible to breakage (Table 1). Single-kernel impact studies on shelled corn (Moreira et al., 1981) and soybeans (Bartsch et al., 1986) demonstrated the moisture and velocity dependence of impact damage. Both studies found that for a given impact velocity, damage greatly increases as moisture content drops below 14, the upper range of typical storage moisture. Impact fracture and internal cracking of seeds dried in the field or at ambient temperatures becomes severe only at velocities above 10 *m/s* (33 *ft/s*). Therefore, the most damage can be expected when grain kernels traveling at these velocities strike a rigid surface or other kernels. Free fall tests have shown slightly greater damage (approximately 10%) for grain impacting a concrete surface as compared to impacting other grain (Fiscus et al., 1971b).

A significant amount of breakage occurs as grain travels through marketing channels. By the time it reaches the end-user, the grain may have been handled nine to 12 times. The high-speed, high-volume handling equipment used to load ships and unload rail cars and trucks at processing plants subjects the grain to high-velocity impacts. The lower the moisture content of the grain when it is handled, the more breakage will occur. Therefore, corn dried to 13 or 14% moisture (the moisture needed to prevent mold growth during long term storage) is more susceptible to breakage than corn at 15% moisture (the moisture typically used for storage over winter).

Kernel velocities vary widely during events from harvesting through processing. Velocities for discharge from an elevator spout or flow from bulk transport during unloading are only 4 to 5 *m/s* (13 to 16 *ft/s*) (Bartsch, 1979). However, the peripheral speed of a combine cylinder is typically 12 to 18 *m/s* (39 to 59 *ft/s*). The velocity of a single kernel during

Table 1. Breakage of Shelled Corn, Soybeans and Wheat as a Result of Free Fall and Compression Between Flat Metal Plates.

Grain	Free Fall Tests[a] 21.9 m (72 ft. Drop Height)					
	Temperature °C (°F)	Moisture (w.b.)	Average (Fines)	Moisture (w.b.)	Orientation	Average Force to Initiate Fracture[b] N (lbs)
Shelled corn	3.9 (25)	12.6	7.74	8.0	Germ side down	400 (90)
					Kernel on edge	191 (43)
Soybeans	0 (32)	11.0	1.89	10.0	Hilum horizontal	53.4 (12)
					Hilum vertical	40.0 (9)
Spring wheat	-2.8 (27)	11.2	0.22	not tested		
Winter Wheat	7.2 (45)	11.1	0.08	8.0	Crease down	57.8 (1)3
					Crease on side	53.4 (12)

[a] Source: Fiscus et al., 1971
[b] Source: Bilanski, 1966

free fall, called the terminal velocity, varies among kernels of a given type of grain and also among grains. For example, the terminal velocity of shelled corn ranges from 8 to 13 *m/s* (26 to 42 *ft/s*) while it ranges from 6 to 9 *m/s* (19 to 30 *ft/s*) for wheat and 9 to 18 *m/s* (30 to 60 *ft/s*) for soybeans (Uhl and Lamp, 1966). Therefore, in free fall only a fraction of the corn kernels, but the majority of soybean kernels reach velocities greater than 10 *m/s* (33 *ft/*s). Recall that 10 *m/s* (33 *ft/s*) is the lowest velocity at which significant impact damage begins to occur. Higher velocities are attained when grain falls in a stream. In tests conducted by Fiscus et al. (1971a) with grain flowing from 20 cm (8 *in*) and 30.5 cm (12 *in*) orifices, the terminal velocities of corn and wheat were exceeded for drop heights of 8.2 *m* (27 *ft*). The velocity of 15 *m/s* (50 *ft/s*) was exceeded for drop heights above 21.5*m* (70 *ft*). For a given drop height, wheat and corn velocities were about equal while soybean velocities were approximately 6% greater than those for wheat and corn.

Eliminating severe impacts would greatly reduce the amount of fine material. However, fine material could still be produced by abrasion and compression of kernels during transport in augers and drag conveyors. The force needed to initiate cracks in various types of grain subjected to a compressive load between two flat plates (Table 1) is dependent on orientation. Kernels break more easily when they are compressed at higher moistures. Soybeans and wheat will fracture under approximately the same force, 40 to 53 N (9 to 12 *lbs*). However, a force two to 10 times greater, 98 to 400 N (22 to 90 *lbs*), is required to initiate fracture of shelled corn. Recall that shelled corn is more easily broken during impact. Therefore, it is likely that equipment which applies a compression load to kernels, such as equipment which scoops or pushes the grain, will cause more damage to wheat and soybeans than to corn. Chapter 5, **Reducing or Controlling Damage to Grain from Handling--A Review**, summarizes much of the available information on damage from various handling techniques.

Testing Grain for Susceptibility to Breakage

Although grain leaving the farm usually has a small percentage of fine material and appears to be sound, it can still be predisposed to breakage during subsequent handling. This tendency for breakage is termed breakage susceptibility and it can be measured using standard techniques. Breakage susceptibility testers propel the grain kernels against a metal surface (or against other kernels) in a controlled manner and, in some cases, also abrade the grain. The impacted grain is sieved to remove the fine material and the percentage weight of fine material produced in the tester is calculated and reported as "breakage susceptibility." The sieves used are usually the same ones specified in the grain standards. Moisture is also measured and reported because of its strong influence upon breakage.

The Stein* Breakage Tester (SBT), a popular research tool that has been used for at least 25 years, uses a 100*g* (.220 *lb*) grain sample. The grain is placed in the metal cup of the tester where it is impacted for a set time (usually 2 *min*) by a rotating metal impeller. Stephens and Foster (1976) found a good correlation between Stein breakage test results and the percentage of fine material produced when grain was spouted from a height of 29 *m* (95 *ft*) into a truck. The weight percentage of fines generated by this handling was approximately one fifth to one eighth of the breakage produced during 2 *min* in the SBT tester. An in-depth summary of breakage susceptibility testing is given in Chapter 6, **Evaluating Grain for Potential Production of Fine Material--Breakage Susceptibility Testing**.

Factors which influence breakage susceptibility include harvesting-machine damage, drying temperature and procedure, and grain variety. In a Nebraska study (Mowitz and Fink, 1987), grain from 11 Midwest farms was sampled and tested for breakage susceptibility prior to harvest and then successively sampled and tested after harvesting, drying, and conveying. Breakage susceptibility, relative to the breakage susceptibility of hand-harvested gently dried shelled corn, increased 32% after combining, an additional 53% after drying, and an additional 17% after handling. The study demonstrated that combine adjustment and drying technique substantially influence breakage through marketing channels. The effect of drying on handling damage is discussed in Chapter 5, **Reducing or Controlling Damage to Grain from Handling: A Review**. Grain varieties differ in their tendency to break during harvesting, drying, and handling. These differences are discussed in Chapter 7, **Genotypic Differences in Breakage Susceptibility of Corn and Soybeans.**

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* Reference to a product or trade name does not imply approval or recommendation of a product by the NC-151 Committee or the Agricultural Experiment Stations.

Problems Associated with Fine Material

The amount of fine material generated during handling can be substantial. Hall (1985) reported that 44,700 *tonnes* (1,760,000 *bu*) of fines were generated during the handling of 788,100 tonnes (31,000,000 *bu*) of corn at a Great Lakes facility. Hill et al. (1979) reported significant increases in amounts of fine material during three separate shipments of exported shelled corn (14.0 to 14.9% moisture). The grain arriving in trucks at the elevator near Peoria, Illinois contained approximately 1.2% BCFM. This grain was transferred to barges which traveled down the Illinois and Mississippi rivers to a Gulf Coast export elevator. Upon unloading from barges and transfer to storage, it averaged 4.6% BCFM. In a shipment of grain from a Lake Erie port elevator to an importer and feed manufacturer in the Netherlands, BCFM increased from 3.7% during loading onto the vessel to 8.0% during unloading at the receiving facility. In the third study, grain was shipped from Indiana and Illinois by unit train to an East Coast port. Grain in storage at the elevator contained 2.9% BCFM and grain in the freight cars arriving at the port contained 3.9% BCFM. A portion of the BCFM was then removed by cleaning and it contained 3.5% BCFM as it was loaded onto the ocean vessel. The BCFM level had increased to 9.5% when it was being moved from storage silos to the steeping tanks of a starch manufacturer in Manchester, England. The corn had been unloaded from the ship using pneumatic suckers and a portion of the fine-material had been removed before it was placed in the storage silos.

Although handling techniques and grain characteristics varied among these shipments, substantial amounts of fine material were generated. Such increases between the time of loading onto the ship and unloading at the receiving facility are of particular interest because the official grade of the grain is determined at the time of loading. Therefore, when a foreign buyer requests U.S. no. 2 corn, it may actually arrive containing more than the grade limit of 3.0% BCFM for U.S. No. 2.

Damage to soybeans during shipment is usually less than damage to corn, but it can still be significant. In a study which included four vessels loaded with soybeans, average percent splits increased from 13.6% at origin to 18.0% at destination (Hill et al., 1981). Foreign material increased from an average of 1.7% to an average of 3.1%. This increase was caused by breakage of the soybeans during handling. The significance of fine material for the grain export market is discussed further in Chapter 2, **Factors that Affect Cost of Fines in the Corn Export Market**.

Fine material in grain is a concern of elevator operators. In a 1987 survey conducted by Purdue University Agricultural Engineering Department, 300 randomly selected grain elevator/storage facility managers were asked which of several factors they considered to be their major quality problems. Of the 150 who responded 73 checked "too much fine material," 62 checked "insect infestation," 32 checked "breakage of grain," and 22 checked "molding during storage." Thus the presence of fine material was a major concern and almost one third were concerned about the related area of grain breakage. Many may have been unaware that the factors are related; the presence of fine material aggravates the two other quality problems mentioned in the survey-- insect infestation and molding. The relationships of fine material to these factors are discussed in Chapter 3, **Effects of Fine Material on Mold Growth in Grain** and Chapter 3, **Effects of Fine Material on Insect Infestation**. Other aspects of fine material in export markets are discussed in Chapter 2, **Factors that Affect the Costs of Fines in the Corn Export Market**.

In addition to its effects on quality, fine material can create a safety hazard and complicate the management of stored grain. Dust, which includes a high proportion of fine grain particles, becomes airborne during handling and then settles on horizontal surfaces within the elevator creating a fire and explosion hazard. When it is suspended in the air dust can be ignited by a spark from machinery or by welding and cutting operations. The initial combustion creates air currents which suspend settled dust which in turn is ignited. Grain dust explosions occur in elevators and grain processing facilities and several in the past two decades have involved loss of lives and extensive damage to property. Concern over explosions prompted a major research and education effort by the National Grain and Feed Association's Fire and Explosion Research Council (Graham, 1981).

Uneven distribution of fines is common when grain falls from a spout into storage because, unlike grain kernels, fine material does not slide and bounce when it falls onto grain. Concentration of fine material can promote mold and insect growth, and interfere with proper air distribution during aeration or drying. Figure 1 (Hall, 1985) shows the distribution of fine material of various sizes after spout filling of a 11,400 tonne (450,000 *bu*) grain tank at a large Great Lakes elevator. The average fine material content of the grain was 4.4%, but levels near the center of the tank were as high as 27%. To a lesser (but significant) extent, segregation occurs during loading of barges and hopper cars at terminal elevators and during ship loading at export facilities. Differences of 2% or more can easily occur in on-farm storage bins, even when a grain spreader is used. There would be much greater differences when a grain spreader is not used. For in-bin low temperature drying systems, uneven distribution of fines can interfere with the drying process. The drying front moves more slowly in areas where there are high concentrations of fines. Therefore, it reaches the top of the bin more quickly in regions where there are fewer fines. However, drying must continue until the areas with high concentrations of fines have also dried. This could extend the drying period and increase costs.

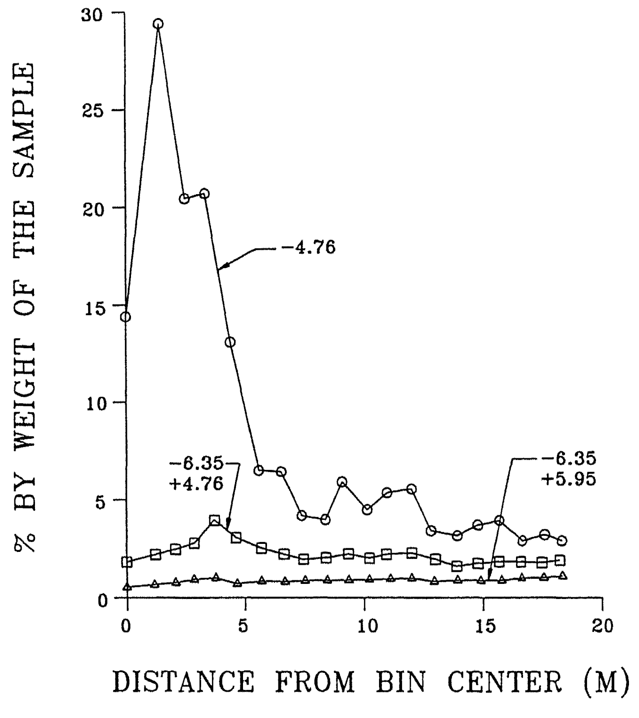

Figure 1. Distribution of fine material after spout filling of an 11,400 tonne (450,000 *bu*) grain storage tank. Labels are as follows: -4.76 indicates the percentage of fine material which passed through a 6.35 mm (12/64 *in*) round hole sieve; -6.35 +4.76 indicates percentage of fine material which passed through a 6.35 mm (16/64 *in*) screen but stayed on top of a 4.35 mm (12/64 *in*) screen; -6.35 +5.95 indicates percentage of fine material which passed through a 6.35 mm (16/64 *in*) screen but remained on top of a 15/64 *in* screen. (Hall, 1984).

Uneven distribution of fine material alters the airflow pattern and makes aeration less effective. Fine material also increases power requirements for aeration and drying. Grain containing 7% fines will have approximately 2.3 times the airflow resistance of grain with 0% fines. Grama et al. (1984) calculated a power index for several levels of fine material. It was defined as 100 multiplied by the ratio of power used by the fan for a given level of fine material to the power used for clean corn. For shelled corn with 7.3% fine material aerated at 0.0034 $m^3/s-t$ (0.2 *cfm/bu*) the power index was 110. This is relatively insignificant. However, for 4.3% fines the power index for a high temperature column dryer operating at an airflow of 1.5 $m^3/s-t$ (80 *cfm/hr*) was 109. For low temperature in-bin drying and 4.3% fines the power index was 116 at an airflow of 0.019 $m^3/s-t$ (1.0 *cfm/bu*).

Fine material also concerns certain end users. In 1987, FGIS/ARS conducted a survey of wheat, corn, and soybean processors and foreign users of wheat (FGIS/ARS, 1988). When they combined their results with those from surveys of foreign users of corn and soybeans conducted by other research groups, they had a total of 178 responses from domestic users and 89 responses from foreign users. Results tabulated included concerns about dockage in wheat, BCFM in corn, and both foreign material and splits in soybeans (Table 2). Although these grading factors are also influenced by the presence of foreign material, such as pieces of plant stalks, any fine material present would be included in this category. Because fine material is more dense than much of the foreign material, in many cases, it would be the major contributor to determination of grade.

Of the users included in the results reported by FGIS, corn wet millers appeared to be the most concerned with fine material. Three fourths of the foreign and domestic users specified it in their contracts. On a scale of 1 to 7 with 7 being most significant it was one of three factors given a 7.0 rating by domestic wet milling companies. Domestic dry millers also emphasized the importance of BCFM, as slightly over half of them specified fine material in their contracts. Domestic dry millers gave it an importance rating of 5.7. However, 6.0 was the highest rating they gave to any of the factors. Of the three major users of corn, domestic feed dealers appeared the least concerned about BCFM. However, almost three quarters of foreign feed dealers specified BCFM in their contracts. Because

Table 2. Importance of Fine Material to Domestic and Foreign Buyers as Indicated by Interest in Grade Factors Influenced by Presence of Fine Material (FGIS/ARS, 1988).

Grain	Factor	User	Proportion of Users Using This Factor		Importance of Factor to Domestic Users Average Score. (Scale of 1-7. Important = 7, Neutral = 4)
			Domestic (%)	Foreign (%)	
Wheat	Dockage	Millers (large)	34%	40 [a]	-
		Millers, hard wheat flour	-	-	5.5[b]
		Millers, whole wheat flour	-	-	5.8[b]
		Millers, soft wheat flour	-	-	5.4[b]
Corn	BCFM	Wet millers	75	78	7.0
		Dry millers	51	(no data)	5.7
		Feed dealers	41[c]	72	5.1[d]
Soybeans	Foreign Material	Oil extraction	40	62	5.8
	Splits	Oil extraction	20	52	4.7

[a] Foreign buyers represented were primarily government purchasing agents. This ranking was the highest among all specifications.

[b] This ranking was relatively low in comparison to other quality factors.

[c] This percentage was the highest for any quality criteria used by feed manufacturers.

[d] Ratings of factors by feed manufacturers ranged from 6.4 to 4.8. This received one of the lower ratings.

foreign users from all three categories placed a relatively high importance on BCFM, generation of BCFM during shipment should be a major concern to grain exporters.

Less concern for fine material in wheat and soybeans may reflect the lower tendency of these grains to break up during shipment. Nevertheless, fine material should also be a concern to exporters of these commodities. Over half of the foreign soybean users specified foreign material and splits in their contracts. About two thirds of the foreign wheat buyers in the survey were government purchasing agencies. Only 40% of the 47 wheat buyers who responded to the survey were specifying dockage in their contracts. However, it was the most frequently specified factor.

Levels of Fine Material in Marketing Channels

The percentages of fine material in grain graded by FGIS are indicative of fine material percentages for the entire crop. During the past several years, FGIS has conducted surveys of new crop grains by randomly inspecting samples in the major growing regions during the first 4 weeks following local harvest (FGIS, 1988a, 1988b, 1988c). Numbers of samples inspected for each crop were: 12,098 for wheat; 3,336 for corn; and 7,497 for soybeans. There are two grade factors which reflect the amount of breakage to wheat: (i) dockage and (ii) shrunken and broken kernels. Although weed seeds and other small particles of foreign material could affect dockage, much of this material is small pieces of wheat. Field and storage mold damage and improper development can affect the percentage of shrunken and broken kernels. However, a substantial portion of this category consists of kernels which have been broken into large fragments. Levels of dockage and broken and shrunken kernels varied among the five major classes of wheat (soft red winter, hard red winter, hard red spring, durum, and white). Average levels of dockage varied from 0.8 to 1.1% and average levels of broken and shrunken kernels varied from 1.0 to 1.8%.

For the samples tested (FGIS, 1988a, 1988b, 1988c), the average percentage of BCFM in corn was

1.82. Soybeans averaged 1.9% foreign material and 8.0% splits. The averages for states and regions were not weighted in proportion to the amount of production; therefore, averages may not represent the average for the entire crop. However, they do give an indication of the percentage of fine material which can be found in grain from country elevators. The average BCFM was within the limit for U.S. No. 1 corn and the averages for foreign material and splits were within the limits for U.S. No 2 soybeans.

Although average percentages of fine material in samples of corn, wheat, and soybeans were relatively low, a significant number of individual samples had much higher levels. This is demonstrated by the distribution curves for these factors. Figure 2 shows the distribution of dockage levels in wheat; Figure 3 gives the distribution of BCFM in corn; and Figures 4 and 5 give distributions of foreign material and splits in soybeans. The distribution curve for broken and shrunken kernels in wheat was not available. A significant number of the wheat samples contained more than 1% dockage. The limit dividing No. 2 from No. 3 corn is 3.05% FM (Federal Register, 1987) and a significant number of corn samples had more than 3.0%. The foreign material in many of the soybean samples exceeded 2%, the limit between No. 2 and No. 3 soybeans. It is likely that the percentages increased as the grain moved through marketing channels. Unless a portion of the fine material was removed by cleaning, the grain would have shifted towards lower grades.

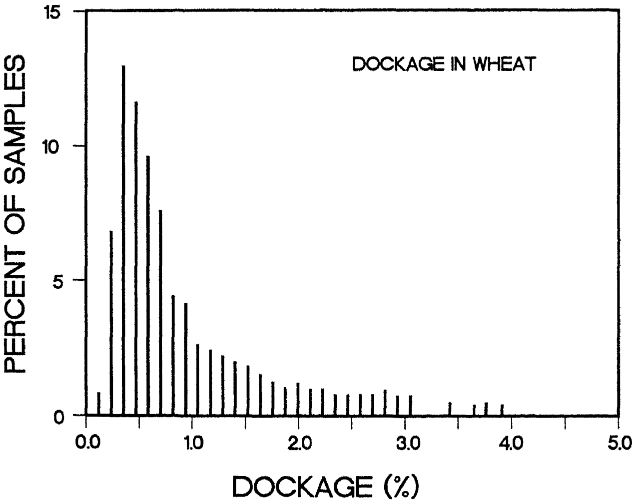

Figure 2. Distribution of Dockage in 12,739 samples of 1987 new crop wheat inspected by the Federal Grain Inspection Service. The distribution represents inspections of wheat in all five categories - soft red winter, hard red winter, hard red spring, durum, and white (FGIS, 1988a).

Averages for grading factors influenced by presence of fines for export grain sampled by FGIS in 1985-87 (Table 3) reflect the quality of a large quantity of grain. For example, the number of samples inspected in 1987 were as follows: 2,160 for wheat representing 99.7% of the total of 29,000 tonnes (1.14 million bushels) inspected; 1,652 for corn representing 98.0% of the 41.4 million tonnes (1.63 billion bushels) inspected; and 975 for soybeans representing 97.3% of the 20.3 million tonnes (800.11 million bushels) inspected.

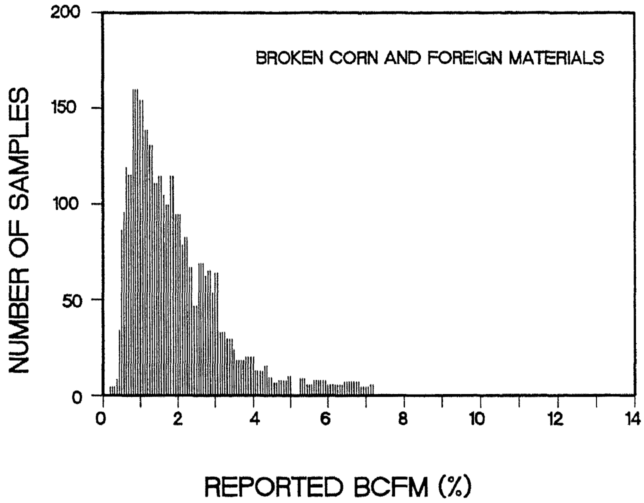

Figure 3. Distribution of BCFM in 2,855 samples of 1987 new crop corn inspected by the Federal Grain Inspection Service. (A total of 3,336 samples were inspected--BCFM was not reported for all samples) (FGIS, 1988b).

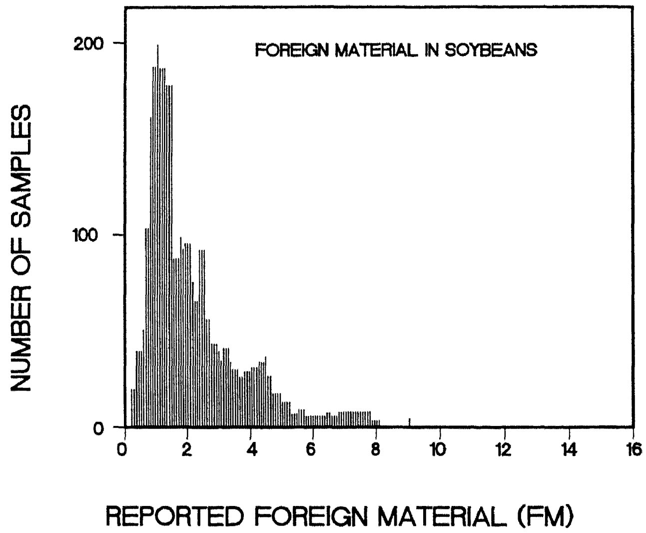

Figure 4. Distribution of foreign material in 2,724 samples of 1987 new crop soybeans inspected by the Federal Grain Inspection Service. (A total of 2,839 samples were inspected--foreign material was not reported on 2,724 samples) (FGIS, 1988c).

Table 3. Summary of Fine Material in Exported Grain Sampled by FGIS as Indicated by the Grade Factors Which Are Influenced by the Presence of Fine Material (FGIS, 1988d).

Grain	No. of Lots Examined in 1987	Factor	Average			Range for 1987
			1985	1986	1987	
Wheat (hard red winter)	56 of U.S. No. 1; 787 of U.S. No. 2; and 1 of U.S. No. 3	Dockage	0.7	0.7	0.6	0.1-1.2
		Shrunken and Broken	2.6	2.7	2.4	0.4-4.0
Wheat (soft red winter)	1 of U.S. No. 1; and 202 of U.S. No. 2	Dockage	0.8	0.8	0.8	0.4-2.1
		Shrunken and Broken	1.0	1.2	1.2	0.5-1.9
Wheat (white)	52 of U.S. No. 1; 328 of U.S. No. 2; and 1 of U.S. No. 3	Dockage	0.7	0.7	0.6	0.2-1.4
		Shrunken and Broken	1.2	1.5	1.3	0.8-2.4
Wheat (hard red spring)	32 of U.S. No. 1; 496 of U.S. No. 2; and 3 of U.S. No. 3	Dockage	0.8	0.9	0.9	0.3-2.5
		Shrunken and Broken	2.0	1.8	1.6	0.7-2.8
Corn (U.S. No. 2)	653	BCFM	3.4	3.3	3.3	0.8-6.5
Corn (U.S. No. 3)	973	BCFM	3.6	3.6	3.6	1.2-4.6
Corn (All lots)	Above plus 8 of U.S. No. 2; 10 of U.S. No. 4; and 7 of U.S. Sample Grade	BCFM	3.4	3.3	3.3	0.8-6.5
Soybeans (U.S. No. 2)	857	Foreign Material	1.8	1.8	1.6	0.1-2.0
		Splits	5.9	9.2	9.2	0.0-20.0
Soybeans (U.S. No. 3)	70	Foreign Material	2.4	2.5	2.6	1.3-3.0
		Splits	6.7	10.6	10.4	5.0-22.0
Soybeans (All lots)	Above plus 39 of No. 1; and 2 of No. 4	Foreign Material	1.9	1.9	1.7	0.0-31.4
		Splits	5.9	9.4	9.3	0.0-51.0

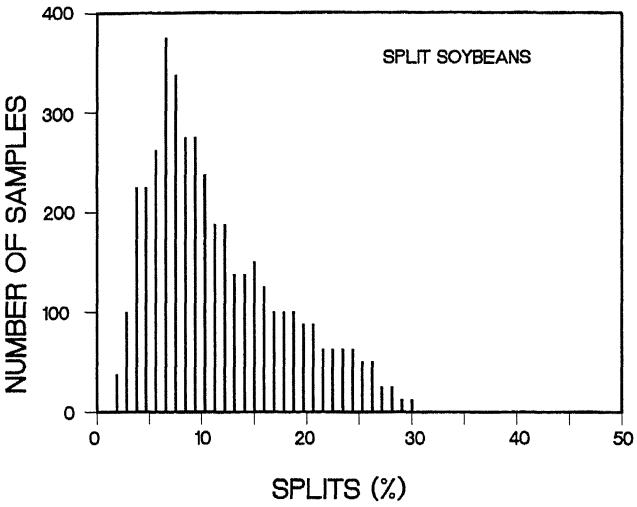

Figure 5. Distribution of split soybeans in 3,114 samples of 1987 new crop soybeans inspected by the Federal Grain Inspection Service. (A total of 7,497 samples were inspected--foreign material was not reported on all samples). Two samples with splits between 55 and 60 were not graphed (FGIS, 1988c).

The averages shown in Table 3 for all lots are within limits for No. 1 wheat and No. 2 corn and soybeans. The number of lots of No. 3 corn exceeded the number of lots of No. 2 corn. Most of the soybeans shipped were U.S. No. 2. These may indicate a greater tolerance for fine material on the part of end users of corn. The average levels of BCFM in No. 2 corn were very close to the limit of 3.0% for that grading factor and the average levels of foreign material in U.S. No. 2 soybeans were very close to the limit of 2.0% for that grading factor. This reflects the ability of exporters to closely control the levels of these factors in their shipments. It also means that a relatively small amount of damage during unloading would increase the BCFM (corn) or foreign material (soybeans) levels above the grade limits in the lots which foreign end users received. Segregation of fines during loading and unloading of vessels could also cause some end users to receive shipments with substantially higher levels of these factors.

The ranges (available only for 1987) indicate that much higher levels were found in some samples. The ranges for 1987 indicate that some of the lots contained very high percentages of fines. Some overseas buyers are apparently willing to accept such high levels. This acceptance may be explained by either the desire to purchase grain at a lower price or the belief that high levels of fine material do not lower the value of the grain for their specific use. Chapter 2, **Cost of Fines in the Export Market**, discusses costs associated with fine material in exported corn along with alternative policies which could bring about a reduction in fine material levels.

Removal of Fine Material

A variety of cleaning equipment is available for on-farm use. Rotating screen cleaners are perhaps the most frequently used. Pierce (1985) reported that models are available with rated capacities ranging from 12.7 to 89.1 t/h (500 to 3500 *bu/h*). He found that capacities vary with moisture content and that capacity was 30 to 40% greater when handling dry corn as compared to wet corn. Hurburgh et al. (1989) evaluated the efficiency of six rotary cleaners removing fine material from dry corn. Removal efficiency decreased with flow rate in five of the models and did not vary with flow rate in the other model. Removal efficiencies of all the cleaners decreased as the size of the fine material increased.

Pierce (1985) describes gravity screen cleaners and perforated auger sections. Both of these devices remove a smaller proportion of the fines than rotary screen cleaners.

Summary

The two major grains and the major oil seed produced in the United States are corn, wheat, and soybeans. Of these three, corn is the most susceptible to breakage as it moves through marketing channels. Corn arriving at country elevators typically has 1 to 3% fine material, while soybeans have 1 to 2% foreign material (much of which is fine material) and wheat usually has less than 1% dockage (much of which is fine material). The tendency of grain to break up during handling, called breakage susceptibility, increases as a result of combine harvesting, drying, and, to a lesser extent, handling. Fine material generated during handling reduces the value of grain to the users, increases the likelihood of insect infestation and molding, and interferes with airflow though the grain during drying and aeration. Although typical percentages of fine material in new crop grain are within the limits for no. 1 or no. 2 grain, a significant amount of grain has higher percentages. Furthermore, percentages of fines are likely to increase as grain moves through marketing channels. The control of fine material in grain is a significant problem for the grain industry. The remainder of the chapters in this publication address specific problems, potential solutions, and additional research that is needed.

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Factors That Affect the Costs of Fines in the Corn Export Market

Lowell D. Hill[a] **Mack Leath**[b]

Introduction

When the first official grades of corn were circulated in 1914, they defined two factors for broken corn and foreign material -- (1) broken and cracked corn and, (2) foreign material including finely broken corn, dirt, cob and other grains. Two sieves were specified in the 1914 grades. Broken corn was defined as material passing through a 16/64-inch sieve and retained on the 9/64-inch. Any material passing through the 9/64-inch sieve was called finely cracked corn and was defined as part of the foreign material factor.

In the 75 years since Dr. Joseph William Tell Duvel promulgated those standards the definitions of broken corn and foreign material have been changed many times. Sieve sizes have been changed, the two factors have been combined into one, and numerous proposals for redefinition have been discussed and rejected. We have come full circle and are now evaluating the separation of BCFM into two factors -- (1) broken corn passing through a 12/64-inch sieve and (2) foreign material including finely broken corn passing through a 6/64-inch sieve. The debate about the correct definitions and sieve sizes continues.

The size of sieve selected for separating "corn" from "broken corn" or "fines" influences the chemical and physical properties of the three fractions of the sample (Hill et al., 1982). The different definitions (and hence the compositions) affect the value of corn screenings removed, and also affect the value of the corn that remains. The definition of the factor BCFM and the grade limits for the factor, create incentives for cleaning and blending and thereby can alter practices of farmers and marketing firms. When considering alternative definitions of BCFM it is essential that the costs associated with fines (i.e., corn screenings) in storage, handling, and use or disposal be included in the cost-benefit equation.

BCFM in the Grades of Other Countries

In evaluating the alternatives it is useful to review the definitions used by other major corn producing and exporting countries. This review does not imply that any country has the best or the ideal definition, or that we should change U.S. grades, standards, or moisture meters just to match those of another country. However, we are operating in an international market and we need to know the standards of other countries before we can effectively evaluate the impact of changing ours.

Grades of grain in most countries include a factor relating to defective kernels (physical or biological defects) and most identify impurities separate from whole grain. The definition of these factors varies slightly among countries and they are sometimes combined with other characteristics. South Africa combines broken kernels and mold damaged kernels into one factor. They have a separate factor for impurities hand picked from the sample. Argentina, China, Thailand, France and Yugoslavia all handpick impurities from the sample. Most countries use the 12/64-inch sieve for defining broken kernels. South Africa is an exception, using a 16/64-inch sieve to separate broken kernels from whole corn in the sample. Thai standards do not specify a sieve but require inspection of each kernel. Any kernel less than half of the original fully matured kernel is classified as broken.

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[a] Department of Agricultural Economics, University of Illinois
[b] Crops Branch, USDA-ERS-NED, Washington, D.C.

In contrast, U.S. corn grades combine broken kernels (passing through the 12/64-in. sieve) with the impurities. The term "foreign material" in U.S. grades for most grains includes broken grains as well as all non-grain material. The difficulty in defining broken corn and foreign material is that no mechanical means exists for making a perfect distinction between small particles of corn and small particles of impurities. Separation based on particle sizes will leave impurities in the corn portion of the sample and small pieces of corn in the fines. Size alone will not separate corn from non-corn material in the sample or in the market channel.

Characteristics of BCFM in U.S. Market Channels

The complexity of separation is well documented in previous studies at both the University of Illinois and the University of Nebraska. Using low level magnification, the material in the various particle sizes were separated into major categories. While the proportion of corn, weed seeds and inert materials varied at each point in the market channel, all particle sizes contained both corn and non-corn material. Corn delivered by farmers to Illinois elevators in 1976 and 1977 contained, on average, 1.96% BCFM. The material above the 12/64-inch sieve was over 99% corn; material below the 12/64-inch sieve, dust and inert comprised .4%; weed seeds 2.9%; and corn by-products (bees wings and plant materials) 9.0% (Table 1). Sieve size had little effect on the composition of the material above the sieve: that portion of the sample contained over 99.8% corn regardless of the sieve size. However, sieve size did have an impact on the content of the BCFM portion of the sample -- the material passing through the sieve. Percent of weed seeds increased to 4.2% with the 8/64-inch sieve; dust and inert to 1.0%; and corn by-products to 17.2% of the weight of the BCFM portion of the sample. Use of the 6/64-inch sieve increased the percent of corn by-products but had little effect on the proportion of weed seeds or dust and inert material (Table 1).

The proportions changed through the market channel, primarily because the total amount of broken corn increased while the impurities remained nearly constant (Table 2). Consequently, the percent of weed seeds, corn by-products and dust and inert material in the BCFM portion of the sample decreased dramatically. The percent of corn within BCFM was much higher when measured at the river and inland sub-terminal elevators than when measured at the time the corn was delivered by farmers.

Characteristics of BCFM in the Export Market

The 1976/1977 study of BCFM did not analyze receipts at export elevators. However, case studies conducted in 1978 and 1979 traced individual shipments through the export elevator to foreign destinations. The proportion of the material passing through the 12/64 inch sieve that was classified as corn was slightly higher at the point of export than it was in shipments from the river or inland sub-terminal elevators (Table 3). There was a large increase in

Table 1. Physical Properties of BCFM at the Country Elevator Using Alternative Sieve Sizes to Define BCFM.[a]

	Percent of sample weight for various sieve sizes used to define BCFM in mm (inch)		
	4.76 (12/64)	3.175 (8/64)	2.381 (6/64)
Corn	87.8	77.7	71.9
Dust and inert	0.4	1.0	1.0
Weed seeds	2.9	4.2	3.8
Corn by-products	9.0	17.2	23.4

[a] Source: p. 19 of Hill et al. (1982).

Table 2. Physical Properties of BCFM at Sub-Terminal Elevators Using Alternative Sieve Sizes to Define BCFM.[a]

	Percent of sample weight for various sieve sizes used to define BCFM in mm (inch)		
	4.76 (12/64)	3.175 (8/64)	2.381 (6/64)
Corn	92.7	86.5	83.2
Dust and inert	0.1	0.3	0.3
Weed seeds	0.7	0.7	0.4
Corn by-products	6.6	12.6	16.3

[a] Source: p. 19 of Hill et al. (1982).

Table 3. Physical Properties of BCFM at Export Origin and Destination for Corn Shipments, Using Sieve Size of 12/64-in., 1978 and 1979.[a]

	Percent of Sample Weight	
	Origin	Destination
Corn	99.40	97.00
Dust & inert	0.20	2.58
Corn by-products	0.16	0.11
Other grain	0.21	0.23
Weed seeds	.00	.00

[a]Source: p. 5 of Hill et al. (1982).

dust between U.S. origins and U.K. destinations. Particles classified as dust were too small to differentiate between corn dust and dust from other sources. The increase in dust was off-set by a decrease in small broken pieces of corn. The percentages of corn by-products, weed seeds and other grains in the samples taken from the vessels in the United Kingdom and the samples taken from the outbound belt by FGIS, USDA at the Gulf were almost the same.

A comparison of Tables 1, 2 and 3 suggests that, between farm deliveries and foreign processors' plants, major increases in broken corn and corn dust and decreases in weed seeds and corn by-products occur as screenings are removed at various points in the market channel.

The high levels of broken grains (BCFM or FM) in the vessels at foreign destinations create opportunities for segregation. Non-uniformity among sublots and shipments was one of the primary concerns identified in the surveys conducted by the Office of Technology Assessment (1989). Segregation that occurred during loading and transit was evaluated in each of the shipments that were followed from origin to destination at the University of Illinois research. Several conclusions related to uniformity of BCFM and fines emerged from this research.

1. Segregation of fine particles occurred during loading but did not change during transit. There was no evidence that fine material moved during two to four weeks' voyage in the ocean vessels. There were no significant differences between origin and destination vessel samples in the BCFM or fine material contents of layers or sectors (p. 23 of Hill et al., 1979).
2. Segregation by particle size during loading resulted in a wide variation in the percent of BCFM, fines and whole kernels in different regions of each hold. Single-probe samples representing approximately 43 metric tons ranged from 2.6 to 14.2 percent BCFM, in the hold 1 of the Union Defender, the vessel in the 1986 study (p. 20 in Hill et al., 1988).
3. The outside perimeter of each hold contained, on average, less BCFM and fines than the center of the hold. For example, the average BCFM in the perimeter samples of hold 1, of the Union Defender in 1986 was 5.8 percent; the average BCFM in the center sectors was 7.3 percent. Moving the loading spout reduces the effect of spout lines, but the whole kernels tend to roll to the outside perimeter where the spouts do not reach (Figure 5 of Hill et al., 1990).
4. There were no significant differences in the average BCFM among holds. The lack of uniformity was not the results of loading sequence or attempts to average a range of BCFM across holds.
5. Uniformity of sublots unloaded from the vessel can be reduced by moving the unloading suckers and drawing from more than one location in the hold or the vessel so the original segregation is reblended. The variance among samples taken from barges as the vessel was unloaded was often less than among samples taken from the vessel prior to unloading (p. 20 in Hill et al., 1988).
6. Segregation of fines and foreign material in corn and soybean shipments to Tilbury, England, showed a sequential pattern during unloading with average FM declining as unloading progressed. This was apparently due to the manner in which the marine legs were positioned (pp. 7 and 13 in Hill et al., 1981). The marine leg was placed in one corner of the hold and gradually lowered to the bottom, with no horizontal movement as long as the corn rolled to the unloader.

Value of Screenings

The value of screenings can be determined in two ways: (1) analysis of nutritional content valued at alternative prices of energy and protein in livestock rations and (2) market prices of corn screenings. The disadvantage of using *nutritional composition* is that it gives a maximum potential value but ignores the influence of varying supplies. The disadvantage of using *market prices* of screenings is the lack of information on: (1) published market prices and (2) quantities available in the market.

Using average nutritional composition of BCFM at the country elevators and rations recommended by livestock nutritionists, the value of screenings were estimated at various prices of energy and protein in the 1976-77 study at the universities of Illinois and Nebraska. When the price of energy is high relative to the price of protein, the larger particle sizes have a higher value than smaller particles. Under extremely high prices of protein the material passing through the 6/64-inch sieve would have a greater value than material through the 12/64-inch sieve because the fines contain a higher percent of protein. These values were derived from rations containing a maximum of 25% screenings. The higher levels of fiber in the 6/64-inch material restricts its use in rations where fiber content is a limiting factor. The cost per pound of the balanced ration for young pigs containing 25 percent corn screenings was almost identical, regardless of the sieve size used to generate the screenings (Table 4). The cost per pound of ration was slightly higher for whole corn compared to corn screenings because the protein content of corn was lower than that of corn screenings and necessitated the addition of protein supplements to balance the ration. The prices of ingredients per hundredweight were held constant at: corn - $4.75, soybean meal - $10.26, screenings - $4.75.

Changes in the definition of BCFM will change market values. However, no data are available from which to estimate the effect of a change in sieve size on the quantity of screenings generated or to estimate the relationship between quantity and price of screenings. Observations of the market response over time indicate that the price of screenings relative to the price of corn is affected by the quantity, the quality and the location of the screenings. The primary use is in livestock feed. Therefore, at a greater distance from the livestock feeding area one would expect the price of screenings to be reduced by at least the cost of transportation. Research is needed to identify the relationships between market prices and the quantity and quality of corn screenings.

Costs Associated With Screenings

Another approach to establishing the value of screenings is to examine some of the costs associated with handling and controlling excess BCFM. The market discounts for BCFM levels above 3% vary by elevator and by season. Surveys of country elevators in Illinois in 1982 showed that the most frequent discount was 1 1/2 cents per bushel for each percent above 3. Discounts at that time ranged from 1 to 3 cents per bushel for each percent (p. 17 in Hill et al., 1983).

Table 4. Least-Cost Rations for Growing Swine Using Corn and Corn Screenings, Balanced on Amino Acid Requirements.[a]

	Corn	Material Passing Through a Screen Size in mm (inch)		
		12/64	8/64	6/64
Digestible energy				
K cal/kg	3,766	3,659	3,681	3,667
K cal/lb.	1,710	1,661	1,671	1,665
Crude Protein				
percent	16.5	16.8	16.8	16.8
Cost of Ration				
¢/kg	12.86	12.80	12.80	12.82
¢/lb.	5.84	5.81	5.81	5.82
Cost of Ration				
¢/1,000 K cal.	3.475	3.498	3.477	3.495

[a] Source: pp. 16-17 of Hill et al. (1982).

Because BCFM at export elevators is primarily broken corn, there is generally a surplus of screenings at ports. Most of the markets for screenings are located in the midwest or near feed processors in the eastern United States. The 1976-77 study on broken corn and foreign material showed that corn shipments from inland and river sub-terminal elevators contained on average 2.6% of BCFM (Table 6 of Hill et al., 1982). Therefore, one of the costs of excess BCFM is the transportation cost from midwest production regions to port areas and back to midwest feeders. The same principles apply to international shipments. Transportation rates for grain and the foreign material included in the vessel are the same. The cost of transporting foreign material from U.S. ports to foreign processing plants is equal to the ocean freight and is generally borne by the importing firm.

Some farmers and exporters have argued that since most export corn is intended for livestock feed, broken corn should have the same value as corn to the importers. However, this is inconsistent logic. Since U.S. markets discount BCFM above 3% despite direct access to livestock feeders, Japanese and Korean importers would be expected to face similar discounts in their feed markets and higher discounts by industrial users. In addition, breakage during loading and unloading create much larger quantities of screenings in proportion to the size of the total feed market at the foreign processing plant than at U.S. locations. If U.S. markets are justified in a market discount of one cent per bushel for each percent above 3%, then it would seem that importers and processors in other countries would experience a loss in value at least equal to that found in the United States. If this line of reasoning is not acceptable, then it could be argued that discounts for BCFM in the U.S. market system are unjustified, since the majority of our corn is used for feed.

There are many additional costs associated with excess BCFM. Most are difficult to quantify but the first step in the analysis is to list these cost factors.

1. Increased insect and mold activity
2. Increased power requirements for a given air flow for aeration during storage
3. Increased cost of handling
4. Risk of dust explosion
5. Cost of dust control
6. Cost of "coring" bins to improve storability
7. Price effect of a major increase in screenings at any point in the market channel

Estimates of the cents-per-bushel cost for each of these problems vary widely. The research results currently available do not provide a reliable total cost estimate. It is a question that warrants additional research.

Predicting Market Response to Reduced BCFM Limits

Corn screenings at the port are clearly out of position with respect to both demand and cost of handling. Any reduction in the limits in the export grade will increase the volume of screenings at the port and adversely influence the market.

Several alternative changes in grades and handling practices to reduce BCFM in exported corn are under discussion: (1) reducing the BCFM target value used by the exporter by changing the cu-sum plan which controls the statistical limits on maximum values and variation for sublots loaded on the vessel, or by changing the grade limits; (2) paying premiums at some point in the market channel for reduced levels of FM or BCFM; (3) using a smaller sieve (3.g., 6/64-inch) to define foreign material; (4) redefining dockage and foreign material.

The immediate effect of the first and second alternatives would be to increase the quantity of screenings at the port. A 1% reduction in the maximum BCFM allowed for export would have generated nearly 35,000 tons of corn screenings at the Gulf Ports alone in 1987/88 marketing year. (1% of U.S. export volume of 3.5 million tons from gulf ports in 1987/88). The handling and transportation costs for moving this volume back to the primary feed markets would lower the value of screenings even more. The normal market response would be to increase the discounts on BCFM at those locations where excess screenings create problems or to increase the operating costs of the export elevator. A similar response has been observed for moisture and damage discounts. Past surveys show that in Illinois the country elevators increase their discounts when a poor quality crop creates problems in handling or finding a market. Export elevators would undoubtedly do the same.

Higher discounts on FM or BCFM will encourage river and inland terminal elevators to ship less FM or receive a lower price. The market will transfer the higher costs and discounts back through the market channel. The market will seek the least-cost way of avoiding discounts. Given the cost of transporting screenings from producing regions to export points, plus all the costs associated with handling and storing screenings, the least-cost strategy is to encourage the removal of FM and BCFM at farms and country elevators. As noted earlier, Illinois country elevator receipts on the average contained 1.9% BCFM. A 1% reduction in the BCFM delivered by farmers would have lowered the quantity of BCFM at Gulf Ports by 35,000 tons using 1987/88 export volume, *if the other firms in the market channel had made no change in their practices.*

If there exists an incentive for country elevators to remove broken corn before shipping, the total screenings could be reduced even more. The quantity of screenings in the production area would be increased. Assuming that (1) screenings at the port are valued at $25 per ton below the price of corn, (2) that transportation of screenings from farm to elevator to export costs $10 per ton, and (3) that cleaning at any point in the market channel costs $1 per ton: the net gain for the total market for a 1% (35,000 tons) reduction in screenings at the Gulf would be $1.2 million. Of that $1.2 million, the export industry is paying nearly $0.3 million to transport screenings from the Midwest to the Gulf. It is difficult to believe that, given time to adjust, the market would not find a way to capture some of that potential gain by introducing incentives to remove some of these screenings prior to delivering the grain to the port.

The redefinition of BCFM using a smaller sieve to segregate fines from broken corn would generate a similar scenario. Unfortunately there is no good estimate of the market value of screenings obtained using smaller sieves. Smaller sieves for defining BC or FM would reduce the quantity of screenings but it would also alter the composition of the two fractions.

A variation on the redefinition of foreign material by sieve size would be use of a separate factor of impurities. Any non-grain material that can be readily removed by scalping or simple cleaning procedures can be removed at much lower cost by shifting responsibility as far back in the market channel as possible. Non grain material generates less cost per ton when it is left on the farm than when it is delivered to the country elevator and then removed; the added cost of transportation means that removal of non-grain material at the country elevator costs less than removal at the export elevator or at the importing elevator. It would seem that there are no real economic benefits derived from shipping corn cobs, bean pods and cockleburrs from Illinois farms to the Japanese processing plant, other than those benefits artificially created by the grading and pricing system.

Summary

This paper has not provided a definitive cost-benefit analysis. The economic gains from reducing fines and foreign material have not been quantified. The detailed calculations derived for such an analysis require knowledge of or numerous assumptions about, market response. Quantification of the costs and benefits of any change in definitions or limits in the grades requires knowledge of the response that will come from those firms that set discounts and that implement grading and handling practices.

Cost data must be acquired on the alternative responses expected from producers and marketing firms. Data are also needed on how the costs and benefits will be allocated among the many who participate in the production and marketing of grain.

The objective in changing grades is to improve the quality of the information they provide. The ultimate question that must be answered is whether the value of the increased information is greater than the cost of obtaining it.

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Effects of Fine Material on Mold Growth in Grain

David B. Sauer[a] Richard A. Meronuck[b] John Tuite[c]

Introduction

Fine material, for the purposes of this discussion, shall be defined as broken pieces of grain, including dust, and may also include some material other than grain. Most definitions of fines include all particle sizes that will pass through the standard sieve used to remove broken grain and foreign material from the particular grain in question.

Fines can affect mold growth principally in three ways. They can be a source of mold spore inoculum, they are more vulnerable to mold growth than are whole kernels, and they restrict airflow, causing uneven drying, aeration, and cooling in a grain mass.

Fines as a Source of Inoculum

In an unpublished study of corn samples from a Midwest elevator, Tuite (1975) found that dilution cultures from screenings (through a 48 mm [12/64"] round-hole screen) had much higher populations of mold spores* than did the whole kernels from the same sample (Table 1). In dilution cultures, grain is ground as a water suspension in a blender, then diluted as needed, and the diluted suspensions are put in culture dishes with agar (Cantone et al., 1983). The data in Table 1 represent 50 inbound samples and 25 outbound samples. The storage fungi, species of *Aspergillus* and *Penicillium*, were commonly 10 times more concentrated in screenings than in the whole corn, especially in the inbound samples. Populations of field fungi, such as *Fusarium* and *Cephalosporium*, were also higher in the screenings, but not by as wide a margin. Removal of screenings may reduce, but certainly not eliminate the mold spore population. Mold spores act as seeds to start new growth of mold colonies. Because they serve to

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[a] USDA, ARS, U.S. Grain Mktg. Res. Lab., Manhattan, KS
[b] Dept. of Plant Pathology, University of Minnesota
[c] Deceased (formerly: Dept. of Botany & Plant Path., Purdue U.)

* Colonies counted by the dilution technique generally grow from spores, so the data are considered to be an estimate of the number of viable mold spores per gram of material.

Table 1. Numbers of Mold Spores in Corn and in Broken Corn and Foreign Material (BCFM) in Inbound and Outbound Samples from a Commercial Grain Handling Facility.[a]

	Spores per g (thousands)			
	Inbound Corn		Outbound Corn	
Kind of Mold	Kernels	BCFM	Kernels	BCFM
Penicillium	65	667	409	1022
Aspergillus glaucus	31	236	9	62
Aspergillus flavus	7	395	0.3	2
Aspergillus fumigatus	4	318	-	127
Mucorales	42	72	5	10
Fusarium and *Cephalosporium*	342	650	28	317

[a]Source: Tuite, 1975

"inoculate" or contaminate clean grain or other material, the contaminating mold spores are referred to as "inoculum." Whether the inoculum reduction that results from grain cleaning would have any effect on storability of the corn is not known.

Grain dust usually contains high concentrations of mold spores, and thus it is a concern for environmental health and worker safety as well as being a source of fungal inoculum to contaminate clean grain. Grain dust sometimes contains mycotoxins (Burg and Shotwell, 1984) and may contribute to allergies and respiratory problems. Palmgren et al. (1983) studied the microflora of settled dust samples collected at New Orleans and Duluth-Superior grain elevators. They reported average *Aspergillus* and *Penicillium* spore counts in the range of 500,000 per gram of dust. Others have found mold spore concentrations in the air in grain handling facilities to be from a few thousand to several million spores per cubic meter of air (Farant and Moore, 1978; Hill et al., 1984; Whidden et al., 1979).

Martin and Sauer (1976) compared the mold populations in corn with populations in the dust removed from it by a cyclone-type dust control system. They also measured spore concentrations in the air exhausted from the cyclone separator into the atmosphere (Table 2). Large capacity cyclones such as these are not very efficient at trapping particles as small as mold spores. As compared to the corn, the collected dust contained more than 10 times the concentration of *Aspergillus* and *Penicillium* spores, and the dust emitted to the atmosphere contained about 100 times more than the collected dust.

Table 2. Numbers of *Aspergillus* and *Penicillium* Spores in Corn, in Corn Dust Collected in a Cyclone Dust Collector, and in the Dust Emitted from the Collector into the Atmosphere during a Bin-to-Bin Grain Transfer of Corn Which had been Moderately Invaded by Storage Fungi.[a]

	Spores/g (thousands)	
	Aspergillus	*Penicillium*
Corn	4	200
Collected Dust	2,500	3,000
Emitted Dust	230,000	300,000

[a] Source: Martin and Sauer, 1976

Martin and Sauer found low numbers of spores in grain and dust when clean grain was being moved through the elevator, but samples collected during the handling of corn which had been invaded by several species of storage fungi had high mold spore populations. Freshly harvested grain typically contains fewer than 1000 spores per gram; visibly moldy grain typically contains more than 1 million spores per gram. In terms of mold spores per ton of grain handled, they found 2-4 billion in the cyclone-collected dust from clean grain and about 70 billion spores per ton of corn in the dust from the corn which had some mold invasion. Dust emitted into the atmosphere was calculated to contain about half as many spores per ton of grain compared to the collected dust. For example, in one lot of corn the dust control system removed 103 billion spores from each ton of grain during a bin-to-bin transfer. Of those, about 70 billion were collected in the dust bin and 33 billion were emitted to the atmosphere (Martin and Sauer, 1976).

There is evidence that adding inoculum to relatively clean grain going into storage can result in faster or more extensive mold invasion of that grain (Seitz et al., 1982b). However, we are not aware of data showing that spore contamination from handling a highly contaminated lot of grain will inoculate a subsequently handled lot of clean grain thereby making it a higher storage risk. Even "clean" grain contains enough mold spores to provide inoculum if moisture and temperature are favorable for their growth. Contamination of one lot of grain by another or by dust from another will not make the difference between spoilage and no spoilage because environmental factors govern mold development. It may, however, determine which species of fungus will predominate in the grain and may accelerate the initial growth of fungi.

Fines as a Substrate for Mold Growth

Some unpublished work has shown that BCFM added to corn resulted in higher levels of invasion by *Aspergillus glaucus*, not only in the BCFM, but in the whole kernels as well. In one test, BCFM was added to corn in amounts from 0 to 18% (Tuite and Rinker, 1980). The corn was stored at 84% RH and 26°C for 10 and 16 days, at which time populations of *A. glaucus* were determined. Dilution cultures, as described above, were used along with whole seed cultures. Whole seed cultures involve washing the kernels in bleach to kill spores on the surface, then placing the seeds on nutrient agar media in culture dishes (Cantone et al., 1983). After several days of incubation, any fungi growing from the seeds are counted and considered to result from infections within the seeds. Adding even a small amount of BCFM resulted in higher mold populations (Table 3). Higher levels of BCFM generally increased mold invasion but increases were less consistent. After 10 days 4% of the kernels were infected with *A. glaucus* in the sample with no BCFM; as levels of BCFM in the samples increased, infection increased from 35 to 62%.

In a similar unpublished study (Tuite et al., 1981), corn at an initial moisture of 15.5% was stored 16 days at 26°C and 84% RH with the same amounts of BCFM as in the 1980 test. Moisture increased to 16.6-16.9% and kernel infection was higher with increasing amounts of BCFM (Table 4). Mold spore counts also were higher in whole kernels from samples with higher BCFM. In both tests mold counts were much higher in BCFM compared to whole kernels.

Kalbasi-Ashtari et al. (1979) found that mechanically damaged corn kernels had higher respiration rates than did visibly intact kernels. They reported a nearly linear relationship between percent damage and total carbon dioxide production (Figure 1). Visible mold damage in the corn in the experimental containers also was proportional to the level of mechanical damage in the original sample.

Table 3. *Aspergillus Glaucus* Infection and Spore Counts in Corn with 0-18% Broken Corn and Foreign Material (BCFM) Stored in the Laboratory at 84% Relative Humidity and 26°C.[a]

BCFM %	% Kernels infected with *A. glaucus* after 10 days	*A. glaucus* per gram (thousands) 10 days Kernels	10 days BCFM	16 days Kernels
0.0	4	1	---	90
1.5	35	8	631	130
3.0	37	11	461	157
6.0	42	17	400	155
18.0	62	149	1583	146

[a]Source: Tuite and Rinker, 1980

Table 4. *Aspergillus Glaucus* Infection and Spore Counts in Corn with 0-18% Broken Corn and Foreign Material (BCFM) Stored 16 Days at 26°C and with Initial Moisture Content of 15.5%.[a]

Percent BCFM	Final Moisture (% w.b.)	% Kernels Infected	Spores/g (thousands) Kernels	Spores/g (thousands) BCFM
0.0	16.9	13	2	-
1.5	16.6	29	3	2
3.0	16.7	29	8	600
6.0	16.8	39	17	600
18.0	16.6	50	21	800

[a]Source: Tuite et al., 1981

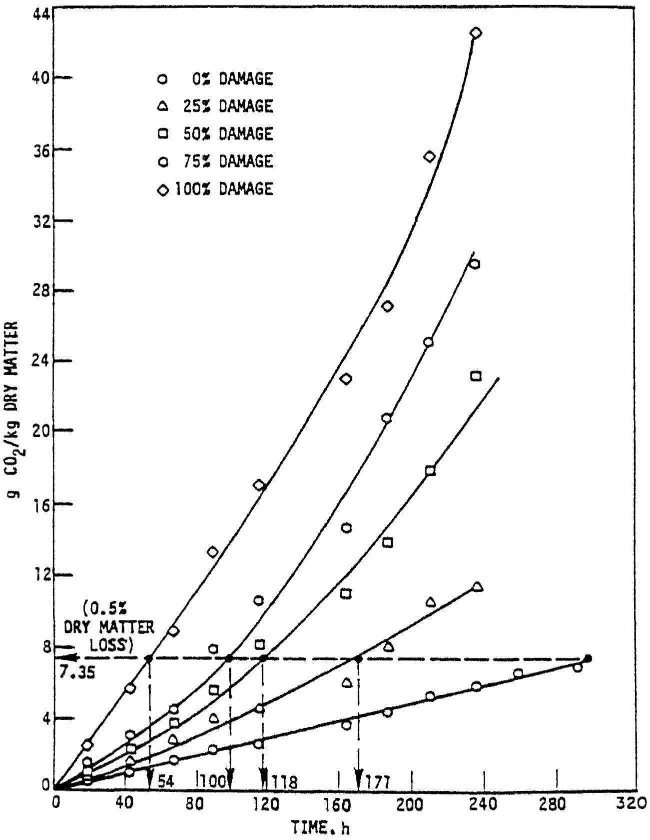

Figure 1. Carbon dioxide production in shelled corn with different amounts of kernel damage and stored at 25°C and 25% moisture. (Kalbasi-Ashtari et al., 1979).

Similar results were reported by Seitz et al. (1982a) in comparisons of corn having initial moisture content of 23.8%, with and without mechanical damage. They found that respiration, ergosterol content, and aflatoxin were higher in samples containing damaged kernels. Respiration and ergosterol production were much higher in a sample of 100% brokens and fines than in whole damaged kernels (Table 5, Figure 2).

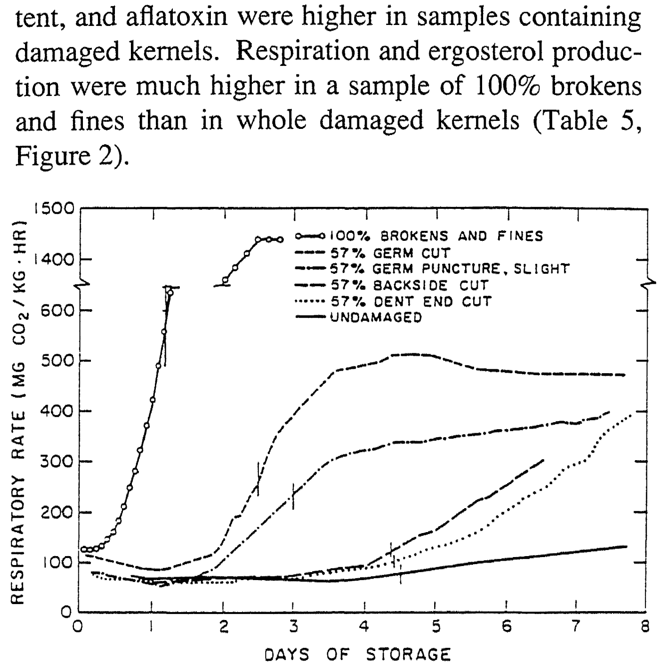

Figure 2. Effect of damage type on respiratory rate of *A. flavus*-inoculated rewetted white corn during storage at 29.4°C and 23.8% initial moisture. Damage types correspond to those in Table 5. Short vertical lines denote when dry matter loss was 0.5%. (Seitz et al., 1982a).

There is considerable evidence and many observations that mechanically damaged grain is much more susceptible to mold growth than is nondamaged grain. The pericarp of an intact kernel presents barriers to fungal growth and penetration, whereas broken surfaces expose an abundance of nutrients that are readily usable by storage fungi. Fines in grain consist mainly of broken kernels, so it seems reasonable to expect higher rates of mold growth as the percentage of fines increases. Further, it seems reasonable that mold should grow faster in smaller pieces of broken grain because they have more exposed surface area. The effect of particle size may be somewhat temporary, however. As fungi colonize the material and grow into the pieces, the effect of surface exposure might become less important.

A report by Hill et al. (1981) indicated that among various particle sizes of corn, the smaller particles were a less favorable medium for mold growth than the larger particles. Their data were based solely on visual observations of samples during storage. Perhaps the smaller particles were largely floury endosperm and the larger particles were of a more varied, more complete nutritional makeup. The authors acknowledged the adverse effects of small fine material in impeding airflow and in contributing to heating. This is perhaps an area needing further investigation.

Table 5. Ergosterol and Aflatoxin Contents of White Corn with Different Types of Damage when Inoculated with *A. Flavus* and Stored at 29.4°C and 23.8% Initial Moisture Content.[a]

Sample	Days Stored	Final Moisture Content (%)	Ergosterol (ppm)	Aflatoxin (ppb)
100% Brokens and fines[b]	2.9	23.5	78.1	8,440
57% of kernels damaged				
Germ cut[c]	7.7	23.7	46.6	19,100
Germ puncture, slight[d]	7.1	24.1	48.2	17,900
Backside cut[e]	6.5	24.1	25.5	15,100
Dent end cut[f]	8.3	23.8	14.5	13,300
Undamaged[g]	7.7	23.7	8.5	1,900

[a] Source: Seitz et al., 1982a.

[b] Determined by sieving: above a 5.84-mm (15/64-in.) sieve, 63%; through the 5.84-mm but above a 4.76-mm (12/64-in.) sieve, 15%; through the 4.76-mm sieve, 22%.

[c] A 2 to 3-mm cut was made lengthwise on the germ with a razor blade.

[d] With the aid of a microscope and a sharp dissecting needle, the pericarp over the germ was punctured, with little or no penetration into germ tissue.

[e] Center of the side opposite the germ was severely cut with a razor blade.

[f] Dent end of the kernel was severely cut with a razor blade.

[g] Determined by examination with a microscope.

Resistance to Airflow

Fine material impedes airflow through grain (Haque et al., 1978). If the fines are uniformly mixed with the grain, the airflow rate with a given fan and motor is reduced with increasing percentage of fines. More commonly, the fines are not uniformly distributed and the aeration or drying air tends to be diverted around areas with fines. These problems are discussed in more detail in the introductory paper, Fine Material in Grain: an Overview.

We are not aware of data that directly relate increased mold growth or spoilage to the airflow resistance of fines, at least not in a quantitative way. However, there have been many observations of this effect in drying and storage studies as well as in farm and commercial storage operations. When grain is dropped into a bin and forms a cone-shaped pile, the whole kernels tend to roll down the slope to the outside of the pile, but the fines tend to stay near where they are dropped. As the pile grows, or as the bin is filled, there is a core or "spoutline" of fines through the center. (See Figure 1 of Fine Material in Grain: an Overview).

Bailey (1982) states that spoutlines in large masses of grain often shorten storage life abruptly. As a rule of thumb, he says that most spoutlines larger than 8 feet in diameter eventually begin to heat. This heating, which may be caused by insect or mold activity or both, starts in the spoutline, then moves upward and outward. If it is not stopped, it can cause catastrophic losses.

In a low-temperature drying test using sulfur dioxide as a preservative, Tuite et al. (1986) observed mold growth in the areas of the bin with fines. They used a grain spreader when filling the bin, so rather than a normal spoutline, they had a concentration of fines in a ring between the center and sidewall. The authors suggested that the fines slowed drying and also blocked sulfur dioxide penetration so that those areas were not protected by its fungicidal properties. They pointed out an additional problem caused by fines: the mold that grows in the fines causes clumping of the grain, which further restricts airflow.

Recommendations for Additional Research

There are several aspects of the problem of fines and mold growth that need further research. Although the relationship between particle size and mold growth is not clear, it seems logical that the greater surface area exposure of smaller particles would make them more vulnerable. Different particle sizes may differ in average nutrient composition. We know that fines and dust contribute to the inoculum level in grain, but we do not know to what extent inoculum level is important. Finally, we need to know more about the relative importance of airflow restriction versus inherent mold susceptibility of fines.

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Effects of Fine Material on Insect Infestation: A Review

Paul W. Flinn[a] **William H. McGaughey**[b] **Wendell E. Burkholder**[c]

Introduction

Fine materials, including weed seeds, cracked grains, grain dust, and fungal spores, both directly and indirectly influence insect infestation in grain. Damaged kernels, cracked grains and grain dust are the preferred diet of some species of stored-product insect pests and the presence of these materials directly influences rates of population increase. Volatile chemicals from some of these grain fractions may also serve as feeding attractants or oviposition stimulants for some species and thereby increase the likelihood of infestation or rates of population growth. Indirectly, all fine materials in grain influence insect behavior and population growth through their effects on the insects' environment (i.e., the temperature and moisture content of the grain) and the persistence and efficacy of insecticides. Also, some fine materials, particularly broken kernels and grain dust, tend to separate from grain during handling and create a sanitation problem in and around storage facilities which constitutes a major reservoir of insects for infesting subsequent lots of grain.

In this paper, we review the available information on the effects of fine material on insect infestation and discuss the implications of fine material on stored grain pest management programs. While fine material constitutes a problem in almost all grains and oil seeds, and its effects are probably similar in all commodities, the scope of this paper will be limited to wheat, millet, grain sorghum and corn.

Composition of Fine Material

As mentioned in Chapter 1, fine material is composed of various fractions of broken and abraded grain, including grain dust. Foreign materials in grain may be composed of a wide range of materials including insect parts, small seeds of weeds or other crops, fungi, small stones, and pieces of leaves, stems, or cobs. Fungi in the grain can serve as a food source for some stored-grain insects, such as the foreign grain beetle *Ahasverus advena* (Waltl). Foreign materials not composed of crop seeds, seed parts or fungi probably provide little or no food value for any grain storage pests and thus have no direct effects upon infestation of the grain. On the other hand, fine material arising from breakage and abrasion of grain constitute a major food source for several species of storage pests and thus may influence susceptibility of grain to those species.

The amount of fine material present in grain marketing channels generally differs between wheat and corn. Wheat is a much more durable grain that is not very susceptible to breakage in harvesting and handling. Foster and Holman (1973) found that the level of fine material did not exceed 1% even after four handlings. In contrast, as discussed in Chapter 1, corn is highly susceptible to breakage in harvesting and handling, particularly at low moisture levels. As a result, fine material in corn may reach very high levels, often increasing as much as 2-2.5% each time it is handled. These differences in quantity of fine material may have little practical effect on the insect species which feed directly upon this material. It appears that even low levels, such as are likely to be found in almost all grain, are adequate to meet the nutritional requirements of moderate insect population levels.

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[a] USDA, ARS, U.S. Grain Mktg. Res. Lab., Manhattan, KS
[b] USDA, ARS, U.S. Grain Mktg. Res. Lab., Manhattan, KS
[c] USDA, ARS, Stored Product Insects Res. Unit., Madison, WI

Indirect Effects of Fine Material on Insect Growth

Higher levels of fine material (which are more likely to be found in corn than wheat) may be important because of their negative effects on aeration and insect control measures. However, quantitative field studies are lacking that document the relationship between distribution of fine material, zones of high temperature and insect infestation. As discussed in Chapter 1, fine material in grain restricts air flow and decreases the efficiency of both drying and aeration of grain (Haque et al., 1978). When fine material is unevenly distributed within the grain mass, which frequently occurs when bins are filled, the air flow is restricted to localized areas in the grain bulk. Therefore regions with fine material remain essentially unaerated. These zones of moist and warmer grain are more favorable for insect reproduction and may allow insects to develop through the winter even though the grain is aerated. It is in these areas that insect-produced "hot spots" frequently develop.

There is some indirect evidence that the presence of fine material in grain can lead to moisture migration due to restricted airflow, which can then cause mold growth and promote the development of fungus-feeding insects (Sauer et al., 1984). However, it is difficult to separate the effects of mold on insect growth from the beneficial effects that higher temperature and moisture also have on insect growth. Moreover, mold growth can occur in grain even when fine material is not present, given adequate conditions and sufficient time. Additional studies are needed to quantify the relationship between fine material, grain fungi and fungus-feeding insects.

Direct Effects of Fine Material on Insect Growth

The development of internal-feeding insects that infest stored grain (rice, granary and maize weevils and the lesser grain borer) is not directly affected by the amount of fine material in grain. They are often called primary insect pests because they do not require grain to be previously damaged by other insects.

Adult weevils are able to bore directly into the kernel and thus do not need fine material or damaged kernels to develop. Weevils reproduce by boring a hole in the grain kernel and then laying eggs in the hole. Thus, small weevil larvae do not require fine material to feed. In experiments on grain sorghum, 1.4 times as many maize weevils, *Sitophilus zeamais* Motschulsky, emerged on whole than on halved kernels of sorghum and only a few insects emerged from cracked sorghum (Morrison 1964). The lesser grain borer, *Rhyzopertha dominica* (F.), lays its eggs on the exterior of the kernel. After the eggs hatch, the larvae feed on the fine material produced by the boring adults, or bore directly into kernels that have been slightly damaged.

In general, the boring insects are much more affected by the secondary effects of fine material in the grain. Fine material restricts air movement and limits the ability to cool all parts of the grain in the fall with aeration or natural cooling. Higher temperatures are more favorable for grain weevils and borers, and populations will increase at faster rates in these areas during the winter months.

The flat and rusty grain beetle and the red flour beetle are often misrepresented as secondary invaders, i.e., that they only infest grain that has been previously damaged by boring insects. It was previously believed that the rusty grain beetle could develop on whole wheat only if a primary insect feeder (such as the rice weevil) was also present (Cotton 1963, Freeman 1952 and Bishop 1959). Rilett (1949) demonstrated that this was not so. He found that the rusty grain beetle developed equally well in whole wheat with and without rice weevils. In one of the first comprehensive life history studies on the rusty grain beetle, Rilett (1949) reported that *Cryptolestes ferrugineus* (Stephens) increased faster on whole wheat than in coarsely ground wheat. Sinha (1975) also showed that rusty grain beetle populations increased faster in wheat without dockage than in wheat containing 5% or 10% dockage (Figure 1). Rilett suggested that protection from cannibalism may be the main reason why the rusty grain beetle increases faster on whole wheat kernels than on cracked wheat. On whole wheat, the burrows of the larvae are sealed with debris just before the larvae pupate. In cracked wheat, pupation does not occur inside grain kernels and thus the pupae have no protection from cannibalistic larvae. In his work with the flat grain beetle, *Cryptolestes pusillus* (Schonh.), Williams (1954) observed more cannibalism among larvae reared on white flour than those reared on wheat kernels.

The rusty grain beetle is able to develop and reproduce on commercial wheat with little or no fine material because a moderate proportion of the kernels are slightly damaged. Tuff and Telford (1964) found

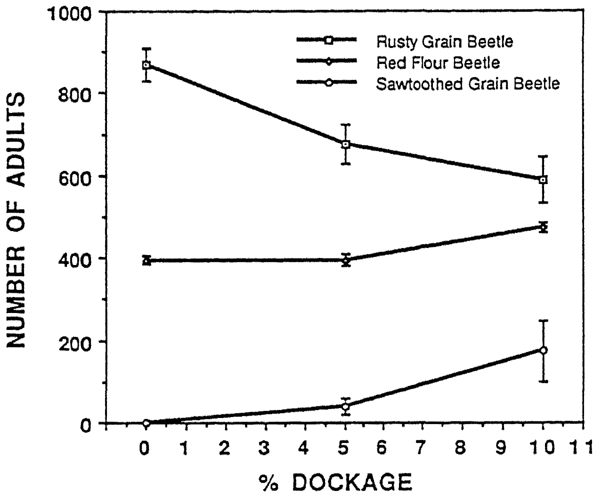

Figure 1. Number of insects after 12 weeks of storage at 33°C and 70% RH in wheat with three levels of fine material (vertical bars indicate SE of the mean). Data from Sinha (1975).

that approximately 50% of the wheat grown in Washington State had hairline fractures or chipped seed coats, and that this damage was primarily due to threshing. Adult rusty grain beetle mortality was 60% on undamaged wheat kernels, compared with less than 10% on kernels with damaged seed coats.

Similarly, Ashby (1961) found that the rusty grain beetle failed to develop on undamaged wheat kernels, but that infestations did develop when a small amount of flour was added to the whole grain. However, Mathlein (1971) reported that only a small percentage of rusty grain beetles were able to attack undamaged wheat kernels. Rilett (1949) showed that larvae in the first instar were able to gain access to the wheat germ (this insect's preferred feeding site) in whole grain which had hairline cracks in the bran, but were unable to attack wheat kernels that had no breaks in the bran layer.

In contrast to wheat, corn that contains fine material is more suitable for rusty grain beetle population growth than clean grain. Both Rilett (1949) and Sheppard (1936) found that undamaged corn was highly resistant to rusty grain beetle attack, presumably due to the hardness of corn. Experiments by Throne and Cülik (1989) showed that the rusty grain beetle produced 10 times more progeny on corn that contained fine material than on whole corn.

Increased progeny in the cracked corn may have been caused by easier access to food as well as reduced cannibalism, because of the greater number of hiding places for eggs and larvae. It should be kept in mind that these experiments were conducted at very high population densities, thereby increasing the effects of cannibalism. Cannibalism is probably less important in the relatively low insect densities that exist in managed grain bins.

There is some evidence that the presence of fine material in grain can affect interactions between species. In a study comparing four species of insects, LeCato (1975) reported that the presence of cracked corn in whole grain altered interspecific interactions. The flat grain beetle had a negative effect on red flour beetle populations (due to cannibalism) only when cracked corn was present in whole grain. Here again, it should be kept in mind that these effects were accentuated because of the very high insect densities used in these experiments.

Survival of young larvae of the confused flour beetle, *Tribolium confusum*, is influenced by the amount of damaged wheat in the grain (Fraenkel and Blewett 1944). The longevity of the red flour beetle, *T. castaneum*, also increases as the proportion of damaged grain to undamaged grain increases (Koura et al., 1971). White (1982) found that survival of red flour beetle larvae was dependent upon their finding kernels with cracked seed coats, preferably with the germ exposed (Figure 2). The larvae were able to find damaged kernels (germ exposed) equally well whether the percentage was 20% (the amount currently found in commercial wheat in Australia) or 5%. Thus, the percentage of wheat kernels in commercial grain with cracked seed coats is probably

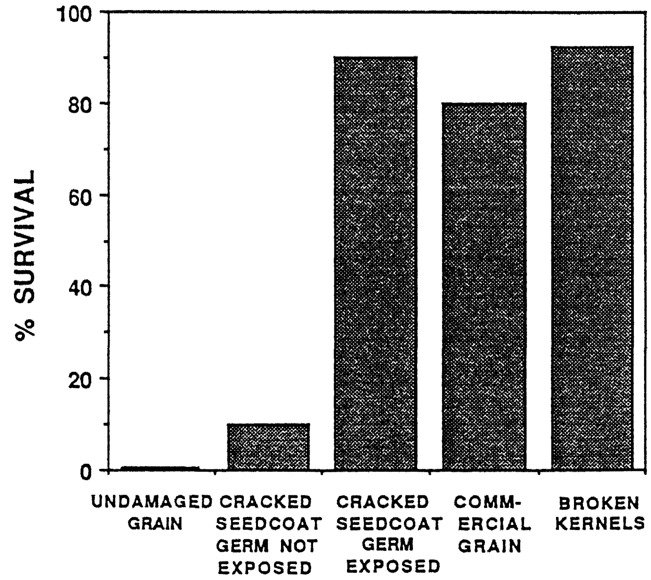

Figure 2. Effect of severity of wheat grain damage on survival of the red flour beetle (*Tribolium castaneum*). Data from White (1982).

high enough that the removal of fines would have little direct effects on red flour beetle population growth. In contrast to the rusty grain beetle and the red flour beetle, the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.), has low survival and rates of fecundity on grain that contains no fine material. Fleming (1988) reported that larval survivorship was 88% in slightly damaged grain and 24% in undamaged wheat and that progeny production was 18 times higher in slightly damaged compared to undamaged wheat.

Sinha (1975) also reported that the sawtoothed grain beetle showed low survivorship and progeny production on wheat that contained no fine material (Figure 1). He showed that the growth rate of the red flour beetle was the same in whole grain and in grain containing 5% fine material, but was slightly higher in grain with 10% fine material. Conversely, increasing the percentage of fine material reduced growth rate of the rusty grain beetle population. In corn, Turney (1957) reported that, in comparison to whole grain, the sawtoothed grain beetle population increased 2, 2.5 and 4 times faster in grain containing 5%, 10% and 15% fine material, respectively.

Effects of Fine Material on Pheromone Traps

Recent studies indicate that a number of stored-grain insects respond to volatiles which are released from freshly cracked grain. In trapping studies with maize weevils, Walgenbach et al. (1987) showed that cracked wheat is significantly more attractive than whole wheat. This study also reported a strong synergistic effect between the male-produced pheromone and cracked wheat. Pinniger et al. (1984) trapped grain insects in bait bags using several food materials, some of which were crushed. Carobs were found to be very attractive to sawtoothed grain beetles, primarily due to hexanoic acid volatiles.

Glycerides and various break-down components in wheat have been shown to have an attractant effect on the confused flour beetle, *Tribolium confusum*, (Tamaki et al., 1971). Similar components in oats attract the sawtoothed grain beetle (Freedman et al., 1982; Mikolajczak et al., 1983). McGregor (1964) showed that in "choice" tests, red flour beetles preferred grain with higher levels of fine material (Figure 3). Adult red flour beetles dispersed from areas of low fine material into areas with higher levels of fine material. More progeny were also found in the areas with high levels of fine material.

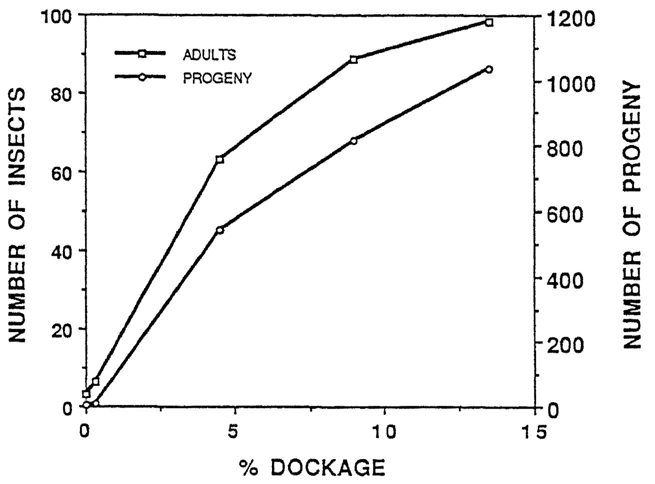

Figure 3. Red flour beetle (*Tribolium castaneum*) adults recovered from various gradients of wheat dockage in 25 test chambers after 1 week exposure period, and average number of progeny recovered after incubating for 8 weeks. Data from McGregor (1964).

The aggregation pheromones of male rice and maize weevils and lesser grain borers appear to be produced only when the insects are feeding. Fine material (frass) created by these insects, as a result of feeding, absorbs the aggregation pheromone. These pheromone-contaminated materials tend to attract other insects. The pheromones are considered to act as both mating and feeding stimulants as well as attractants. Therefore, insect-produced fine material is likely to further promote insect infestations, resulting in additional grain damage and production of fine material.

Certain insect traps, especially the plastic probe trap, perform much better when cracked grain is used as one of the insect lures. Adults of the red flour beetle have been reported to be highly attracted to corn volatiles when compared with wheat, millet, barley, rice and sorghum in multichoice tests (Bekon and Lessard 1988). A blend of mineral oil, unrefined wheat germ oil and a pentane extract of raw rolled oats were attractive to adults of the sawtoothed grain beetle and confused flour beetle, as well as larvae of *Trogoderma variabile* (Barak and Burkholder, 1985).

Freshly harvested or turned grain may be particularly attractive to insects. Moving grain always causes some kernel damage. Freshly cracked grain appears to be highly attractive to grain insects, probably because of the volatiles released. It is possible that fewer insects are attracted to grain with lower amounts of fine material. Attractance may, however, be correlated with how recently the grain was moved and the proportion of recently damaged kernels.

Effects of Fine Material on Protectants and Fumigation

Whether fine material in grain reduces the effectiveness of protectants against stored-grain insects is somewhat controversial. Strong and Sbur (1960) found that malathion remained toxic to the rice weevil longer on clean wheat than on wheat which contained fine material. When liquid malathion was applied to wheat with different amounts of fine material, a larger proportion of it was recovered from the fine material fraction than from the whole wheat fraction (Anderegg and Madisen, 1983). This may be the result of the cracked grain having a larger surface area than whole grain. Malathion residues accumulated and were degraded more rapidly in the fine material fraction than in the whole wheat fraction. In contrast, Kadoum and LaHue (1969) found that the amount of fine material had no effect on the rate of malathion disappearance. The disagreement between the two studies may have been caused by the type of fine material used. Anderegg and Madisen added fresh, coarsely-ground wheat to whole grain to simulate dockage; whereas, Kadoum and LaHue used natural dockage that was present in the grain at harvest. Anderegg and Madisen suggest that the increased degradation observed in grain containing fine material may be due to exposure of the protectant to tissue containing hydrolytic enzymes. If this is so, then Anderegg and Madisen may have overestimated the effects of fine material in their study by using freshly ground grain rather than naturally occurring dockage. The latter probably contains much lower levels of hydrolytic enzymes than freshly ground grain. In the Anderegg and Madisen study, the effect of fine material on malathion degradation was not more than 18%. Temperature and humidity have a much greater effect on insecticide degradation. For example, when stored for 20 days at 26.7°C, grain with 12% moisture has 29% less malathion than grain with 11% moisture (Champ et al., 1969). Indirectly, fine materials accelerate protectant degradation by interfering with drying and cooling, thereby leaving regions at higher temperatures and moistures. Both high temperature and moisture greatly increase rates of protectant degradation (Champ et al., 1969).

The problems involved in fumigating grain containing pockets of fine material are similar to those involved with aeration: fine material restricts the movement of gasses (air or fumigant) within the grain mass, particularly in those areas where fine material density is the greatest. Unfortunately, as explained above, these are the areas that are most likely to need fumigation. Fine material also increases the amount of surface area and thus, the sorptive capacity of the grain. As a result, increased dosages of fumigants may be required when significant amounts of fine material are present (Harein 1961). However, only with liquid fumigants are increased dosages used to offset sorptive losses, and they are no longer approved for use in grain. Currently, aluminum phosphide is most often used for grain fumigation and it is probably much less affected by the sorptive properties of fine material than are liquid fumigants.

Summary and Conclusions

In determining the effects of fine material on rate of insect population growth, it is important to differentiate between the effects of fine material in wheat and corn. The amount of fine material in stored wheat probably has only a minor effect on population growth rates of the major insect pest. However, the amount of fine material in corn may affect the reproductive potential of some insect pests. For example, the rusty grain beetle requires fine material for optimal development on corn, but does not require it for optimal development on wheat. However, internal feeders, such as the lesser grain borer and the rice, granary and maize weevils, do not require fine material for optimal growth rates on either wheat or corn. The sawtoothed grain beetle is the only major wheat pest that requires fine material for optimal growth. The rusty grain beetle and red flour beetle feed on wheat kernels that have microscopic cracks in the seed coat; about 50% of commercial wheat kernels have these cracks. For the sawtoothed grain beetle, lack of damaged or cracked grain could be a limiting factor for young larvae after the population has reached a high density. However, at the relatively low insect population densities present in managed bins, there may be sufficient fine material and damaged kernels that, even in so-called clean grain, fine material does not limit their population growth. It is recognized that the grain weevils and borers create frass and damaged kernels. These insects can therefore make food available for insects which cannot feed on whole grain, such as the sawtoothed grain beetle. However, significant amounts of fine material are only produced when there are high weevil or borer densities. Therefore, any additional damage caused by the sawtoothed beetle would be trivial.

The indirect effects of fine material on insect infestations are more likely to be a problem with corn than with wheat. For example, inadequate aeration, due to uneven distribution of fine material, will more often be a problem with corn, because higher levels of fine material are usually found in the former, due to its greater breakage susceptibility. Uneven cooling of the grain leaves certain regions of the grain at higher temperatures, which allows insects to multiply during winter months. In addition, complete fumigation of the grain may be more difficult to achieve with corn than with wheat due to higher levels of fine material.

The use of a grain spreader may decrease the probability of infestation in grain with high levels of fine material. For example, if a spreader is not used, fine material can collect in the center of the bin beneath the spoutline. This makes the area difficult to aerate and thus, it can become an optimal habitat for insect development in the fall and winter. However, grain spreaders can cause an overall increase in resistance to air flow (Stephens and Foster, 1976).

Removal of fines before storage on the farm and at country elevators should increase its storability, due to increased aeration efficiency. Cleaning the grain before storage will probably be more efficacious with corn than with wheat because of the higher percentages of fine material usually found in corn. At least one study has evaluated the economics of fine removal (Kiser 1984). Additional studies are needed on the economic aspects of grain cleaning in relation to insect infestation.

While extensive data are available on the direct effects of fine material on insect growth, there is little information on the indirect effects. Further research is needed on the relationship between fine material, decreased uniformity of aeration and insect infestation.

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Reducing or Controlling Damage to Grain from Handling: A Review

Charles R. Martin[a] **George H. Foster**[b]

Introduction

Mechanical damage susceptibility of grains and oil seeds is related to the ability of the kernels to withstand impact and abrasion. Wheat has a strong kernel structure and generally resists damage during handling. Soybeans have two structurally strong halves held together by a weaker bond that may break upon impact. However, the market is tolerant of the presence of some splits. Corn, a more brittle or less resilient kernel, tends to break into random sized particles upon impact. Mechanical damage in yellow dent corn contributes to problems related to safe handling and efficient storage. Damage also reduces the value for some end uses.

Exposed starchy endosperm of broken grain, especially corn, is easily abraded into dust. Emitted dust can become a health hazard to workers who inhale airborne particles. Settled dust becomes a fire and explosion hazard and OSHA's "action level" for priority housekeeping areas requires immediate removal when layers exceed 3.2 mm (1/8 in). Segregation of fine material in bins interferes with the uniform air movement required to maintain grain quality during storage. Any dust that is separated from the grain is shrinkage or weight loss. Capital investments and labor requirements for house cleaning and for dust control increase the cost of grain handling.

Dust Cloud Generation and Control

Dust cloud generation during grain handling is related to the residual dustiness of the grain and the design of the handling facility. Residual dustiness is the amount of fine dust present in grain and is usually related to the type of grain. Dust is composed of very small particles that are created by mechanical damage. Most grains are coated with a natural oil or wax that tends to retain dust particles smaller than 50 µm on the kernel surface.

Residual dust can be defined as the fine dust that clings to kernels and fragments of kernels (Martin and Lai, 1978). It will pass through a 120 mesh sieve, which has openings of 125 µm. The amount of residual dust can be determined by washing the grain with isopropyl alcohol, filtering the dust particles from the suspension with filter paper, evaporating the alcohol remaining on the filter paper, and determining the weight of the filter paper with dust.

Conventional grain cleaning by screening and aspirating separates particles larger than 50 µm but does not separate the clinging particles very effectively. When the kernels are agitated or impacted during handling, a portion of the residual dust is emitted into the air and flows with the air until the particles settle or impinge on another surface. The handling method determines the degree of agitating and impacting to which the grain is subjected while the handling facility design determines how the air flows within the facility. Most grain elevators control dust clouds with a pneumatic dust control system and separate the dust from the air with bag house filters or cyclone separators.

Martin and Lai (1978) showed a relation between the amount of residual fine dust in three different No. 1 grade grains and the amount of fine dust collected by the dust control system during the handling of these grain lots (Table 1). Corn had the highest values of both residual and collected fine dust. Sorghum had intermediate levels of dust while wheat had the lowest values. The study also demonstrated that the fine residual dust content did not always correlate very highly with the fine material content of the grain samples as determined by screening with the appropriate screen size used in grading grain.

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[a] U.S. Grain Mktg. Res. Lab., USDA-ARS, Manhattan, KS

[b] Deceased (formerly: Agricultural Engrg. Dept., Purdue Univ.)

The correlation coefficients were 0.653 for corn, 0.330 for sorghum, and 0.375 for wheat. The vast difference in particle sizes of fine dust and fine broken material caused the particles to segregate in different ways during handling with the result that individual grain samples were dusty. Fine material was present as measured with official grading procedures. Thus, the amount of dust in a sample of grain is not always a good indication of the dustiness of a lot from which the sample is drawn.

Converse and Eckhoff (1989) showed the effect of in-bin drying temperature on BCFM generation and corn dustiness as determined by the dust collected by a cyclone (Table 2). The average dust removed per handling during 22 repeated handlings was lowest for natural air, intermediate for the 80°C temperature, and highest for the 105°C temperature. Controlled dust removal data for this test were consistent with the average BCFM generated during each repeated handling. Controlled dust removal averaged 0.20% for each of two other test lots dried in a batch dryer with 100°C and 70°C air. Drying temperature, and the related breakage susceptibility, had a greater effect on corn dustiness than the grain moisture content during handling.

Table 1. Comparison of Cyclone-Tailing and Grain-Sample Residual Dusts.[a]

Grain	Fine Dust[b] Collected During Grain Handling %	Average Residual Dust in Grain Sample %
Corn	0.080	0.082
Sorghum	0.037	0.070
Wheat	0.028	0.025

[a] Source: Martin and Lai, 1978.
[b] Fine and residual dust consist of particles that pass through a 120-mesh sieve.

Martin and Sauer (1976) showed that the dust collected after a lot of corn was passed over a commercial cleaner was 0.105% of the corn weight compared to 0.122% collected before cleaning. A single cleaning of corn did not remove enough dust to make a noticeable difference in dust cloud generation during subsequent handling. In a repeated handling study by Martin and Stephens (1977) where the same test lot of corn was handled 20 times, the average amount of dust removed per handling was nearly constant at 0.088% of the corn weight although the BCFM content increased a constant 0.6% with each handling. Dust removal by a pneumatic system minimized the accumulation of fine dust that would occur without continuous cleaning. In work reported by Chang et al. (1985) the use of a grain flow regulator reduced the dust concentration inside a grain bin by 80% compared to the dust concentration from grain flowing from an open spout.

The fine respirable dust (particles smaller than 10 µm) emitted can be controlled by spraying the grain with a liquid additive to increase the bond between dust particles and the grain surface. Additives that have been tested by the US Grain Marketing Research Laboratory (Lai et al., 1981) include mineral oil and deodorized soybean oil. The most effective level of treatment was between 200 and 300 parts per million by weight. The use of additives to control dust emissions from commercial corn is becoming widely accepted, but some wheat millers

Table 2. Average Corn Dust Collected and BCFM Created By Repeated Handling after In-Bin Drying.[a,b]

Lot No.	Temperature of Drying Air	Grain Moisture %	Dust Loss Per Handling %	BCFM Created Per Handling %
1	Ambient	12.0	0.08	0.64
2	80°C followed by ambient air	12.5	0.15	0.96
3	105°C	15.0	0.21	1.20

[a] Source: Converse and Eckhoff, 1989.
[b] Average based on 20 handlings. Dust was collected by a cyclone.

have stated that wheat treated with oil additives causes operational problems with their mills, reduces flour quality, and in some cases is unacceptable.

Damage Related to Impact Velocity

Technological changes in corn harvesting introduced field shelling and created the need for rapid drying. Impact during shelling creates hairline cracks and abraded pericarps in addition to broken kernels. At 13.4% moisture content, the number of internally cracked kernels and the number of kernels with external damage averaged near 90% when impacted at a velocity of 18 m/s (3500 fpm) (Moreira et al., 1981). When subjected to a Stein breakage tester, these kernels had a breakage level of nearly 30%. The corn had been harvested by hand at 21% m.c., and was dried in the laboratory at 21°C over a period of 3 days with the help of a fan. About 60% of the kernels had stress cracks and these were discarded so that impact tests were run only on sound kernels. At an impact velocity of 10 m/s (2000 fpm) the number of kernels with internal cracks and external damage averaged about 7%, and Stein breakage averaged of about 6%. Damage increased substantially at velocities of 14 m/s or greater.

Damage Related to Handling Methods

High temperature drying causes stress cracks to develop and increases the overall brittleness of corn (Thompson and Foster, 1963). In the movement of corn through the marketing channels it is dropped repeatedly into deep bins causing high velocity impacts which break the kernels. The segregation of broken kernels and fine particles in bulk grain interferes with the uniform air movement required to maintain grain quality during storage (Stephens and Foster, 1976).

Mechanical damage to grain caused by commercial handling methods was reported by Fiscus et al. (1971a) and by Foster and Holman (1973). Free-fall dropping of corn, as occurs in filling a bin, caused the highest level of breakage among the handling methods tested. Corn drawn from shipments in commerce had breakage levels ranging up to nearly 14% when it dropped 30 m (100 ft) and impacted on concrete at a 45 degree angle to the grain stream (Table 3). Corn dropped 12 m (40 ft) had breakage levels up to 5.9%, but the average of six tests was only 2.5%. Average breakage was reduced somewhat when impacting other corn and was somewhat less when dropped from a 30 cm (12 in) discharge as compared to that from a 20 cm (8 in) discharge.

Table 3. Corn Breakage In Free Fall.[a]

Test condition[b]	Average %	Range %
Drop height m		
30 (100 ft)	10.2	6.9-14.0
21 (70 ft)	6.2	2.3- 7.9
12 (40 ft)	2.5	0.2- 5.9
Impact surface		
Concrete - 45°	7.7	0.8-14.0
Grain - 90°	6.0	0.2-12.7
Discharge stream size, cm		
20 (8 in)	7.7	0.9-14.0
30 (12 in)	5.4	0.2-13.6

[a] Source: Foster and Holman, 1973.
[b] Six tests each test condition

Comparison studies on grain stream velocities (Fiscus et al., 1971b) resulting from various drop heights showed a velocity up to 20 m/s (4000 fpm) in 26 m (85 ft) of free-fall, and about 11 m/s (2200 fpm) when dropped from 12 m (40 ft). Velocity measurements in this and other handling schemes tested -- spouting, grain throwers and bucket elevators -- suggested that for corn the maximum impact velocity should be limited to about 10 m/s (2000 fpm) which is approximately the terminal velocity of a single seed.

The average breakage levels for corn for the three handling methods other than free-fall were about 1.1% in the boot of a bucket elevator, 1.5% for a grain thrower such as used to level-load rail boxcars or ship holds, and approximately 3% for the spouting tests. Damage increased with an increase in height from which the corn dropped into the spout and also varied with the type of spout end used.

Free-fall drop tests with soybeans showed breakage levels up to 8.3% and averages of about 2%. This is less than half that of corn. For all tests on wheat, the breakage level from handling was 1% or less.

The moisture content and temperature of the grain handled affected the breakage level observed in the tests by Fiscus. A decrease in moisture of a little over two percentage points (15 to 13%) resulted in nearly a three-fold increase in corn breakage.

Handling the corn at 26°C (80°F) instead of at 5°C (40°F) reduced breakage by nearly 50%.

Tests have shown that repeated handling of grain results in breakage and fine material increases approximately proportional to the number of times handled (Martin and Stephens, 1977). This finding is especially important in handling brittle corn and grains destined for export which are handled repeatedly. Fiscus et al. (1971) and Holman (1973) reported that, for up to four handlings, the amount of corn breakage generated in grain thrower tests was about the same each time the grain was handled. The accumulated breakage was slightly higher when the fines and breakage were retained in the lot after each handling than it was when the fines were removed. Three lots of soybeans at slightly different moisture levels were repeatedly dropped 30 m (100 ft) onto a sloped concrete floor. There was some reduction in breakage in the second, third and fourth drop of the same lot of beans at moisture contents of 10.7 and 11.0%. However, there was no discernible breakage reduction in repeated handling of a lot at 12.6% m.c.

Research results by Converse and Eckhoff (1989) show breakage and dust emissions from handling six different lots of shelled corn up to 20 times. The lot dried in a batch dryer at a drying temperature of 100°C had an accumulated breakage for the 20 transfers of just over 50%. This lot of corn was at 10.6% m.c., nearly two percentage points lower than the lots dried in a low temperature dryer. The lot dried at 70°C had an accumulated breakage of about 34%. In contrast, those lots dried with natural air or by a combination of 80°C air followed by natural air in a bin dryer had accumulated breakage of from 12 to 20% (Table 2). In the lots dried at low temperature or by combination drying, the accumulated breakage increased approximately linearly through the 20 handlings. In the lot dried with high air temperature in a batch dryer, the breakage increased approximately linearly through ten handlings and at a much reduced rate during the following ten handlings. There was a change in the handling procedure for the last ten transfers which accommodated the high percentage of fine material in the lot. This probably contributed to the reduced breakage.

Grain is also handled by drag elevators and conveyors, auger elevators and conveyors and by pneumatic systems. The so-called "mass-flow" conveyors have become more common, particularly in centralized farm grain handling centers. Grain damage in these types of conveyors was studied by Converse et al. (1985). A lot of corn dried with natural air and a lot of unknown history obtained from commercial sources was passed three times through two different drag conveyors of 7.3 m (24 ft) length. The fine material produced by the drag conveyor was relatively small, ranging from 0.15 to 0.25% for the commercial lot of corn and 0.03 to 0.06% for the corn dried with natural air.

There are limited test data for the grain damage associated with use of auger elevators and conveyors. Conveyors of the U-trough configuration seldom cause significant damage when operated at the recommended loading and speed. Tests on 15 cm (6 in) round tube floating augers running at 0 degree to 50 degree angle of incline were reported by Hall (1974). Conveying 13% moisture corn, that had been dried with ambient air, for 48 m (150 ft) created 0.10 to 0.50% fine material when the auger ran full and at normal speeds. Running the auger at 1/4 capacity increased the percent breakage from 4 to 8 times that when the auger was operated at full capacity. Results with soybeans were similar to those with corn. In an earlier study by Sands and Hall (1971) corn dried with air at 115°C (240°F) and conveyed in a 15 cm (6 in) auger for distances up to 46 m (150 ft) had approximately twice the level of fine material as corn conveyed after drying with ambient air.

The damage associated with pneumatic conveying of grain was studied by Chung et al. (1973), by Susai and Gustafson (1982), and by Baker et al. (1986). Chung reported from 0.2 to 20% breakage generated in corn conveyed in a small pressure pneumatic system with 5 cm (2 in) tubes. Breakage in 20% moisture corn was nominal up to conveying air velocities of 36 m/s (7200 fpm). When conveying 12% moisture corn, breakage increased rapidly at air velocities above about 25 m/s (5000 fpm) and reached over 20% when conveyed a total distance of about 500 m (1600 ft). Chung concluded that the conveying air velocity should not exceed 27 m/s (5400 fpm) when conveying low moisture corn.

Baker et al. (1986) reported on tests with a 10 cm (4-in) pressure pneumatic system and air velocities of 15 to 30 m/s (3000 to 6000 fpm). When the system was operated at the recommended air velocity of 20 m/s (4000 fpm) the average fines (breakage) generated was 0.12% in non-brittle corn and 0.30% in brittle corn. Breakage levels approached 1.5% in the brittle corn at conveying air velocities of 30 m/s (6000 fpm), but remained under 0.5% in the non-brittle corn. The conveying distance was 50 m (160 ft) and the grain discharged through a small cyclone. Mass flow rate of the conveyor had little effect on breakage.

Susai and Gustafson (1982) reported from 0.4 to 2.1% breakage generated in a combination vacuum pickup and pressure discharge pneumatic conveying system.

Approaches to Reducing Damage from Handling

Grain damage can be reduced using two approaches:

1. Modification of production, harvesting and drying procedures to obtain a more resilient and tougher product that is less subject to damage from handling.
2. Reduction of abrasion, shear and impact forces in handling methods and devices.

As we have seen in the foregoing discussion, the problem with brittleness in grain is largely confined to corn. There are varietal differences, as discussed in Chapter 7, **Genotypic Differences in Breakage Susceptibility of Corn and Soybeans**. Harvesting also contributes to damage. However, artificial drying is the major contributor to brittleness. Thompson and Foster (1963) related the drying treatment to stress cracks and breakage in artificially dried corn. Foster (1973) later showed that breakage, as indicated by a sample breakage tester, was seven times greater in corn dried in a conventional heated air dryer than it was in corn dried slowly with unheated air. At least two modified drying regimes have been developed: (1) dryeration, heated air drying followed by tempering and slow cooling, and (2) a combination of high temperature drying followed by low-heat or no-heat drying. Both substantially reduce the breakage tendency of corn. Other studies confirmed the higher breakage in corn dried rapidly at high temperatures (Martin and Stephens, 1977; Stephens and Foster, 1977; Baker et al., 1986; Converse et al., 1989). It was generally concluded that reduction in corn brittleness was the most promising approach to controlling breakage.

Approaches to gentler handling have been confined largely to reduction of grain velocity and/or the resultant impact forces. Keller et al. (1972) found that there was five to six times greater damage when corn kernels impacted steel or concrete than when they impacted a more resilient urethane surface. Reducing the angle of impact from 90 degree to 45 degree reduced the mean damage by 25%. Corn impacting other corn was damaged less than corn impacting concrete at 45 degrees (Fiscus et al., 1971a).

Dropping grain, particularly corn, into bins or other containers in free-fall or through spouts caused the most breakage of handling methods tested by Fiscus et al. (1971a). A free-fall drop height of more than 12 m (40 ft) caused substantial damage to corn (Table 3). Foster and Holman (1973) showed that corn could be repeatedly dropped 12 m (40 ft) from three to 28 times without exceeding the breakage generated in one 30 m (100 ft) drop. The lower numbers of drops were for corn at 12.6% m.c. while the higher numbers were for 15.2% m.c. corn. When spouts were used to drop the grain 12 or 30 m (40 or 100 ft), the lower moisture grain responded as it did in the free fall tests. However, for 15.2% m.c. corn, only about half as many 12 m (40 ft) drops through the spout were needed to achieve the same amount of breakage as one 30 m (100 ft) drop.

Stephens and Foster (1977) studied devices to reduce damage to corn handled through gravity spouts. They dropped corn about 40 m (130 ft) through a combination of vertical and inclined spouting. A commercially available cushion box was used on the end of the spout discharging into a truck. A commercial flow retarder was placed in the inclined spout 18 m (60 ft) above the discharge and tested with and without the cushion box. An experimental air cushion device that forced air up a 3 m (10 ft) section counter to the grain flow was also studied. All devices tested reduced breakage, but by a relatively small amount. The authors concluded: "The difference in breakage increase per handling between heat-dried and naturally-dried corn was much greater than were differences related to the flow retarders used."

The various studies on breakage suggest that when corn impacts non-resilient surfaces the velocity at impact should be 12 m/s (2400 fpm) or less. Grain velocities may exceed 12 m/s if the grain is decelerated before impact. A 90 degree long-radius elbow on the end of a vertical spout reduces grain velocity. A cyclone on the end of a spout is often used to decelerate grain in pneumatic systems. It is an effective means of reducing breakage (McKenzie and Foster 1979, McKenzie 1985). In McKenzie and Foster's 1979 report, the breakage level was 22% for corn dropping 18 m (60 ft) through a vertical spout discharging into a plywood box. When a 90 degree elbow with a rubber sock was placed on the discharge breakage was reduced by 44%. When the elbow was directed into a cyclone, the breakage was reduced 54%. In later tests with corn dried with heated air to near 11% m.c. the 18 m (60 ft) vertical drop resulted in 60% breakage. In this breakage prone corn, addition of a 90 degree elbow and a cyclone reduced breakage by 73%.

McKenzie and Foster (1979) found average breakage reductions of only 10 to 13% with use of a cushion box or a bucket cascade retarder. In the cushion box, grain impacted other grain and changed direction. The bucket cascade retarder was a vertical section containing elevator buckets in which grain cascaded from one bucket to the next.

Grain ladders that prevent the product stream from reaching excessive velocities have been used in seed houses, some processing plants and occasionally in deep bins or silos filled with commercial grain. Drops of more than about 3 m (10 ft) may reduce viability of seed beans. In some seed houses, reverse operating bucket elevators are used to gently lower beans. Such devices are expensive and take up room. In commercial storages it is difficult to design them to withstand forces created by settling grain.

Caution is needed when decelerating grain. The energy in the moving grain must be dissipated when it is decelerated, just as the energy of a moving vehicle must be dissipated in stopping or braking. This was demonstrated by McKenzie and Foster's (1979) tests with a device referred to as a "grain brake." A flat spiral of decreasing pitch was fitted into a section of spout. Although it effectively reduced grain velocity, it became so hot when handling large volumes of grain for more than a few minutes that there was danger of igniting dust in the grain. Elbows on the end of vertical spouts used to fill box rail cars have been observed to glow a dull red in subdued light. Heat dissipation is not the only concern. Steps have to be taken to reduce wear in elbows and other grain decelerating devices. Spout linings such as high density plastic materials are often used to control wear.

Flow retarding devices are also usually sensitive to flow volume or loading. For example, the air cushion device described above was effective only at low grain-flow rates. Overflow provisions must be incorporated in most flow retarders.

The research to date on grain flow retarding devices and methods has been encouraging. However, considerably more research and development is needed and it is likely to be forthcoming if demand warrants.

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Evaluating Grain for Potential Production of Fine Material – Breakage Susceptibility Testing

Steven R. Eckhoff[a]

Introduction

The following is a working definition for corn breakage susceptibility: it is a measure of the degree to which a seed or kernel will break apart into unacceptable sized fractions during handling, transport, and storage. This definition is easy to understand and can be directly related to observable events. For example, assume two grain lots are shipped from a source with identical grade specifications and characteristics. These lots are shipped to the same destination using identical handling procedures, equipment, etc. but they arrive at the destination in different conditions. One of the lots arrives with a much higher amount of broken grain and might well be considerably less valuable to the purchaser (depending upon the intended use). Differences in breakage susceptibility can explain why the grain lots arrived with different amounts of broken kernels even though all the grade factors were identical.

One problem with the above definition is that it does not relate the physical and chemical characteristics of the grain to its breakage susceptibility. Breakage susceptibility is a physical property of the grain kernel but its value appears to depend upon a combination of other physical properties or characteristics such as density, hardness, pericarp damage, severity of stress cracking or pericarp thickness. It would be desirable to relate these characteristics to the breakage value in order for plant geneticists to selectively breed for decreased breakage susceptibility. These relationships will also give rise to methods for measuring or reducing breakage susceptibility.

If breakage susceptibility were a fundamental physical property, then different methods of measuring the property would give similar results. Since it is not, the results and the interpretation of the results from different breakage testers vary. Different testers may emphasize or correlate more strongly to different more fundamental physical characteristics.

Regardless of the problems stated above, the definition is usable. It is pragmatic. The challenge then in measuring breakage susceptibility is to develop instruments, testing procedures, and an understanding of the relationship of breakage susceptibility to physical and chemical factors in the grain, so that the concept can benefit the marketing and utilization of cereal grains and oilseeds.

This manuscript summarizes the types of breakage susceptibility testers which have been studied, describes changes in breakage susceptibility with measurable factors such as moisture content and temperature, assesses how well the measured values correlate to actual breakage generation, and postulates some future needs and directions in breakage susceptibility testing research.

Types of Instruments Utilized in Breakage Susceptibility Testing

The instruments used in measuring breakage susceptibility try to simulate the mechanical forces or the force environment to which kernels are subjected during normal grain handling. There are two basic types of instruments: single impact testers and multiple impact testers. Single impact testers subject each kernel to a single impact of constant force. A major portion of the handling breakage occurs when the grain is dropped into large storage tanks. The single impact testers are designed to simulate this.

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[a] Agricultural Engineering Department, University of Illinois

Multiple impact testers subject kernels to many impacts of varying magnitude, impact at various locations on the kernel, and impact surfaces which differ. These testers attempt to simulate the abrasive handling and kernel to kernel impacts that occur in augers and flowing grain. They also simulate the repeated handling that occurs as grain is moved through the market channel.

While breakage susceptibilities of a variety of cereal grains and oil seeds have been studied (Bartsch et al., 1979; Hoki and Pickett 1973; Mitchell and Routhwaite 1964; Paulsen et al., 1981), the breakage susceptibility research has been primarily directed towards corn. Of the major crops in the United States (corn, grain sorghum, wheat, and soybeans), corn is the only one not primarily dried in the field. Drying conditions have a major effect on the level of breakage susceptibility in grain kernels.

Single Impact Testers (Wisconsin Breakage Tester)

Many single impact testers have been developed and studied, including the Illinois Centrifugal Tester (Paulsen et al., 1981), the Missouri Corn Cracker (Moentono et al., 1984), the Ohio Impacter (Sharda and Herum, 1977), the USGMRL Grain Accelerator (Miller et al., 1979, 1981a), and the Wisconsin Breakage Tester (Finner and Singh 1983). These singulate kernels, accelerate the kernels to a given velocity and then allow the kernels to individually impact upon a specific surface.

The Illinois Centrifugal Tester, the Ohio Impacter, the Missouri Corn Cracker* and the Wisconsin Breakage Tester accelerate the kernels by dropping them onto the center of a rotating disk. The kernels are discharged from the rotor by centrifugal force. The USGMRL Grain Accelerator uses two parallel rotating rubber rollers to accelerate the grain. The kernels are dropped into the nip of the rapidly rotating rolls and are thrown out the other side onto an impact surface.

The impact surfaces of the instruments differ. The Illinois, Missouri and Wisconsin testers impact the kernels on metal surfaces. The impact surface in the Ohio Impacter is a flat metal screen. Ideally the screen reduces tangential bouncing of the kernels after impact. The USGMRL Accelerator impacts the kernels on a bed of other kernels. The rationale for using kernels as an impact surface is that most of the kernels that free fall during bin loading impact on other kernels.

Of these testers, the Wisconsin Breakage Tester (WBT) (Figure 1) has received the most attention and has been the subject of several extensive evaluations. The four channels on the rotating disk are the passages through which the kernels are accelerated. The kernels impact the surrounding metal housing and are collected at the bottom.

A 200 gram sample is first sieved through a 4.76 mm (12/64 in.) sieve to remove any foreign material and pre-broken kernels and is then dropped onto the rotating plate from a vibrating feeder. The feed rate into the instrument can be varied from 75 g per

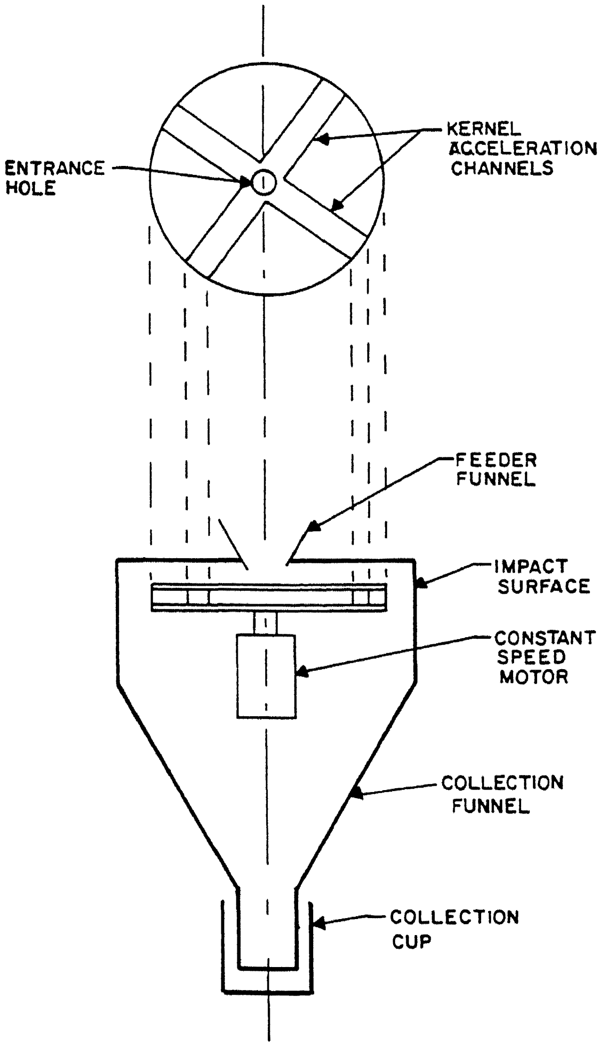

Figure 1. Design of the Wisconsin Breakage Tester (WBT).

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* Editor's note: Some researchers consider the Missouri Corn Cracker to be a multiple impact device as the impeller blades can strike a kernel several times depending on where the kernel enters relative to the exit sleeve. However, there would still be fewer impacts than in the Stein Breakage Tester.

minute to 725 g per minute with no statistical difference in results (Eckhoff et al., 1988a), although a rate of around 300 g per minute is recommended. The collected sample is then sieved through a precision 4.76 mm (12/64 in.) sieve and the percent of the original sample that passes through the sieve is designated as the percent breakage susceptibility. Several studies have been performed using a 6.35 mm (16/64 in.) round hole sieve and some researchers feel that this size sieve more accurately measures breakage as the 4.76 mm (12/64 in.) sieve does not pass half broken kernels or other large fragments. No definitive conclusion has been reached on this issue.

Multiple Impact Testers (Stein Breakage Tester)

Two primary multiple impact testers have been studied, the Stein Breakage Tester (SBT) and the Cargill Grain Breakage Tester. The Cargill Grain Breakage Tester (McGinty 1970) uses a rubber impeller to throw the grain repeatedly against the test chamber wall. The chamber is designed to collect the kernels that have been slung by the impeller and feed them back to the impeller.

The Stein Breakage Tester (Stephens and Foster 1976), shown in Figure 2, is the only breakage susceptibility tester commercially available and is manufactured by the Fred Stein Instrument Company of Atchison, Kansas. It has a small chamber where 100 g of sample are repeatedly impacted by an impeller and thrown against the chamber walls.

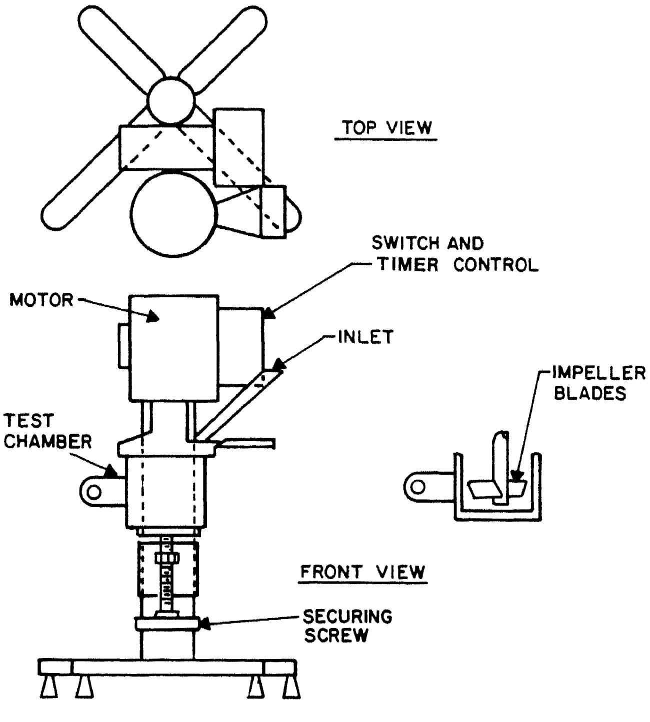

Figure 2. Design of the Stein Breakage Tester (SBT).

In the operation of the Stein Breakage Tester, a presieved sample of 100 g is loaded into the chamber inlet. A slide gate allows the corn to drop uniformly, in a repeatable manner, into the test chamber. Improper filling of the test chamber with grain can affect the breakage value. Once the grain is in the chamber, the motor is started and the grain is impacted by the impeller. The kernels randomly impact upon the impeller, the side of the test chamber or other kernels. The length of the impact time can be varied and is controlled by an automatic timer. The recommended length of time is 2 min although some researchers have used a 4 min test when studying high quality corn.

After the test period the instrument automatically shuts off and the grain can be removed from the test chamber by loosening the securing screw and physically detaching the test chamber. The grain is sieved on a 4.76 mm (12/64 in.) round hole precision sieve and the percent of the original sample passing through the sieve is designated as the percent breakage susceptibility.

Stein (SBT) and Wisconsin (WBT) Breakage Susceptibility Testers

Comparison of Particle Size Distribution

The Stein and Wisconsin Breakage testers produce different types of breakage. The WBT subjects kernels to a larger impact force than does the SBT. This larger force causes even some sound kernels to break. As a result, the corn material from a WBT that passes through a 4.76 mm (12/64 in.) sieve has only a small amount of dust or small particles and tends to be pieces of endosperm. The overs on the sieve analysis have a large proportion of kernel pieces which will not pass through a 4.76 mm (12/64 in.) sieve.

The tangential velocity of the SBT impeller is less than the kernel velocity from the WBT. This contributes to the larger proportion of whole kernels in samples taken from the SBT. The Stein creates more dust and smaller particles, probably because there is more kernel to kernel abrasion. Once a kernel breaks in the SBT, the resultant particles are further reduced in size by these kernel to kernel impacts and by the continued action of the impeller.

Herum and Hamdy (1981) compared the particle size distributions created by the SBT CK-2M, the Ohio centrifugal tester, and the handling of the corn sample through a feed elevator. The results (Figure 3) show that the centrifugal tester, which is very similar in operation to the WBT, creates far fewer small particles than does the SBT. The actual particle size distribution from a sample removed from corn handled in an elevator had an even higher percentage of small particles.

Gunasekaran (1988) compared the weight retained on 7.94 mm (20/64 in.), 6.35 mm (16/64 in.), and 4.76 mm (12/64 in.) sieves for corn samples dried at different temperatures and run through the WBT and SBT (Table 1). The changes in the weight retained on the sieves were linear over the drying temperature range of 20°C to 65°C. In the case of the WBT there was an increasing proportion of material passing through the 4.76 mm (12/64 in.) sieve as temperature increased. This was accompanied by a decrease in material retained on the two larger sieves. This means that the WBT broke the sample into smaller pieces and broke more of the whole kernels. There was also an increase in the amount retained on the 4.76 mm (12/64 in.) sieve indicating that after drying at 65°C the corn was breaking into particles that were smaller than those generated with corn dried at lower temperatures. Furthermore, these particles were not floury or dusty. Dutta (1986) looked at the average particle size of corn that went through a WBT and found that there was no correlation between particle size and breakage susceptibility values.

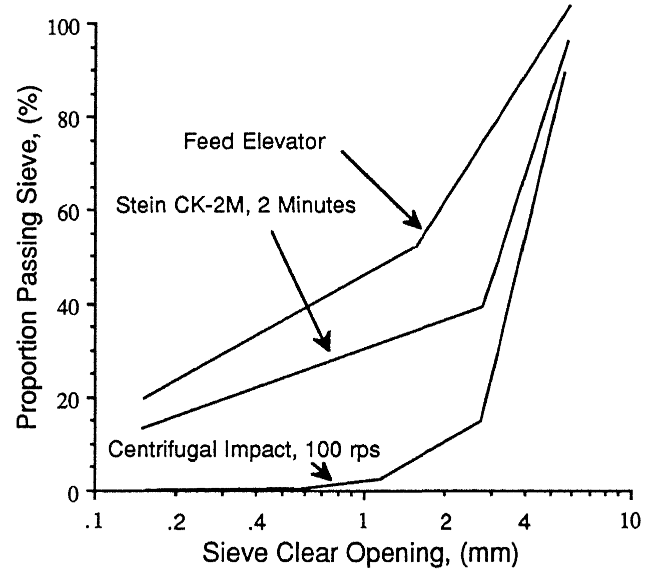

Figure 3. Distribution of particle sizes from a feed elevator, Stein CK-2M, and the Ohio Impacter. Corn dried on the ear slowly (Herum and Hamdy, 1981).

The results in Table 1 for the SBT indicate that drying temperature did not affect the weight percent of whole or nearly whole kernels (kernels that remained on top of the 7.94 mm sieve). The large broken fragments (those retained on the 6.35 mm sieve) were the size fractions most greatly affected. Almost all the increase in throughs resulted from the decrease in the amount retained on the 6.35 mm (16/64 in.) sieve. This, along with the constant amount of material retained on the 4.76 mm (12/64 in.) sieve, indicates that the SBT reduces large fragments (those passing through the 7.94 mm sieve but retained by the 6.35 mm sieve) into flour or dust. It is more like an attrition process than a splitting of kernels such as occurs in the WBT.

Table 1. Weight Percent of Corn Fractions Retained on Three Sizes of Sieves after Wisconsin (WBT) or Stein (SBT) Breakage Testing of Shelled Corn Dried at Several Air Temperatures (Gunasekaran, 1988).

	WBT Weight Percent Retained on Sieve				SBT Weight Percent Retained on Sieve			
Sieve Size mm (in)	20°C	35°C	50°C	65°C	20°C	35°C	50°C	65°C
7.94 (20/64)	16%	16%	8%	9%	22%	23%	21%	21%
6.35 (16/64)	61%	54%	40%	40%	71%	68%	59%	54%
4.76 (12/64)	15%	17%	23%	21%	3%	3%	4%	4%
Throughs	8%	13%	29%	30%	4%	6%	16%	21%

Standard Error of Measurement

Researchers generally consider that breakage values from the WBT have lower standard deviations and coefficients of variation than values from the SBT. Dutta (1986) found that the standard deviation for WBT results averaged 0.53% for 200 randomly selected samples. Wu (1987) reported the average standard deviation of 190 test samples was 0.505% for the WBT. Watson and Herum (1986) reported that the average standard deviation of results from the SBT were three times those from the WBT (1.49% vs 0.523%).

The large standard deviations of SBT results reported by Watson and Herum do not seem to be representative. Miller et al. (1981b) reported an average standard deviation of 0.775% for 10 samples and McGinty (1970) reported an average standard deviation of 0.782% for 6 samples. Eckhoff et al. (1987) reported an average standard deviation of 0.582% for the same 190 samples tested by Wu (1987). It appears that the standard deviation of the SBT breakage values is only slightly higher than that of the WBT. The coefficient of variation will generally be higher for the SBT when evaluating low breakage susceptibility corn because lower mean breakage values are measured by the SBT.

Figure 4 shows the variation of standard deviation with breakage susceptibility value for the WBT (Wu, 1987). There is considerable variability but a significant linear trend of increased standard deviation for an increase in breakage. Similar variability exists with the SBT values.

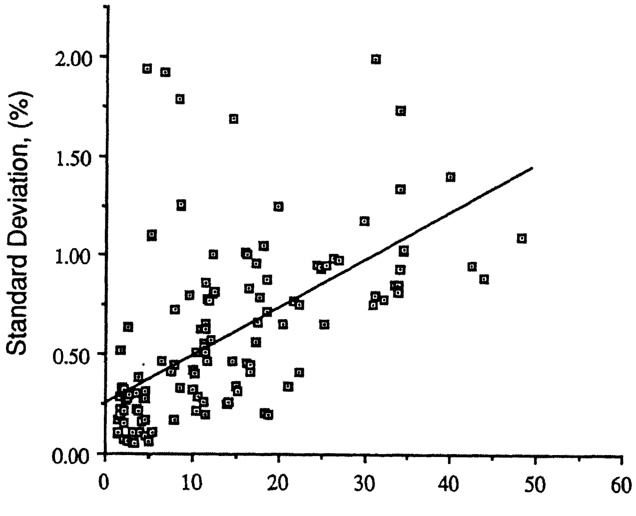

Figure 4. Standard deviation of WBT results as a function of breakage value (Eckhoff et al., 1988b).

Machine to Machine Variability

The variability between individual machines will depend upon the care taken in the manufacturing of the machines. Miller et al. (1981 a,b) found that the blade characteristics of the CK-2 model varied considerably from instrument to instrument. Their study lead to the development of the CK-2M model in which dimensional variations were corrected.

Even with these improvements to the SBT some variation between instruments is likely. Variations in motor speeds due to line voltage or changes in the blade and cup characteristics will cause differences. Visual inspections of these surfaces should be performed to insure reproducible results.

The WBT is not commercially produced. Only 24 of the instruments were built by Cargill for preliminary evaluations by researchers. Eckhoff et al. (1988a) reported that there were several critical dimensions not held constant among these 24 prototypes. If the instrument were to be mass produced the effects of these dimensional variations would have to be determined.

Past, Current, and Potential Modifications to the Instruments

When the WBT was first designed, kernels were fed into the impeller by a feeder of the type used in a seed planter. This feeder proved to be unsatisfactory and it was replaced with a vibrating feeder which has been successful.

There is currently no work being done to modify the WBT although there are two areas where modification may be beneficial. One modification would be a change in the rpm of the rotating plate. As discussed earlier, the WBT damages a considerable number of sound kernels because of its large impact force. The current rpm was selected on the basis of coefficient of variation in the test results rather than upon the type of breakage produced.

The second modification that could be beneficial to the WBT is a change of the impact surface. As will be discussed in a later section, "Future Needs in Assessing Breakage Susceptibility," there is a possibility that "Broken Corn Generation Rate" (BCGR) can be related to actual breakage. Eckhoff et. al. (1987) tried different impact surfaces in their pneumatic impactor. They found that a rubber belt material gave a BCGR similar to that observed during actual repeated handling. The WBT could be modified and used as a device for estimating BCGR.

As previously mentioned, the SBT has been modified in the past. Dr. Stan Watson and Dr. Floyd Herum of Ohio State University have recently been working on modifications to the tester which would decrease sample test time and would increase its potential for automation. Watson and Herum (1986) reported on one modification in which breakage values similar to those from the 2 min SBT tests could be achieved in 30 s. They increased the tip velocity of the impeller by 24% by increasing the impeller and cup diameter.

Corn Physical and/or Chemical Characteristics Which Affect Breakage Susceptibility

Moisture Content

Breakage susceptibility values from both the WBT and SBT are very sensitive to moisture content. This relationship between breakage susceptibility and moisture content has significant interactions with variety of corn, drying conditions, and corn temperature.

In general, the relationship between moisture content and breakage susceptibility is exponential with breakage values increasing as moisture decreases. Paulsen (1983) compared the moisture dependence of the WBT, SBT and Illinois testers. He developed exponential relationships for the WBT and Illinois tester but used a quadratic equation for the SBT. Others (Eckhoff et al., 1987; Herum and Blaisdell, 1981; Thompson and Foster, 1963) have used an exponential relationship for the SBT.

Figure 5 shows this exponential relationship between moisture content and Wisconsin breakage values for five varieties of corn dried using different procedures. It appears that breakage values could be easily adjusted for changes in the moisture content. While the relationship has a high correlation coefficient, the variability due to drying procedure and variety (at any moisture content) is too large to allow the relationship to be used in the market channel. For example, at 10% moisture content, the breakage values measured ranged from 15% to 40% (Figure 5). As will be discussed later, this difference represents a four fold difference in the rate at which these two samples would generate fine material. Such a variation is totally unacceptable.

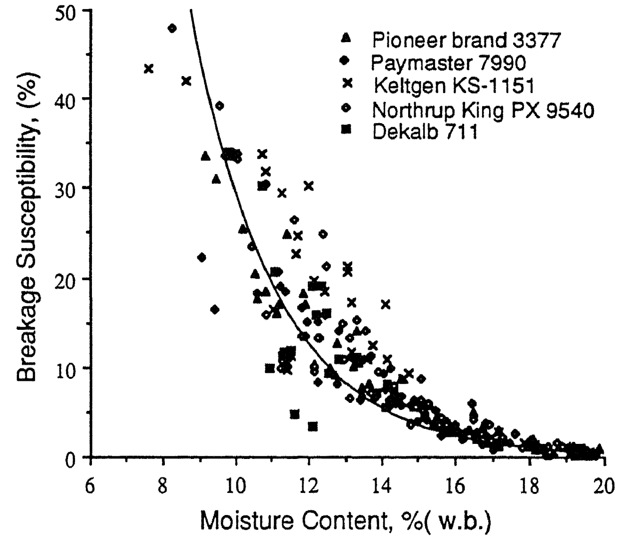

Figure 5. Relationship between moisture content and WBT breakage susceptibility for five corn varieties dried using different drying procedures (Eckhoff et al., 1988a).

Dutta (1986) developed an exponential moisture adjustment equation for his data. His criteria for acceptability was based upon statistical significance rather than absolute variability. Although such relationships meet statistical criteria, they are unacceptable from a practical standpoint.

Herum and Blaisdell (1981) showed that the moisture dependence of breakage susceptibility followed an exponential relationship as moisture content decreased to approximately 8% and then tapered off. The resulting curve was sigmoidal. This is reasonable in that there is a point where the mechanical/structural characteristics of the corn kernel do not significantly change with a decrease in moisture content. However, this moisture is lower than would normally be encountered in commerce.

Corn Temperature

Herum and Blaisdell (1981) studied the effect of corn temperature on the breakage susceptibility of corn dried at high temperatures. They tested three instruments: the Ohio Impacter, the SBT CK-2M, and a modified SBT with a larger impeller. For corn temperatures ranging from 4 to 38°C (39 to 100°F, they found that breakage susceptibility increased with decreasing temperature regardless of the type of tester used.

Eckhoff et al. (1988b, 1987) found that the effect of temperature on the WBT values followed an exponential relationship over the temperature range 14°C to 90°C or 57 to 194°F (Figure 6). There was some confounding of the effect by the drying procedure. Temperature effects were larger for corn dried at high temperatures and smaller for corn dried with ambient air. Changes in breakage values were significant over the range in temperature at which corn is normally handled. They also found an interaction between the effects of moisture and temperature. The temperature dependence increased at lower moisture contents. Furthermore, the two varieties tested had different temperature dependencies.

Eckhoff et al. (1987) determined the temperature effect for the SBT. Results were similar to those for the WBT but the SBT values did not follow an exponential relationship at temperatures below freezing. At temperatures below freezing the SBT created considerably more fine material than at higher temperatures.

Genotype and Environmental Factors

As previously discussed in the sections on moisture and temperature dependence, the genotype of the corn can affect breakage susceptibility. Paulsen et al. (1983), Pomeranz et al. (1986), and Stroshine et al. (1981, 1986) have shown that there are some specific genotypes that have lower breakage susceptibility and others which have higher breakage values. Martin et al. (1987) showed that kernels which are smaller and rounder tend to have lower breakage susceptibility. The implication of their findings is that factors which result in smaller kernels will tend to reduce breakage susceptibility. Such factors would include drought or heat stress. Stroshine's work also showed the effect of environment as year to year variations in the same genotype were considerable, although the relative rank of the genotypes remained fairly constant. These factors are discussed in more detail in the chapter titled **Hybrid/Varietal Differences in Breakage Susceptibility of Corn and Soybeans.**

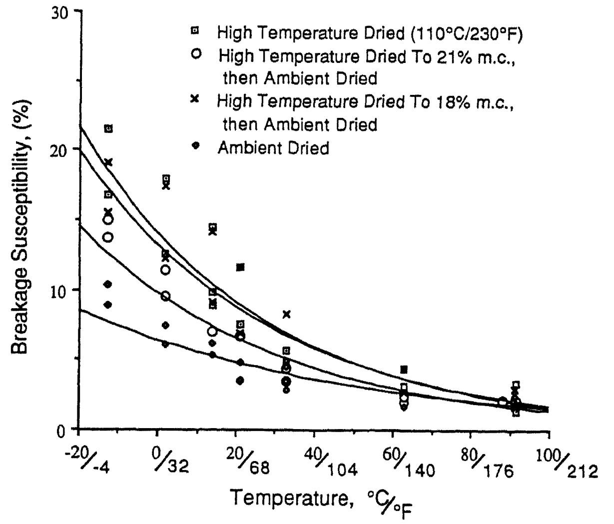

Figure 6. Effect of corn temperature on WBT results at different drying conditions (Eckhoff et al., 1988a).

Mold Infection, Insect Damage, and Rodent Damage

Eckhoff et al. (1984) found that extensive molding of shelled corn (84% of the kernels with visually detectable mold) only slightly increased the SBT breakage susceptibility. Eckhoff et al. (1988a) rewetted two corn varieties from 14% (wet basis) to 18% (wet basis) and stored them at 4°C (39°F) and 28°C (82°F) for 60 days. The samples stored at 28°C (82°F) were visibly moldy but the breakage susceptibility values of the molded and mold free corn were not significantly different. The effects of insect and rodent damage on breakage susceptibility have not been studied in detail. The effect of insect damage should depend upon the type of insect. Some insects act primarily upon the germ or the surface of the kernels. These would not weaken the kernel as much as insects which burrow into the kernel. In general, insects and rodents probably do not greatly change the mechanical characteristics of the kernels at the levels of damage normally found in commerce.

Grain Management Procedures Which Affect Breakage Susceptibility

Drying

For corn at a given moisture, the procedure used to dry corn has the greatest effect on breakage susceptibility. Drying at fast rates and at high temperatures creates stress cracks which weaken the corn kernels. Gustafson and Morey (1978), Gunasekaran and Paulsen (1985) and others have shown that increases in the rate of moisture removal cause an increase in breakage susceptibility.

Figures 7 and 8 show, respectively, SBT and WBT breakage susceptibility as a function of the drying procedure. The breakage susceptibility curves for the different drying treatments converge at approximately 15-16% moisture. This indicates that in this moisture range it will not be possible to use the breakage testers as a means of distinguishing corn

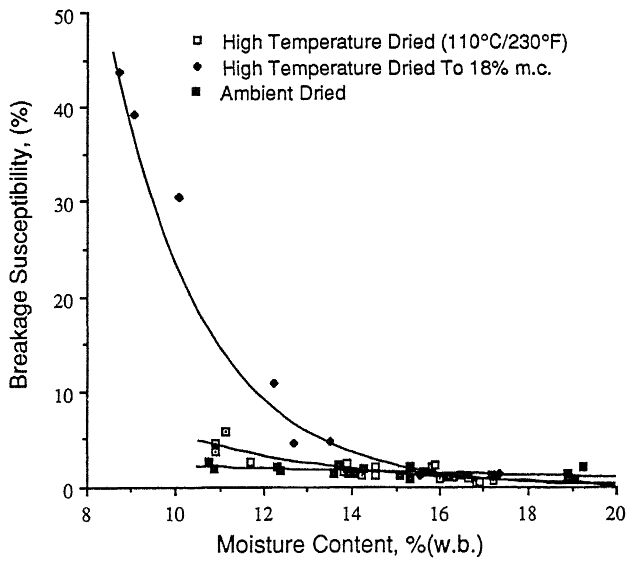

Figure 7. Effect of drying procedure and moisture content interaction on SBT breakage values (Eckhoff et al., 1987).

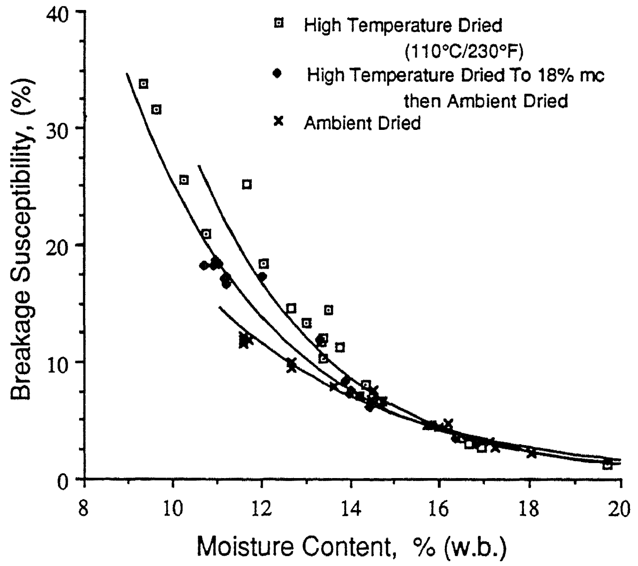

Figure 8. Effect of drying procedure and moisture content interaction on WBT breakage values (Eckhoff et al., 1988a).

dried at high temperatures from corn dried at low temperatures. The SBT can better discriminate between drying conditions at the lower moisture contents.

Eckhoff et al. (1987) found that the SBT and WBT values were very similar for corn dried at high temperatures but that the SBT gave much lower values for corn dried with air at ambient temperatures or corn dried by combination drying (first partially dried with air at high temperatures and then dried to a safe storage moisture using air at ambient temperatures). Figures 9 to 11 compare the breakage susceptibility values for samples of corn varying in variety and moisture content.

The SBT and WBT values of corn dried at high temperatures (Figure 9) had similar regression curves although the SBT values were higher at the lower moisture contents. The regression curves appear similar because the curves are steep in the low moisture range. A similar relationship between the SBT and WBT values was reported by Gunasekaran and Paulsen (1985). SBT values are lower for corn dried at moderate and low temperatures but are higher than the WBT values for corn dried at high temperatures.

Figure 12 shows the relationship between the SBT and WBT values determined on identical samples of corn varying in moisture content, temperature, and variety and dried using different procedures. At WBT values less than 13% the SBT values are smaller and increase more slowly (slope = 0.24). For WBT values greater than 13% the SBT values begin to increase more rapidly than the WBT values (slope = 1.92). The two instruments give nearly equal values at breakage values of approximately 27%. For values greater than the 27% the SBT gives larger breakage values on identical samples.

Blending

In commercial operations corn samples with different moisture contents are often blended to achieve a target moisture. A certain amount of blending occurs naturally because corn arriving at elevators or dried in high capacity dryers varies in moisture by several percentage points.

Nguyen et al. (1984) blended low moisture corn (8-10% w.b.), dried with air at room temperature with high moisture (24.7% w.b.) corn. They found that the blended corn had SBT breakage values which were higher than predicted by the weighted averages of the breakage susceptibilities of the individual components. Salter and Pierce (1988) performed a similar study using low moisture corn (9.8-12.8% w.b.) blended with high moisture corn (16.1-17.8% W.b.). They found just the opposite of Nguyen et al. (1984) in that the blend had a lower SBT breakage susceptibility. The result of the two studies may differ because of effects of hybrid, harvest moisture or unrecorded differences in the drying and handling procedures used in the studies. Wu et al. (1988) blended samples of corn at the same moisture but with different WBT breakage susceptibility values. They found that the corn blended in this

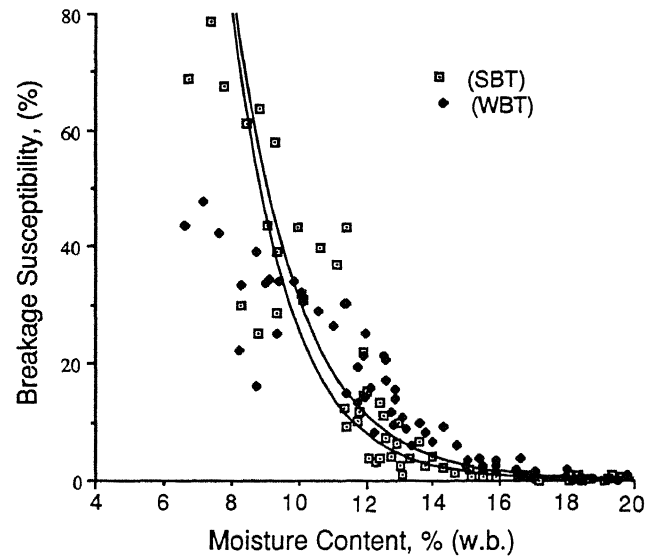

Figure 9. Comparison of the moisture effect on WBT and SBT breakage values for corn samples dried at 110°C (Eckhoff et al., 1987).

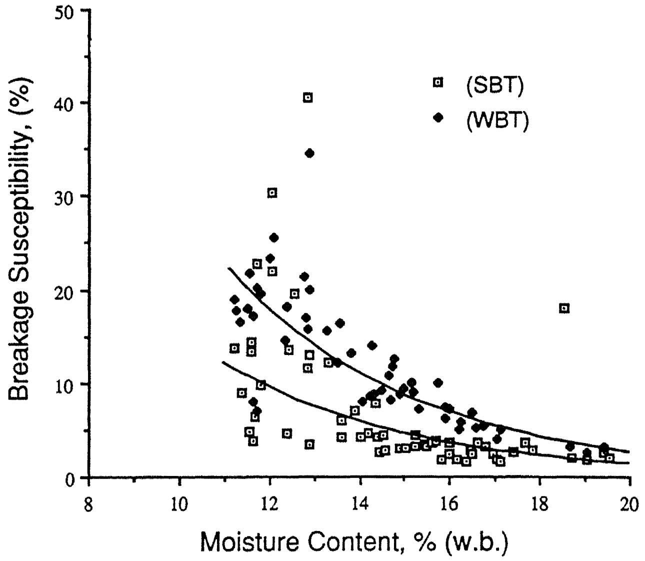

Figure 10. Comparison of the moisture effect on WBT and SBT breakage values for corn samples dried using combination drying. Corn was dried to 18% moisture using 110°C (230°F) and then dried to moisture shown using ambient air (Eckhoff et al., 1987).

manner had a greater WBT breakage susceptibility than the non-blended corn. It is obvious that the effect of blending of corn samples differing in moisture is not well understood.

Tempering

Tempering refers to procedures which either create or reduce internal moisture gradients. For example, in corn dry milling, corn is tempered by adding water to toughen the pericarp of the corn kernel and to increase germ resiliency. The term tempering is also used to describe the holding of hot corn during the drying process with no air movement through the corn. This type of tempering relaxes the internal moisture gradients within the corn kernel.

The equilibration of moisture after drying and before cooling is a good method of reducing breakage susceptibility in corn dried at high temperatures (Gustafson et al., 1982; Emam et al., 1979). Both research studies found that the majority of the benefit of tempering can be achieved in short tempering times (15-30 min). The moisture gradients in the kernel are the primary cause of stress crack development and any procedure which minimizes the development of large moisture gradients will decrease the number of kernels with stress cracks (Litchfield and Okos, 1988).

Addition of water to the corn to rehydrate it seems to only marginally affect the breakage susceptibility. Wu et al. (1988) found no consistent trends in the effect of rehydration. Salter and Pierce (1988) found a slight increase in breakage susceptibility between rewetted corn and corn initially dried to the rewetted moisture. They found the effect was less when moisture was added in increments less than or equal to 1.5 percentage points of moisture.

Correlation of Breakage Tester Results to Actual Handling Breakage

The ultimate value of a breakage tester is its ability to predict actual fine material generation during handling. Stephens and Foster (1976) studied the relationship between the SBT CK-2 values and breakage generated by elevating a sample of corn and dropping it down a spout into a truck. They handled approximately 24 samples that had been dried in different manners and therefore had different levels of breakage susceptibility. They found that the tester breakage correlated well (r^2 greater than 0.94) with the amount of broken corn actually created.

Herum and Hamdy (1981) repeatedly handled four lots of corn in a feed elevator and measured the amount of fine material generated. They found that the rate of fine material generation was constant for any given sample. They were unable to find a good correlation between rate of fine material generation and breakage values from a SBT CK-2M, a modified SBT or the Ohio Impacter.

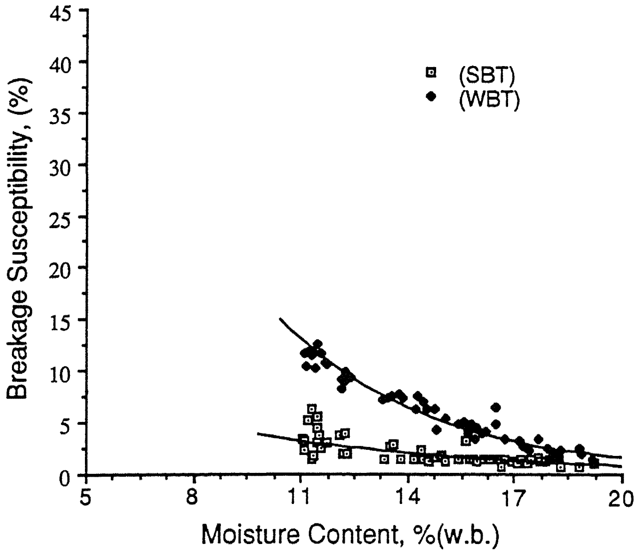

Figure 11. Comparison of the moisture effect on WBT and SBT breakage values for corn samples dried using ambient air (Eckhoff et al., 1987).

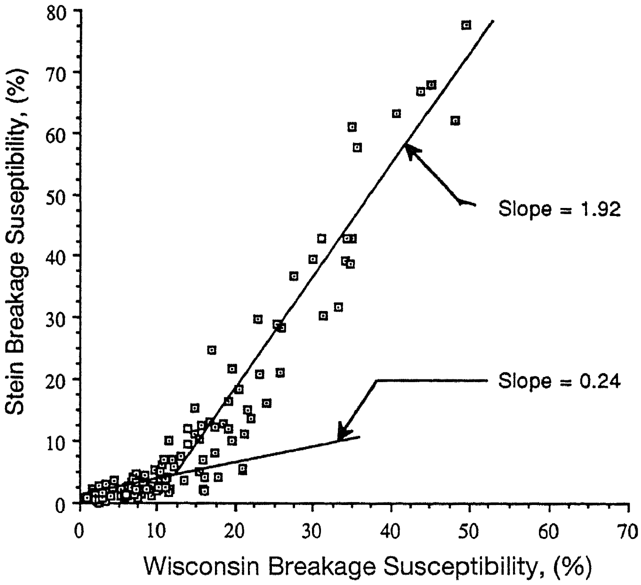

Figure 12. Relationship of SBT breakage values to WBT breakage values for samples of varying moisture content, temperature, variety, and drying conditions (Eckhoff et al., 1987).

Working with an installation similar to a commercial site elevator, Eckhoff et al. (1987) repeatedly handled six 1000 bushel lots of a single variety of corn which had been dried using different procedures. The results shown in Figure 13 relate the amount of total BCFM in the sample to the number of times the corn lot was handled through the elevator. The "Adjusted Cumulative BCFM" is the total BCFM minus the initial BCFM in the sample at the start of the test. The interesting result was that the rate of generation of BCFM was relatively constant for any lot of corn. This agreed with the results of Herum and Hamdy (1981b) who showed that fine material was generated at a constant rate. It was generally assumed that there would be a point at which the rate of generation would decrease since only the strong kernels would remain intact. However, BCFM values of over 50% were achieved with no sign of a decrease in the rate of BCFM generation.

The slope of the cumulative BCFM relationship is called the "Broken Corn Generation Rate (BCGR)." This rate increased as breakage susceptibility increased. The breakage susceptibility also increased with the severity of drying.

Samples of the six corn lots were used to develop a laboratory test procedure which simulated the repeated handling of the corn in the elevator. A pneumatic impacting device was developed in which each handling through the device was similar to one pass through the elevator. This laboratory tester was

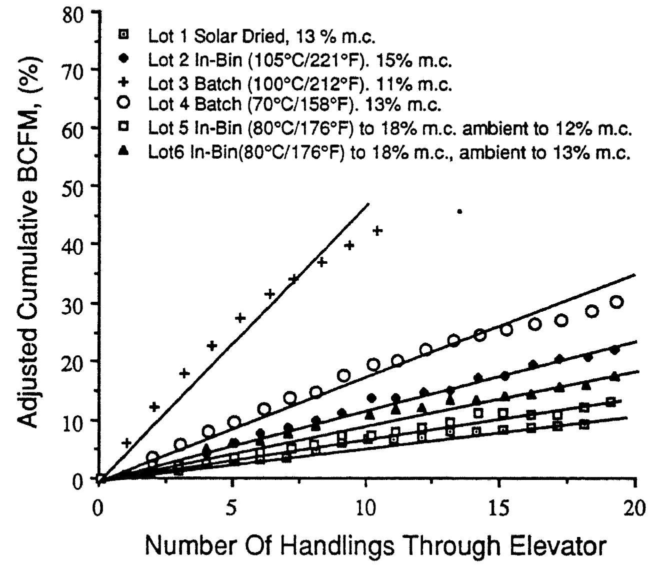

Figure 13. Cumulative BCFM in six, 25 tonne (1000 bu) lots of corn repeatedly handled through a grain elevator (Eckhoff et al., 1987).

used to test approximately 100 samples of corn of varying moisture content, temperature, and variety that had been dried by various procedures. The generation rates in the impacting device were correlated to both WBT (Figure 14) and SBT (Figure 15) breakage values. The WBT results were dependent upon drying rate while the SBT results were less dependent on drying rate.

The WBT has been advocated as a good instrument because it has the ability to discriminate differences in breakage susceptibility in high quality (rela-

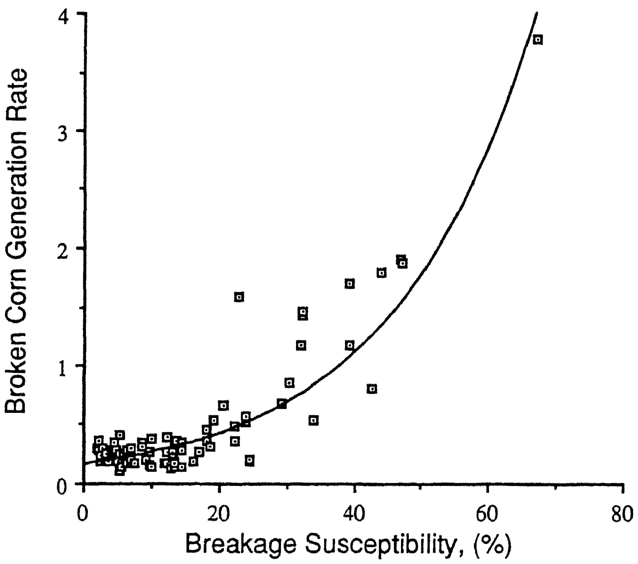

Figure 14. Relationship of WBT breakage susceptibility values to broken corn generation rates determined by the laboratory procedure (Eckhoff et al., 1987).

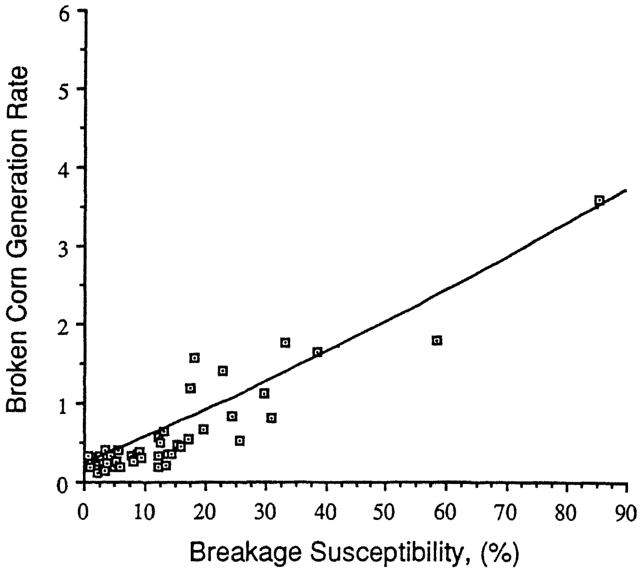

Figure 15. Relationship of SBT breakage susceptibility values to broken corn generation rates determined by the laboratory procedure (Eckhoff et al., 1987).

tively low breakage) corn. However, for WBT breakage values in the range of 0 to 20%, there was very little change in broken corn generation rate (Figure 14). The greater ability of the WBT to discriminate between low breakage susceptibility samples does not appear to be necessary when evaluating actual handling data. For the SBT there was a nearly linear relationship between breakage values and broken corn generation rate (Figure 15). Note that the generation rate changes with SBT value over the entire range in breakage susceptibility. The slope of the line relating BCGR to SBT breakage susceptibility is relatively low. This means the BCGR cannot be predicted very accurately with the SBT. However, the SBT could be useful as a screening procedure in which cut-off values would be used to classify the sample.

Future Needs in Assessing Breakage Susceptibility and Utilizing Test Results in the Marketing of Corn

Single Kernel Breakage Susceptibility Testing

When corn samples with differing breakage susceptibility are blended, the blended sample will have an intermediate breakage value. However, the kernels having the higher breakage susceptibility will still be more likely to break during handling. An individual kernel breakage susceptibility tester would identify blended samples. It might also be useful in investigating the variability in the relationship between breakage generation rate and breakage susceptibility.

Some processes, such as corn dry milling, are more sensitive to the effects of individual kernel variations in breakage susceptibility. For example, a mixture of 75% corn with low breakage (SBT value of 5%) and 25% corn with high breakage (SBT value of 20%) would have an average breakage susceptibility of 8.75%. This sample will dry mill differently than a sample with a uniform kernel breakage susceptibility of 8.75%. The high breakage corn in the mixture will produce fewer large grits and will tend to be broken into smaller, less valuable mill products.

Standardized Test to Correlate Elevator Damage to Breakage Susceptibility

Large scale testing to correlate elevator damage to breakage susceptibility is expensive. An alternative used by Eckhoff et al. (1987) was to determine breakage in a pneumatic device and results with breakage of a limited number of samples handled in an elevator. The device could be used to determine the breakage generation rate on a large number of samples. Unfortunately, the components of the device used by Eckhoff are not readily available. A method is needed that can be easily replicated in any laboratory so data from different laboratories can be compared.

Prediction of Broken Corn Generation Rates for Different Handling Processes: An Energy Dissipation Concept

Broken corn generation rates will vary from elevator to elevator depending upon the specific equipment and handling procedures used in the elevator. The relationship between broken corn generation rate and breakage susceptibility determined by Eckhoff et al. (1987) is for a specific elevator. It is impractical for each elevator to determine a similar relationship. A generalized method for predicting the broken corn generation rate is needed.

Dr. Charles Hurburgh of Iowa State University (1986, Personal Communication) suggested that each unit element of a grain elevator be assigned an "energy dissipation value" based upon its ability to create damage in corn. Values for each component could be added to determine overall value. This could in turn be related to breakage susceptibility. The additive nature of the energy dissipation values seems plausible since the rate of broken corn generation in repeated handling is linear. Such a system would allow elevator operators to evaluate the expected breakage from alternative methods of moving the grain through the elevator. It would also aid in the design of new elevators or in the expansion of existing elevators.

For this concept to be viable, research should be performed similar to the research performed by Stephens and Foster (1976) on the individual components of the handling system. Once an energy dissipation value is determined for a specific piece of equipment it would be applicable to all systems which use that equipment.

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Genotypic Differences in Breakage Susceptibility of Corn and Soybeans

M.R. Paulsen[a] **L.L. Darrah**[b] **R.L. Stroshine**[c]

Introduction

Corn and soybean varieties differ in their susceptibility to breakage during harvesting and handling. The predisposition to breakage susceptibility begins at the point of production. The producer's choice of variety or genotype can influence the amount of subsequent breakage which occurs as the grain passes through marketing channels. The amount of fine material generated could be reduced if producers considered breakage susceptibility when selecting a variety for planting. Research has identified specific traits which contribute to reduced susceptibility to breakage among corn genotypes. Very few studies have focused on identifying soybean traits associated with breakage. However, the observed variations in breakage among soybean varieties suggest that there is such an association. If breakage can be related to specific traits, then breeding programs could develop genotypes and varieties less prone to breakage by breeding for these traits. This paper summarizes research on genotype and varietal differences and makes recommendations for future work.

Corn

Several studies have investigated genotypic effects on breakage. Jennings (1974) studied physical quality differences among genotypes in Iowa. He investigated test weight, physical damage (fast-green dye tests), fine material, breakage susceptibility, kernel size/shape, and pericarp thickness on corn samples dried at 37°C (99°F) to 12 ± 1% moisture content.* The breakage susceptibility tests were performed with the CK-2 Stein Breakage Susceptibility Tester (SBT). Samples were impacted for 2 min and then sieved in a 4.76 mm (12/64 in) round hole sieve. He found that percentages of breakage susceptibility, fine material, and physical damage were positively correlated with harvest moisture, and were negatively correlated with test weight. Delay in planting and/or harvesting early were correlated with lower test weight, more physical damage, more fine material, and increased breakage susceptibility. Pericarp thickness did not affect either fine material or breakage susceptibility. Large-kernel genotypes tended to have lower test weights than small-kernel genotypes, and large-kernel genotypes shrank more upon drying than small-kernel genotypes. Yield was not correlated to physical damage, fine material, breakage susceptibility, or dry test weight.

To facilitate comparison of genotypes, Jennings (1974) computed a quality index, *QI*, for combine harvested samples as follows:

$$QI = 150 - \frac{100\,[a\,FM,\,\%] + P.D.,\,\% + [b\,Brk.\,Susc.,\,\%]}{\text{Dry Test Weight, lb/bu}} \tag{1}$$

where *a*, *b* are constants for local growing areas, P.D. represents physically damaged kernels as determined by fast-green dye, % by weight, and FM is fine material, % by weight. The quality index ranged from 10 to 117. Using a custom built plot harvester, Jennings found that the following inbreds

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[a] Agricultural Engineering Department, University of Illinois

[b] Plant Genetics Research Unit, USDA, Dept. of Agronomy, University of Missouri

[c] Agricultural Engineering Department, Purdue University

* All moisture contents reported in this study are expressed as percent wet basis unless otherwise indicated.

consistently produced corn grain with higher quality indices: (IA2EARSYN#1)C2-15, Q98-10-1-4-1-1-1(B79), B14A, B74, CBS#1(C3-87), and (CBS#1C4)SSS(-7). Corn grain from single crosses using these inbreds was usually near or below average in harvest moisture. Thus, lower harvest moistures alone may have helped to improve the quality index. The inbreds B57, Pa887P, N28, B45, and B37 consistently contributed to corn grain with a low quality index and above average harvest moisture contents.

Johnson and Russell (1982) investigated 80 inbreds and 40 single-cross hybrids grown at two locations in 1976 and 1979. Samples for this study were dried at 60°C (140°F), as reported by Russell et al. (1985). Johnson and Russell (1982) found a statistically significant negative correlation (r=-0.59) between kernel hardness and kernel specific gravity. Softer kernels had lower specific gravities. The negative correlation (r=-0.59) between CK-2 SBT breakage susceptibility (4 min, 4.76 mm sieve) and kernel specific gravity was also statistically significant. They concluded that selection for increased density would result in a more breakage resistant hybrid.

LeFord and Russell (1985) studied both the potential for selection of corn genotypes that produce grain resistant to physical injury, and relationships among physical traits during inbreeding. They evaluated samples from the S_1 and S_2 lines of both BS17 and BS1(HS)C1 synthetics. Samples were dried at 66°C (150°F) and then eight traits were evaluated along with CK-2 SBT breakage (4-min, 4.76-mm sieve). Table 1 summarizes a portion of their results, the factors which give statistically significant correlations with SBT breakage susceptibility. The authors concluded that S_1 lines with flinty kernels tended to produce S_2 lines with dense kernels and that S_1 lines with low breakage susceptibility tended to produce early-flowering S_2 lines with smaller kernels. They also concluded that S_1 lines with large kernels tended to produce S_2 lines that were more susceptible to breakage. The results of both Johnson and Russell (1982) and LeFord and Russell (1985) were summarized in Russell et al. (1985).

Table 1. Correlation coefficients between SBT breakage and various physical traits for S_1 and S_2 lines derived from the BS17 and BS1(HS)C1 synthetics.[a,b]

Trait	BS17		BS1(HS)C1	
	S1	S2	S1	S2
300 kernel weight	0.15	0.46**	0.44**	0.36**
300 kernel volume	0.15	0.49**	0.50**	0.45**
kernel density	-0.01	-0.34**	-0.47**	-0.56**
endosperm rating[c]	0.13	-0.06	0.29**	0.18
shear strength	-0.10	0.12	-0.18	0.29**

[a] Source: LeFord and Russell (1985).

[b] Correlation coefficients significant at the 0.01 levels indicated with a **.

[c] Endosperm rating: r=1 is flint and r=5 is soft dent.

Moentono et al. (1984) evaluated 14 entries including up to eight cycles of selection for stalk crushing strength in two synthetic populations under three levels of nitrogen fertilization (80, 160, and 240 kg/ha N or 71, 143, 214 lb/A N) and at three plant densities (33,300, 44,400, and 55,500 plants/ha or 13,500, 18,000, or 22,500 plants/A) for two years at three locations. Corn was dried in the field to about 12% moisture content. Selection involved crushing a 5.1 cm (2 in) section of slowly dried stalk removed from the second expanded internode above the ground by crushing it parallel to its longitudinal axis. Selection using this criterion resulted in a more dense stalk with a thicker rind. Kernel breakage susceptibility of the selections was studied using a speed-regulated, motor-driven, enclosed six-blade impeller. The impeller rotated at approximately 1800 rpm resulting in a tangential velocity of 18.6 m/s (61 ft/s). The kernels were fed uniformly into the impeller by a vibrating feed hopper, struck by the blades of the rotating impeller, and thrown against the wall of the impeller housing at a high velocity. Material was screened before and after impaction using a 6.0 mm (15/64 in) round-hole sieve. Breakage susceptibility was determined using the weight of material that passed through the screen in relation to the initial sample weight.

Moentono and coworkers found kernel breakage susceptibility was significantly affected by environment and plant density. They observed that, for both populations, changes in breakage susceptibility were linearly and negatively related to: (1) nitrogen level, and (2) selection for increased stalk crushing strength. Interactions of cycles of selection with nitrogen level or plant density were not significant. Predicted kernel breakage susceptibility at 160 kg/ha N (143 lb/A N) and 44,400 plants/ha (18,000 plants/A) decreased by 0.3%/cycle in one synthetic (white endosperm) population and 0.6%/cycle in the other (yellow endosperm population). Some of the observed correlated responses to stalk strength selection may have been due to changes in kernel size as related to yield. However, yield changes were in opposite directions for the two synthetic populations. The yellow endosperm population with the 0.6% decrease in breakage susceptibility/cycle also had a predicted decrease in yield from 6350 kg/ha (101 bu/A) for cycle 0 down to 6050 kg/ha (96 bu/A) for cycle 8. Apparently, increased stalk crushing strength for the yellow endosperm population caused the plants to be less responsive to increased levels of nitrogen. For the white endosperm population, yields increased from 6000 kg/ha (95.6 bu/A) for cycle 0 to 6900 kg/ha (110 bu/A) for cycle 8 as crushing strength increased and as breakage susceptibility decreased by 0.3%/cycle.

Bauer and Carter (1986) used the Wisconsin Breakage Tester (WBT) to study effects of planting date, maturity group, plant density, moisture availability and soil nitrogen fertility on breakage susceptibility of three commercial yellow corn genotypes from each of three maturity groups. Ear corn was dried at 32°C (90°F) to 11% moisture content and hand shelled. Their results on effects of nitrogen fertilization and plant density agreed with the trends reported by Moentono et al. (1984). Although the breakage susceptibility decreased in response to nitrogen application rate, the incremental decrease in breakage susceptibility between the average and high nitrogen application rates was less than the incremental decrease between the zero and average application rates. Bauer and Carter also found that breakage susceptibility increased as plant density increased. For grain grown under dryland conditions, irrigation increased the breakage susceptibility. Delayed planting increased breakage susceptibility and genotypes from the later maturity groups had lower breakage susceptibilities.

Ochieng et al. (1985) studied effects of weevil damage and endosperm mutation type on the breakage susceptibility of various genotypes. Breakage susceptibility was measured using the technique described by Moentono et al. (1984), except that the breakage tester tangential velocity was 35.4 m/s (116 ft/s). Amount of weevil damage and breakage susceptibility were highly correlated (r=0.82) in a set of inbred lines differing in genotype and endosperm mutation type (normal, opaque-2, amylose extender, and waxy). When compared in two inbred genotypes, differences in breakage susceptibility for normal versus amylose extender mutant endosperm and normal versus waxy mutant endosperm were not significant. Differences between normal and opaque-2 mutant endosperm were significant for one of two inbreds.

Grain from 1980 and 1981 regional white food corn performance tests (Darrah and Zuber, 1981, 1982) was evaluated for kernel breakage susceptibility as described by Moentono et al. (1984), but using a 6.4 mm (16/64 in.) sieve. Samples from one replication at each location were dried at 40°C (104°F) to about 11.5% moisture content before testing. In the 1980 test, grain from nine locations, representing diverse growing conditions, was evaluated. In the 1981 test, grain was received from eleven locations, including IA, IL, IN, KS, KY, MO, TN, TX, and VA. The combined means showed that there were six entries that had significantly more breakage than the mean of all entries common in the two tests. Five common entries, ACCO UC1800W, Golden Harvest H-2644W, Sturdy Grow SG908W, Mo17 x N28, and US13 were significantly less susceptible to breakage than the average entry (Table 2). Included were high yielding entries with resistance to breakage.

Effects of Drying on Breakage of Corn Genotypes

Most of the corn in major growing areas of the United States is shelled in the field at moistures above those safe for storage. It is dried artificially and more than half is dried at temperatures well above ambient (20°C {68°F} or more). The more rapidly the moisture is removed, the greater the increase in breakage susceptibility. Thompson and Foster (1963) found a linear relationship between percentages of kernels with severe stress cracking (checked kernels) and moisture removal in points per hour (r=0.94). SBT breakage susceptibility was in turn linearly correlated with severe stress cracking (r=0.79). Their data suggest that the more rapid the drying rate, the greater the increase in breakage susceptibility.

Stroshine et al. (1986) determined CK-2M SBT breakage susceptibility (2-min. 4.76 mm {12/64 in} sieve) for hybrids dried at 93°C (200°F) from 25% to 15% moisture content and then conditioned in an environmental chamber to approximately 11.5 ± 0.5% moisture. Their results illustrate that, although high temperature drying greatly increases breakage susceptibility, genotypic differences remain. The fastest drying hybrid was B73 x Mo17 for each of two years. It was significantly above average in breakage susceptibility in 1980 and also above

Table 2. Combined Means for Percentages of Breakage Susceptibility of Corn Grown at Nine Locations in 1980 and Eleven Locations in 1981 for Common Entries in Regional White Food Corn Performance Tests.

Hybrid	1980	1981	Combined
ACCO UC1800W	27.5	40.2	33.9
Funk G-4747W-1	39.5	47.9	43.7
Funk G-4787w	31.2	42.9	37.1
Golden Harvest H-2644W	28.7	42.7	35.7
Golden Harvest H-2660W	37.4	50.2	43.8
Jacques W-200	33.1	49.0	41.1
Lynks SC-WLA	37.6	48.8	43.2
Lynks SC-WM	35.4	49.8	42.6
Meacham's MV78	35.3	51.0	43.2
Meacham's MV88	38.2	50.1	44.2
Meacham's MX50	30.1	47.2	38.7
MFA C4W	35.7	47.2	41.5
Princeton SX90	35.4	50.8	43.1
Princeton SP936	36.9	47.4	42.2
Sturdy Grow SG908W	27.3	41.1	34.2
Sturdy Grow SG921W	32.0	45.3	38.7
Sturdy Grow SG935W	36.2	47.9	42.1
Whisnand 75W	33.9	46.2	40.1
Whisnand 77W	35.2	47.3	41.3
Yellow check B73 x Mo17	30.9	45.4	38.2
Yellow check Mo17 x N28	29.8	41.7	35.8
Yellow check US13	29.8	41.7	35.8
Mean	33.5	46.4	40.0
LSD P = 0.05[a]	4.1	4.5	3.0
CV%[a]	14.8	10.5	

[a] Based on the genotype by environment interaction and mean for all entries in the test. For the combined LSD P = 0.05. Each year was weighted equally. Table adapted from Darrah and Zuber 1981, 1982.

average in 1981 (Table 3). The A632 x H95 single-cross hybrid was consistently low in breakage susceptibility in both 1980 and 1981, and had relatively long drying times in both years.

Paulsen et al. (1983) used both the CK-2M SBT (2-min., 4.76 mm {12/64 in} sieve) and a centrifugal impact device (2200 rpm, 23 m/s or 75 ft/s peripheral velocity) to test breakage susceptibility on common Corn-Belt genotypes grown over a four-year period. The corn was hand shelled and dried at low temperature to about 13.5% moisture with 24°C (75°F) air. Four genotypes were also dried at high temperature with 60°C (140°F) air. Stress cracks ranged from 0 to 4% in the corn dried at low temperature, and from 86 to 97% in the corn dried at high temperature, respectively. Percent breakage in centrifugally impacted corn ranged from 1.6 to 3.5% for corn dried at 24°C (75°F); percent breakage of corn dried at 60°C (140°F) was four times greater, ranging from 4.6 to 10.7% (Table 4).

Percentages of floaters in a 1.275 specific gravity solution provided an indication of kernel hardness (ratio of corneous to floury endosperm), and were inversely related to test weight. FRB73 x FR16 had the lowest number of floaters, indicating a relatively dense or hard kernel. FRMo17 x H100 had the highest number of floaters, indicating it was the least dense. Breakage susceptibility values for the impactor device were significantly and negatively correlated ($r=-0.89$) to the percentage of floaters for the corn dried at high temperature; while breakage susceptibility values for the CK-2M SBT were weakly and positively correlated ($r=0.56$) to the percentage of floaters. (The maximum tip velocity of the SBT is approximately 8 m/s or 26 ft/s). These results suggest that drying at high temperatures reduces kernel

Table 3. Breakage Susceptibility, Thin-Layer Drying Time for Removal of 10 Points (Wet Basis) of Moisture for Samples of Hybrids Grown in 1980 and 1981. Table adapted from Stroshine et al. (1986).[a]

	Stein Breakage, %[b]		Drying Time, min[c]	
Hybrid	**1980**	**1981**	**1980**	**1981**
B73 x Mo17	28.3e	8.7b	31.0a	28.5a
A632 x H95	5.2a	3.2a	...	38.1cd
Mo17 x H100	12.6b	12.3c	...	35.2bc
H95 x B73	11.6b	2.7a	...	33.0b
DeKalb XL55A	25.4d	12.2c	36.8c	37.7cd
DeKalb XL67	24.2d	6.1b	34.8b	33.3b
DeKalb XL25A	21.6c	7.0b	39.6d	40.4d
Pioneer Brand 3732	31.7f	12.1c	...	...
G4435 x 9232K	30.7f	29.1d	...	...
Average	21.2	10.4	35.6	35.2

[a] Numbers followed by different letters are significantly different (Student-Newman-Keuls multiple range test; P=0.05).

[b] Percentage by weight of fine material through a 4.76-mm (12/64 in.) round-hole sieve after a 2-min test. Samples had been dried at 93°C (200°F) and conditioned to moistures of 11.3-11.8% in 1980 and 11.3-12.4% in 1981. Numbers shown are the averages of four tests in 1980 and five tests in 1981.

[c] Time required to dry 1 kg (2.2 lb) of shelled corn spread in a thin layer from an initial moisture of approximately 25% (wet basis) to a final moisture of approximately 15% using air at 93°C (200°F). Values for 1980 are averages of three tests. Values for 1981 are averages of seven tests for all hybrids except B73 x Mo17, for which there were six tests, and A632 x H95, for which there were four tests.

Table 4. Breakage Susceptibilities for 1980 Corn Genotypes after Centrifugal Impacting at 2200 RPM and SBT Testing. Corresponding Means for Floaters and Test Weight are also shown. (Six Replications). Table adapted from Paulsen et al. (1983).

Genotype	**Oven moisture, %**	**Impactor breakage,[a] %**	**CK-2M Stein breakage,[a] %**	**Floaters, %**	**Test weight, kg/m³ (lb/bu)**
(Dried with air at 24°C, 75°F)					
FRB73 x FR16	13.3	3.50	0.18	4.6	814 (63.2)
FRB73 x Mo17	14.0	3.35	0.62	60.8	776 (60.3)
FRB73 x FR18	13.4	2.67	0.38	6.8	806 (62.6)
B84 x FRMo17	13.7	2.63	0.63	74.9	778 (60.4)
FRMo17 x H100	13.7	2.27	0.58	87.8	751 (58.3)
FRB73 x FR19	13.6	2.12	0.45	13.9	801 (62.2)
FRB73 x Pa91	13.6	2.01	0.47	8.4	798 (62.0)
(FR4AxFR4C) x FRMo17	13.6	1.92	0.52	55.3	774 (60.1)
FrMo17 x FR19	14.1	1.89	0.28	61.4	773 (60.1)
FRMo17 x FR6734	13.6	1.59	0.53	65.7	778 (60.4)
LSD P = 0.05		0.31	NS	6.8	3
(Dried with air at 60°C, 140°F)					
FRB73 x FR18	13.2	10.67	0.90	25.6	795 (61.8)
FRB73 x FR16	13.3	9.81	0.25	6.0	812 (63.1)
FRB73 x Mo17	13.5	6.28	1.43	73.3	772 (60.0)
(FR4AxFR4C) x FRMo17	13.4	4.57	0.68	74.2	770 (59.8)
LSD P = 0.05		0.47	0.38	3.9	2

[a] Percentages of Grain Passing Through a 4.76-mm (12/64 in.) Sieve.

density and makes the kernels more susceptible to breakage by high-velocity impacts such as those produced by the centrifugal impact tester. For the genotypes dried at low temperatures, significant correlations of impactor device and SBT breakage susceptibilities with percentages of floaters were not found. The authors noted genotypes containing FR4A x FR4C as a female parent were consistently low in breakage susceptibility. They also observed that drying at high temperatures increased breakage susceptibility by a factor of two to six. Breakage susceptibility was affected more by high temperature drying than by differences in genotype.

Dutta (1986) dried four hybrids and then determined their WBT breakage susceptibility: Pioneer Brand 3780, 3720, 3732, and Ames Best SX37. He sieved samples with a 4.76 mm (12/64 in) sieve, as described by Singh and Finner (1983). He found that Pioneer Brand 3780 was significantly lower in breakage susceptibility than the other three hybrids when dried at 93°C (200°F). Of the four hybrids, Pioneer Brand 3720 was the most susceptible to breakage when dried at 93°C (200°F). After low-temperature drying at 20°C (68°F), the four hybrids were not significantly different in breakage susceptibility. Koeckeritz et al. (1988) dried NDC688 and NDG068 and found no significant difference in WBT breakage susceptibility between naturally-dried samples; but significant differences were found between the two varieties when they were dried at either 60°C (140°F) or 82°C (180°F). These studies suggest that varietal differences in breakage susceptibility can increase with severity of drying treatment.

Effects of harvest moisture and drying temperature were studied in a set of 20 hybrids in three Missouri environments (Fox and Darrah, 1989). Grain was harvested at 28, 22, and 16% moisture and dried at either 49°C (120°F) or 71°C (160°F). Breakage susceptibility was measured on a WBT. Hybrid, harvest moisture, drying temperature, and their interactions had a significant effect on breakage susceptibility. Values ranged from 15.9% for Paymaster 8201 to 22.5% for AgriPro HP771, the hybrid with the highest density (1.25 g/cm^3). Three hybrids, Lynk's LX4406, EK Premium EK9920, and Paymaster 7190, had approximately the same breakage susceptibility as Paymaster 8201 (least breakage). Their kernel density was similar to that of AgriPro HP771. These results suggest that it is possible to have relatively high kernel density and low breakage susceptibility.

In the study by Fox and Darrah, harvest moisture affected breakage susceptibility and there appeared to be a critical harvest moisture below which the breakage susceptibility decreased significantly. Asgrow 5291 harvested at 22% moisture had high breakage susceptibility (similar to that at 28% harvest moisture) while Garst 8388 harvested at 22% moisture had low breakage susceptibility (similar to that at 16% harvest moisture, Figures 1 and 2). In all 20 hybrids, grain harvested at the highest moisture (28%) and dried at the highest temperature (71°C, 160°F) had the greatest susceptibility to breakage, while grain harvested at the lowest moisture (16%) and dried at the lowest temperature (49°C, 120°F) was the least susceptible to breakage.

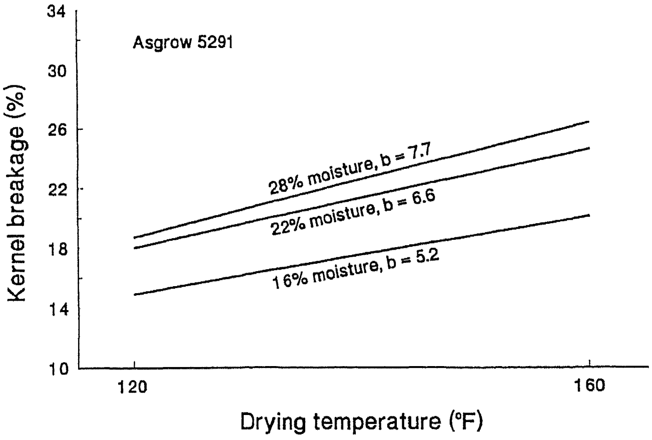

Figure 1. Kernel breakage susceptibility of Asgrow 5291 as affected by harvest moisture and drying temperature. Data represent three environments with four replications each. (Fox and Darrah, 1989).

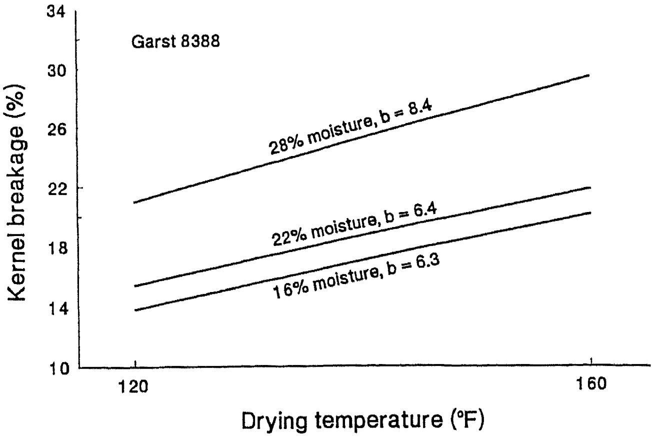

Figure 2. Kernel breakage susceptibility of Garst 8388 as affected by harvest moisture and drying temperature. Data represent three environments with four replications each. (Fox and Darrah, 1989).

Eckhoff et al. (1987) determined CK-2M SBT breakage susceptibility (2-min. 4.76 mm sieve) for

Pioneer Brand 3377, Paymaster 7990, Keltgen KS-1151, Northrup King PX 9540, and DeKalb 711 corn hybrids. The hybrids were combine harvested at 25% moisture content and given three different drying treatments: a) 110°C (230°F) to the desired final moisture content; b) 110°C (230°F) to 18% moisture content followed by ambient air drying; and c) ambient air drying. Figure 3 illustrates the resulting CK-2M SBT as a function of moisture content for each of the drying conditions and each of the five hybrids. Under the more severe drying conditions, the Northrup King PX 9540 and Keltgen KS-1151 hybrids appeared to have higher than average SBT breakage susceptibility. In all three drying treatments, the breakage susceptibility increased as moisture decreased. However, the breakage susceptibility of the corn dried with air at ambient conditions remained low even at 10% moisture. Furthermore, below 14% moisture the breakage susceptibility was greater in the more severe drying treatment (110°C or 230°F to final moisture) than in the treatment of intermediate severity (110°C or 230°F to 18% moisture followed by drying with ambient air).

The research summarized in this section supports the early work of Thompson and Foster (1963) which related breakage susceptibility to drying rate. However, results by Stroshine et al. (1986), Dutta (1986), Koeckeritz et al. (1988), Fox and Darrah (1989), and Eckhoff et al. (1988) suggest that the drying rate effect on breakage susceptibility varies among genotypes. Therefore, selection of appropriate hybrids could reduce the amount of subsequent grain breakage. Stroshine et al. (1986) reported that genotypes varied significantly in the time required to lose 10 percentage points of moisture during thin-layer drying tests at 93°C (200°F). These differences result in differences in efficiency during high-temperature drying (Martins and Stroshine, 1987).

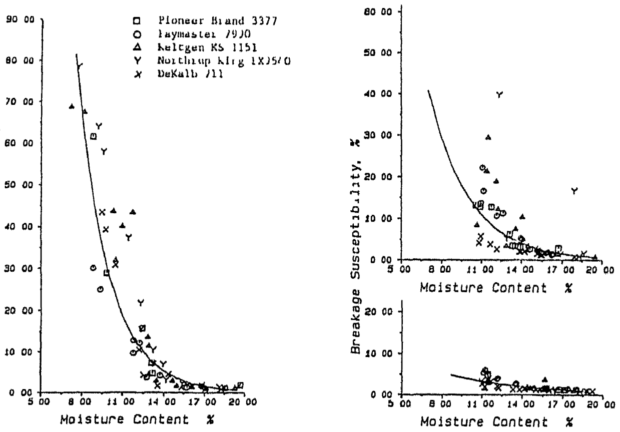

Figure 3. CK-2M SBT breakage susceptibility (% fines through a 4.76 mm or 12/64 in sieve) versus moisture content for five hybrids: left – corn dried at 110°C (230°F); top right – corn dried at 110°C (230°F) to 18% followed by ambient air; bottom right – corn dried with ambient air only. (Eckhoff et al., 1987).

Crane et al. (1959) found that slow drying hybrids had higher osmotic potential and exchanged water slowly when placed in a sucrose solution. Purdy and Crane (1967) and Stroshine et al. (1987) reported that hybrids with thinner pericarps had faster drying rates. Stroshine et al. (1987) found kernel pericarp thickness varied from 59.0 to 111.7 x 10^{-6} m (0.00232 to 0.00439 in.) and that drying time increased by 10% as pericarp thickness increased over that range. In tests with a high temperature column batch dryer Martins and Stroshine (1987) found that DeKalb T1100 kernels with physically damaged pericarps dried more quickly than kernels with pericarps with low damage.

One question of concern is whether genotypes which have lower breakage susceptibility dry more slowly than those with high breakage susceptibility. An analysis of data collected during five growing seasons between 1980 and 1984 showed no statistically significant correlation (at the 5% level of significance) between drying rates for constant temperature drying tests and SBT breakage susceptibility (Stroshine, 1989). Decreases in kernel density, kernel volume (cm^3/kernel) and pericarp thickness significantly decrease drying rate (Stroshine et al., 1987). Although decreases in density would increase breakage susceptibility (see "Effects of endosperm mechanical properties and kernel hardness on breakage") reduction of kernel volume would decrease breakage susceptibility (see "Effects of kernel size and shape on breakage") and pericarp thickness may not affect breakage susceptibility (Jennings 1974); therefore, it appears feasible to both increase drying rate and decrease breakage susceptibility by breeding.

Effects of Kernel Size and Shape on Breakage

Martin et al. (1987) determined breakage susceptibility for three commercial corn hybrids: Stauffer 8100, Stauffer 8500, and Bo-Jac 562. They were harvested with a combine at moistures between 19 and

23% and dried in bins in 4 to 5 days using ambient air. The three genotypes had average densities of 1.34, 1.32, and 1.29 g/cm^3, respectively. Log$_{10}$ of NIR values for the reciprocals of reflectance at 1680 nm were 358, 344, and 257 for the three hybrids, respectively. The genotypes followed a trend noted by several researchers: hard dense genotypes have higher NIR absorbance that soft genotypes. Similar NIR absorbance results were found by Weller et al. (1987). At 14.7% moisture content the Bo-Jac 562 genotype (least dense) had the highest CK-2M SBT breakage susceptibility (2.1%), while the Stauffer 8100 genotype (most dense) had the lowest breakage susceptibility (1.1%). The Stauffer 8100 genotype also had the lowest WBT breakage susceptibility (7.7%), while Stauffer 8500 had the highest with (9.1%). A comparison of the results of SBT and WBT tests, which were conducted on kernels at 14.7% moisture, revealed a large difference between the percentage of whole kernels with no damage. With the SBT, 75 to 88% of the kernels were completely whole after testing; while for the WBT only 12 to 16% were whole. This is indicative of the large amount of splitting of kernels which occurs with the WBT due to a large primary impact. There are often several secondary impacts as the kernels impact the WBT casing. However, in the SBT multiple impacts occur during the entire testing period and this produces fine material with smaller particles.

Martin et al. (1987) also categorized kernels from the three genotypes into rounds and flats and into size categories. Large round kernels from all three genotypes had the highest levels of severe damage (fast green dye test, kernels broken into pieces of less than one-half kernel) and breakage susceptibility for both SBT and WBT tests. The extra large flat kernels consistently sustained higher levels of severe damage than the small, medium, or large flat kernels for both SBT and WBT tests. The extra large flat kernels had slightly higher WBT breakage than the small, medium, or large flat kernels. For the flat kernels, SBT breakage did not appear to change with size. Pomeranz et al. (1986) investigated ten hybrids dried under mild conditions and three samples from commercial channels dried under various conditions. CK-2M SBT breakage susceptibility (6 min) was correlated to 100-kernel weight (r=0.54), indicating small kernels were more resistant to breakage than large kernels.

Effects of Endosperm Mechanical Properties, Kernel Hardness, and Kernel Density on Breakage

Extremely soft genotypes, such as those containing the opaque-2 gene have high amounts of breakage during handling (Alexander and Creech, 1977); extremely hard genotypes, such as flint corn, appear to be more susceptible to stress cracking than dent types (Paulsen and Hill, 1985; Kirleis and Stroshine, 1990). Yellow dent hybrids also vary in the ratio of vitreous to floury endosperm, which adds to the variability in kernel density, mechanical strength properties, and breakage susceptibility. Typically, a moisture deficiency during the kernel filling period may reduce starch content, producing smaller kernels with proportionately increased protein percentage. Low 100-kernel weights are often indicative of small kernels. Low test weights are often indicative of kernels having one of the following: inadequate moisture for filling, inadequate time for maturing, soft endosperm kernels, high moisture content, or high physical damage to the kernel pericarp. In many of the breakage susceptibility studies, it was reported that kernels with high SBT breakage values often had low test weight, and low 100-kernel weights. On samples of ten genotypes dried at ambient temperature, Pomeranz et al. (1986) found CK-2M SBT breakage susceptibility (6-min test) was negatively correlated (r=-0.74) with kernel density and test weight (r=-0.84).

Kirleis and Stroshine (1990) determined CK-2M SBT and WBT breakage susceptibilities, stress crack index, and milling evaluation factor (an index of suitability for dry milling) for FRB73 x Mo17, MBS73 x MBS847, and FR23 x FR140 genotypes grown in 1985. The three genotypes were rated as having soft, intermediate, and hard endosperm, respectively. SBT breakage susceptibility of the soft genotype increased as drying temperature increased (Figure 4). Conversely, WBT breakage increased most significantly for the hard genotype as drying temperature increased (Figure 5). An explanation is that as drying temperature increased, the hard endosperm corn became more severely stress-cracked than the soft genotype, allowing increases in WBT breakage susceptibility due to a high prevalence of stress cracks (Figure 6). Milling evaluation factor data indicated that the three genotypes were correctly classified for

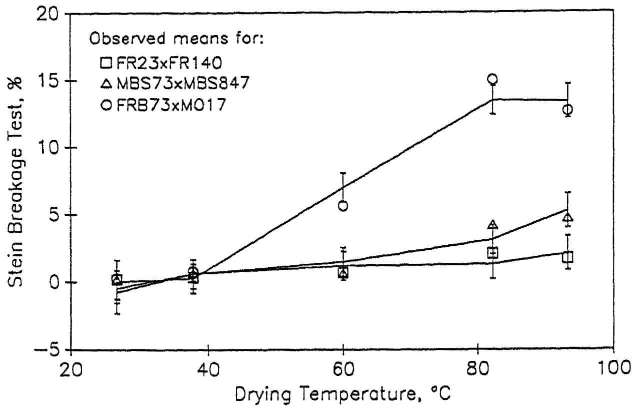

Figure 4. CK-2M SBT breakage susceptibility (% fines through a 4.76 mm, or 12/64 in, sieve) as a function of drying temperature for three dent corn genotypes. (Kirleis and Stroshine, 1990).

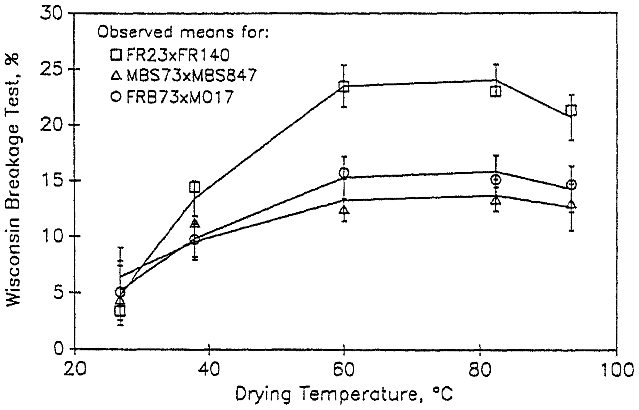

Figure 5. WBT breakage susceptibility (% fines through a 4.76 mm, or 12/64 in, sieve) as a function of drying temperature for three dent corn genotypes. (Kirleis and Stroshine, 1990).

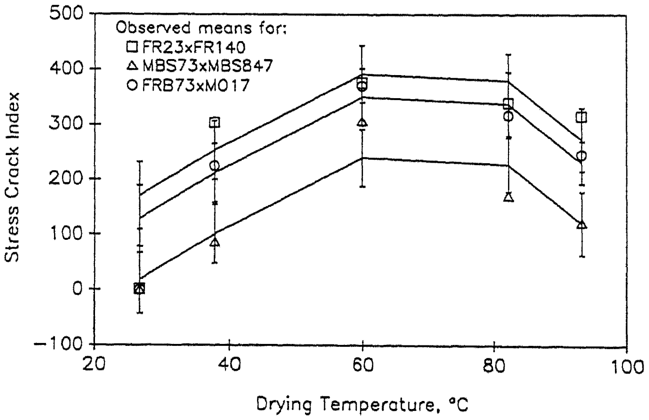

Figure 6. Stress crack index as a function of drying temperature for three dent corn genotypes. Stress crack index = 1 x % single cracks + 3 x % multiple cracks + 5 x % kernels checked. (Kirleis and Stroshine, 1990).

hardness. Of the two testers, the WBT showed the most sensitivity to increased severity of stress cracking.

Weller et al. (1987) determined breakage susceptibility using both the WBT and CK-2M SBT for four genotypes with a range of hardness: FR27 x FRMo17, B73 x LH38, LH51 x LH119, and FR27 x Va22. Corn was dried at 93, 71, 49, and 27°C (200, 160, 120, and 80°F) to 14% moisture content. The following results were based on averages for 48 tests for each genotype: WBT values were 5.2, 4.8, 7.1, and 11.5%, respectively; average SBT values were 0.6, 0.8, 0.7, and 1.5 %; kernel densities were 1.25, 1.26, 1.28, and 1.30 g/cm^3; and stress crack percentages were 67, 60, 75, and 77%, respectively. Thus, there was a tendency for high density (harder) single crosses to have a slightly higher percentage of stress cracks, and consequently higher WBT breakage susceptibility values (largely due to drying effects) than the lower density hybrids.

Gunasekaran and Paulsen (1985) investigated two genotypes and again found higher WBT values for the FRB27 x Va22 (hard) genotype than for the FRB27 x Mo17 (soft) genotype (Table 5). The genotype with the higher WBT breakage susceptibility had a higher test weight, higher true kernel density, and higher stress crack percentages than the low density (soft) hybrid. Under quasi-static compressive loading of individual kernels, the FRB27 x Mo17 cross required a much higher force (350 Newtons, 78.7 lbf) to reach the kernel bio-yield point than the harder FRB27 x Va22 cross (212 Newtons, 47.7 lbf) for corn dried at 20°C (68°F). The softer genotype (FRB27 x Mo17) also withstood much higher compressive energies (58 mJ, 0.51 in-lbf) than FRB27 x Va22 (32 mJ, 0.28 in-lbf). CK-2M SBT values for the hard hybrid dried at 20°C (68°F) were 2.14% compared to 2.54% for the soft hybrid. Thus, the hard-endosperm genotype had higher WBT values and lower CK-2M SBT values than the soft-endosperm genotype for corn dried at 20°C (68°F). As drying temperature increased, SBT breakage values increased by greater amounts for the hard genotype than for the soft genotype. Results of Slover (1986) support these observations. She found that WBT breakage was higher for flint corn than for dent corn while CK-2M SBT breakage was lower.

We propose the following explanations for the differing responses of the flint and dent kernels in the WBT and SBT. The maximum impact velocity of the CK-2M SBT is approximately 8 m/s (26 ft/s)

Table 5. Density, Drying Rate, Breakage Susceptibility, Bio-Yield Force, and Bio-Yield Compressive Energy as a Function of Drying Air Temperature for FRB27 x Mo17 and FRB27 x Va22 Genotypes. Kernels Equilibrated to 14% Moisture Content. Table adapted from Gunasekaran and Paulsen (1985).

Drying air temp, °C	Bulk density, kg/m^3 (lb/bu)	True density, g/cm^3	Drying rate, g H_2O/h-kg (lb H_2O/h-bu)	WBT, %	CK-2M Stein, %	Bio-yield force, N (lbf)	Bio-yield compressive energy, mJ (in-lbf)
			FRB27 x Mo17 (Soft)				
20	776.4 (60.3)	1.245	3.38 (0.189)	4.92	2.54	350.32 (78.8)	57.98 (0.513)
35	777.5 (60.4)	1.236	10.41 (0.583)	6.18	4.36	275.76 (62.0)	62.39 (0.552)
50	753.0 (58.5)	1.210	18.91 (1.060)	10.65	12.19	214.28 (48.2)	37.90 (0.336)
65	752.6 (58.5)	1.214	37.02 (2.075)	11.28	14.19	164.12 (36.9)	22.76 (0.202)
			FRB27 x Va22 (Hard)				
20	816.5 (63.4)	1.278	5.02 (0.281)	9.47	2.14	211.99 (47.7)	31.59 (0.280)
35	812.2 (63.1)	1.274	12.20 (0.684)	12.90	11.10	198.46 (44.6)	30.61 (0.271)
50	754.0 (58.6)	1.234	29.92 (1.677)	13.81	20.41	112.62 (25.3)	14.32 (0.127)
65	750.0 (58.3)	1.204	60.79 (3.408)	16.45	28.25	74.56 (16.8)	12.73 (0.113)

whereas the maximum velocity of the WBT is 22 m/s (72 ft/s). Therefore, a primary impact in the WBT creates greater kernel stress than the multiple impacts in the SBT. The data from Gunasekaran and Paulsen (Table 5) indicate that the failure force was always lower for the hard genotype than for the soft genotype. The hard genotype always had a greater WBT breakage and drying temperatures above 20°C (68°F) the hard genotype also had a greater SBT breakage. At drying temperatures above 20°C (68°F), the failure strength of the hard genotype may have decreased to the point that even the lower impact velocity in the SBT was sufficient to cause kernel breakage. A second explanation of the differences in response to the two breakage testers can be developed from the data presented by Kirleis and Stroshine (Figure 6). For drying temperatures above 38°C (100°F) there was more stress cracking in flint kernels. Kernels with stress cracks may fail more easily than kernels without stress cracks. The higher impact velocity in the WBT probably creates kernel stresses closer to the ultimate strength of kernels with stress cracks. This may cause a greater percentage of the flint kernels to fail in the WBT as a result of impact.

Breakage by Genotype in Combine Harvesting Studies

A relatively small amount of fine material is produced by harvesting corn with combines *if the combine is properly adjusted.* Paulsen and Nave (1980) determined the percentage of fine material in Golden Harvest 2500 harvested with three types of combines:

an axial flow, a twin rotor, and a conventional cylinder combine. The fine material was consistently less than 1%, severe damage (fast green dye test of Chowdhury and Buchele, 1976) was less than 15%, and SBT breakage ranged from 0.9 to 4.5%. However, genotypes differ in their tendencies to be damaged during harvesting. This is illustrated by data taken from Martins (1988). In his experiments, five genotypes were grown in the same field and harvested with an axial flow combine at moisture contents of 19.0 to 19.7%. The percentages of fine material generated varied from 0.1 to 0.6% (Table 6). Results of fast green dye tests on the samples were used to compute the values of damage index (Chowdhury and Buchele, 1976). Damage indices also varied among hybrids. Although B73 x Mo17 had a moderate percentage of fine material, it had the highest levels of severe and major damage and the highest damage index.

Differences in fine material produced by combine harvesting are related to differences in breakage susceptibility. Although combine harvesting may not generate large amounts of fine material it increases breakage susceptibility and thereby increases the likelihood of subsequent damage during harvesting. Racop et al. (1984b) examined the damage produced by combine harvesting of genotypes DeKalb XL55A and Funks G4435. They were grown in adjacent plots and harvested on the same day at similar moisture contents. CK-2M SBT breakage susceptibilities (4-min) were determined on samples taken from the grain tank and on samples harvested and shelled by hand (Table 7). The hand shelled samples of DeKalb

Table 6. Damage to Corn Hybrids Harvested in 1986 with an Axial Flow Combine with a Rotor Speed of 500 RPM. Table adapted from Martins (1988).

Hybrid	Harvest moisture, %	Fines, %	Damage				
			Severe, %	Major, %	Minor, %	None, %	Index
LH74 x LH123	19.5	0.3	3.8	3.3	11.9	80.7	16.5
Funks G4522	19.1	0.6	4.8	3.5	10.3	81.2	17.3
FR35 x FR20a	19.2	0.1	3.8	4.2	6.5	85.4	16.3
FRB73 x Mo17	19.7	0.3	5.1	5.4	7.4	81.1	18.3
DeKalb T1100	19.0	0.3	4.0	4.0	14.7	77.0	17.3

Table 7. Damage to Two Corn Hybrids Harvested with a Conventional Cylinder Combine. Table adapted from Racop et al. (1983) and Racop et al. (1984a, 1984b).

Hybrid	Harvest moisture, %	Fine Material %	Minor Damage %	Major Damage %	Severe Damage %	Damage Index	CK-2M Stein Breakage susceptibility, % (4 min.)	
							Combine shelled	Hand shelled
DeKalb XL55A	20.3	0.72[a]	17.8[a]	27.2[b]	5.45	31.1[a]	5.07[b]	2.94
Funks G4435	21.1	0.93[a]	24.7[a]	15.8[b]	4.15	25.1[a]	7.70[b]	3.64

[a] Denotes differences in a column are statistically significant at the P=0.05 level.
[b] Denotes differences in a column are statistically significant at the P=0.01 level.

XL55A and those harvested with the combine had lower breakage susceptibilities and lower levels of fine material in the grain tank than Funks G4435. Furthermore, the breakage susceptibilities of the samples harvested with the combine were approximately double those of the samples harvested and shelled by hand. DeKalb XL55A had greater percentages of severe and major damage than Funks G4435 but a lower percentage of minor damage. This suggests that Funks 4435 broke into smaller pieces.

Soybeans

Although the breakage susceptibility of corn has been extensively investigated there have been only a few studies on breakage in soybeans. Miller et al. (1981) found differences in CK-2M SBT breakage (4 min test) in two groups of soybean samples. They defined percent breakage as the percent by weight of material which passed through a 3.97 by 19.05 mm (10/64 by 3/4 in) slotted sieve. One of the two groups consisted of samples collected from commercial elevators. The samples had varying percentages of splits. The other group consisted of inspection samples collected by the Federal Grain Inspection Service. Miller and his coworkers found substantial differences in SBT breakage among the samples. Both moisture and temperature affected breakage. Between 6 and 12% moisture, SBT breakage increased between 1.35 and 2.16 percentage points for each percentage point decrease in moisture. As temperature decreased from 39 to 4°C (102 to 39°F), breakage increased linearly by 2% for sound soybeans and 6% for breakage prone soybeans. They also found a good correlation between SBT breakage and breakage resulting from impact of soybeans on soybeans at a velocity of 31.5 m/s (103 ft/s). Their study illustrated that soybeans differ substantially in breakage susceptibility but it did not relate differences to variety.

Relatively little work has been done to establish differences in breakage susceptibility of soybean varieties or to relate them to specific seed characteristics. The results of research with corn genotypes suggest that seed characteristics such as composition, seedcoat cracking, kernel size, and kernel density would affect breakage and that growing conditions and maturity group would also cause differences. However, most of the work has been done with the objective of investigating factors which affect the quality of soybeans used for seed rather than factors which affect susceptibility to breakage. For example, McDonald (1985) mentioned that the highest quality seeds were produced when there was adequate soil water availability. Potential for damage from freezing of seeds prior to harvest is a concern for some producers and McDonald found that once soybeans reach physiological maturity (55% moisture), freeze damage is rare unless the temperature drops substantially below 0°C (32°F). Freezing does not affect seed protein content but it does lower oil concentration.

Bartsch et al. (1986), who also studied seed quality, determined the effects of impact velocity, moisture and impact location on damage. They evaluated damage to Amsoy-71 and Williams soybeans caused by impact at five orientations, three moistures (8, 13, and 18%) and impact velocities of 5, 10, and 15 m/s (16.4, 32.8, and 49.2 ft/s). Seed damage was evaluated on 50-seed samples using the tetrazolium test and the results were used to compute a vigor index. The seeds were placed in one of eight categories. Categories with smaller numbers represented seeds with less damage. The vigor index was calculated by multiplying the number of seeds in each category by weighting factors of 10,8,6,4, and 0 for seeds in categories 1,2,3,4,and 5 or 6, respectively. Thus a high vigor index represented minimal damage to the seeds. The maximum vigor index was 500 (50 seeds x 10). They found that vigor index decreased with impact velocity, that impact to the seed radicle caused the most damage, and that impact to the side caused the least damage. Their results also suggested that there are varietal differences in susceptibility to damage. The Amsoy 71 seeds had a significantly higher vigor index than Williams seeds.

A Purdue University study by Stroshine and Wang (1984), demonstrated that soybean varieties differ in resistance to breakage and physical damage. Nine soybean varieties were compared. Soybean plants were cut at ground level, placed in plastic bags, and taken to a laboratory for storage at ambient temperatures. The soybeans were shelled from the pods by hand, cleaned, and stored at 2°C (36°F) prior to testing. One hundred fifty seeds from each variety were individually impacted using the impact tester developed by Bartsch et al. (1986). Results for 10 and 15 m/s (32.8 and 49.2 ft/s) impacts are shown in Table 8. At 10 m/s (32.8 ft/s), numbers of whole soybeans with damage and numbers of split and broken soybeans were relatively small even though moisture was relatively low. However, at 15 m/s (49.2 ft/s) between 26 and 60% of the whole soybeans were damaged and between 3 and 20% of the soybeans were split or broken. Numbers of whole soybeans with damage varied significantly among varieties at both impact velocities, but differences in numbers of split and broken beans were only obvious at the 15 m/s impact velocity. Hand-shelled samples were also tested for breakage susceptibility using the WBT. Varieties differed significantly in breakage susceptibility and samples high in breakage susceptibility also showed high levels of damage (low vigor) in the impact tests (Table 9).

Two studies by Paulsen indicate that seed size may affect the breakage susceptibility of seeds. Paulsen et al. (1981a) used a centrifugal impactor to impact Beeson, Corsoy, and Williams soybeans at controlled velocities. Percentages of split soybeans and fine material increased as impact velocity increased and as soybean moistures decreased from 17% to 8% moisture. Beeson, a large-seeded soybean, was more susceptible to damage from impact than the other two varieties. Paulsen (1978) measured the fracture resistance of Amsoy-71, Corsoy,

Table 8. Impact Damage to Soybeans. Moisture Content Ranged from 9.2 to 9.6% w.b. Data from Stroshine and Wang (1984).

Variety	Moisture wet basis, %	Whole soybeans with damage, %		Split and broken soybeans, %	
		10 m/s (33 ft/s)	15 m/s (49 ft/s)	10 m/s (33 ft/s)	15 m/s (49ft/s)
Hobbit	9.2	2.5	26.5	0.4	3.7
Lincoln	9.4	8.8	45.4	0.0	8.1
Cumberland	9.2	9.9	32.1	0.0	11.9
Corsoy	9.2	10.1	49.4	1.9	19.9
Williams	9.4	12.9	32.5	0.2	8.4
Pella	9.3	13.2	47.4	0.6	14.2
Wayne	9.3	15.0	49.9	0.0	11.0
Calland	9.6	17.7	32.9	0.0	12.8
Century	9.2	21.8	60.6	0.0	20.0

Table 9. Changes in Vigor Index and Percent of Good Seed after Impact at 15 m/s velocity. Percent Breakage Measured on the WBT for Soybeans at 9.2 to 9.6% w.b. Moisture Content. Data from Stroshine and Wang (1984).

Variety	Change in vigor index[a]	Change in percent good seed[b]	WBT, %
Williams	-518	-43.3	53.0
Hobbit	-535	-44.0	55.4
Cumberland	-564	-47.5	49.1
Calland	-873	-47.9	--
Lincoln	-668	-57.3	74.7
Pella	-664	-57.3	73.5
Wayne	-726	-70.2	74.0
Century	-863	-83.7	81.5
Corsoy	-815	-83.8	82.7

[a] One hundred seeds were evaluated using the tetrazolium test and the vigor index was computed using the weighting factor described by Bartsch et al. (1986). Maximum value of vigor index is 1000. Values ranged from 120 to 925.

[b] Percent good seed is defined as percentage of unbroken seeds which were evaluated as having no visible damage, or slight surface damage, or surface damage and internal damage away from the radicle. The controls typically had 98% good seed.

and Williams soybeans under compressive loading. Small soybeans absorbed more energy per unit volume (had a greater toughness) than larger soybeans. The force to cause seedcoat rupture was approximately equal among the varieties tested. No other studies could be found which related breakage susceptibility to specific seed characteristics.

One study demonstrated that soybean varieties differ in their susceptibility to damage during harvesting by combines. Paulsen et al. (1981b) harvested Beeson and Williams soybeans at combine cylinder speeds of 430, 600, and 750 rpm. The Beeson variety sustained higher percentages of splits and seedcoat cracks and had a higher SBT breakage susceptibility than the Williams variety at all cylinder speeds.

Summary and Recommendations

Corn genotypes vary in breakage susceptibility. In some situations, breakage susceptibility measurements and relative breakage susceptibilities are dependent on whether the SBT or WBT breakage tester is used for the evaluation. The WBT results appear to be very sensitive to differences in kernel stress cracking. Since hard endosperm corn develops stress cracks more easily than soft endosperm corn, and since hard endosperm corn tends to fail at lower values of applied force, WBT values are often higher for hard endosperm corn than for soft endosperm corn. A two to ten fold increase in breakage can occur as a result of drying with air at temperatures 20°C (68°F) or greater above ambient. Commercially available hybrids differ in breakage susceptibility after drying. However, there is some evidence that the magnitudes of the responses vary. In one study, breeding for improved stalk strength reduced breakage susceptibility.

Comparisons between hand-harvested hand-shelled samples and samples harvested with a combine suggest that combine harvesting approximately doubles the breakage susceptibility of shelled corn. The higher the harvest moisture, the greater the pericarp damage caused by the combine and the greater the increase in breakage susceptibility. There appears to be a "critical" harvest moisture below which the harvesting effect on breakage susceptibility is reduced. This critical moisture may vary among genotypes.

Cultural practices and relative maturity also appear to affect breakage susceptibility. Higher levels of nitrogen fertilization and decreased plant density tend to decrease breakage susceptibility. Genotypes from later maturity groups may have lower breakage and delayed planting of a given genotype may increase breakage susceptibility. For corn grown under dryland conditions, irrigation may increase breakage susceptibility.

Differences in breakage susceptibility have been related to differences in corn kernel characteristics. Genotypes with large round kernels tend to have higher breakage susceptibilities; and those with lower kernel weights tend to have lower breakage susceptibilities. Low kernel weight is often associated with smaller kernels which tend to break less than large kernels. However, low kernel weight can lead to higher SBT breakage if the kernel weight is low due to lack of kernel filling or low kernel density. SBT breakage decreases as kernel density increases and as kernel hardness increases. However, dense hard kernels are also more susceptible to stress cracking during rapid drying and this complicates the evaluation of breakage susceptibility.

Reduction of shelled corn breakage susceptibility through breeding appears to be possible. A significant reduction could probably be achieved by screening potential releases with a breakage tester. However, caution should be used when screening because it could lead to inadvertent introduction of undesirable traits such as slow drying rate. It appears to be possible to reduce breakage susceptibility without reducing drying rate. This is possible for the following reasons: (1) reduction in kernel volume reduces breakage susceptibility and increases drying rate, (2) reduction in pericarp thickness, which results in an increase in drying rate, does not affect breakage susceptibility, and (3) over five growing seasons, one study found no significant correlation between drying rate and SBT breakage. A breeding program focused on reduction of breakage susceptibility and improvement of other quality traits could be aimed at incorporating desirable kernel traits into high-yielding disease-resistant genotypes.

Although the breakage susceptibility of corn has been studied extensively, the breakage susceptibility of soybean varieties has received little attention. Soybean varieties do vary substantially in their resistance to breakage. Very few kernel physical properties have been linked to these differences. Varieties with large seeds are in general more susceptible to splitting and physical damage than those with small seeds. Additional research is needed to identify other important factors. Characteristics which should be studied include density, seedcoat cracking, seed composition (e.g., protein and oil), maturity group, and growing conditions.

Several important procedures should be followed to maximize the usefulness of future studies of breakage susceptibility of corn and soybeans. Comparison of results of existing studies is complicated by the diversity of growing conditions and genotypes studied. To facilitate such comparisons, future studies should include a set of standardized measurements including the following: 1000 kernel weight (adjusted to the basis of g dry matter), kernel true density, endosperm hardness (corn only), and pericarp or seedcoat damage. It would also be desirable to have information on average kernel dimensions (major, minor, intermediate diameters) and kernel shape (e.g., sphericity). For testing of corn, the effects of harvesting method should also be determined and a standardized drying test procedure should be developed and used. Finally, it would be highly desirable to include a "standard" genotype in any evaluation. In the case of corn, B73 x Mo17 would be an appropriate choice for studies conducted where a "full season" hybrid can be grown. Other genotypes could be chosen as standards for tests on corn with a shorter relative maturity. In the case of soybeans, a popular variety from each maturity group should be chosen.

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