

# *U.S. Corn*

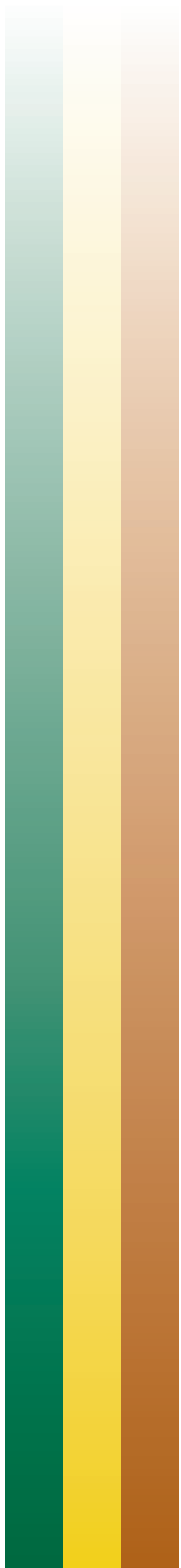
*Storage in Tropical Climates*





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# **Executive Summary and Recommendations**

## **Characteristics of U. S. Corn**

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**Appearance** Kernels of corn from the United States are larger and flatter than corn from some countries. A more rounded kernel is often indicative of a flint type grain, which is harder than U. S. corn. Yellow corn contains pigments (carotenes and xanthophylls) that impart the characteristic yellow color. U. S. corn usually has less of these pigments, and therefore is lighter in color than corn from other countries. This can result in a lighter-colored feed that may produce less yellow color in the skin of poultry and in the egg yolk. This is easily remedied by the addition of corn zein, gluten meal, or yellow/orange pigments from a variety of other sources.

**Hardness** U. S. corn is a semi-soft, dent corn that contains two types of endosperm cells in the same kernel. Part of the endosperm consists of cells containing a hard, crystalline combination of starch and protein. The remainder of the endosperm consists of a softer, more opaque starch and protein combination. Due to this characteristic, the high-yielding U. S. varieties tend to be softer and break easier than corn from some parts of the world. Softer grain requires less energy and less time to grind than harder grain.

**Nutrition** The protein, energy, and overall nutrient content of U. S. corn is similar to that of corn from other parts of the world.

**Moisture** Unlike most of the corn-exporting areas of the world, the majority of U. S. corn is produced where cold, wet weather prevails at harvest time and during the first six months of storage. Most U. S. corn is harvested at moisture contents too high for storage, and is dried in grain dryers. Most U. S. corn is stored cold at moisture contents of 14–17%. In order to meet an importer's specification of 14.5% moisture content maximum, the exporter often must aggressively seek and accumulate the low-moisture grain from the stocks available in storage.

## **Grades, Contract Specifications, and Storability**

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**Grades limit damage and BCFM** Most U. S. commodity corn is exported under contracts specifying US # 2 or better. The grade limit for U. S. # 2 is 3% Broken Corn and Foreign Material (BCFM), meaning that the grain leaving the export elevator for the ship must contain no more than 3%, on average, of material that passes through a 12/64-inch (4.8 mm), round-hole sieve. Damaged kernels (kernels discolored by the action of weather or disease) are limited to 5% for a U. S. #2. However, the average damaged kernel content of exported corn is less than 3%.

***U. S. grades do not limit moisture*** Moisture is not a grading factor because it is easily changed without changing the inherent quality and nutritional value of the grain. Therefore, it is important that importers in tropical countries limit moisture by contract specification if they must store the grain for more than a few weeks. A limit of 14.0 or 14.5% is usually not expensive, but is an important safeguard.

***Moisture and equivalent value*** Moisture adds weight without adding nutrients, i.e. proteins, starches, fats, vitamins and minerals. The equivalent value of grain at any moisture content can be calculated by multiplying the price per ton by the dry weight ratio at the different moisture contents. Consider the example of a buyer who is willing to pay \$120/ton for some commodity at 15% moisture. If he purchased the same commodity at 14% moisture content, he would receive more nutrients per ton. The dry weight ratio in this example is  $(100\% - 14\% \text{ m.c.}) / (100\% - 15\% \text{ m.c.}) = 1.01176$ . The equivalent value per ton of the commodity at 14% moisture content is  $\$120 * 1.01176$ , or = \$121.4/ton. In other words, at 14.0% moisture content and \$121.4/ton the buyer pays no more per kilogram of nutrition than at \$120/ton for the same commodity at 15% m.c.

## Fine Material

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***Definitions*** Fine material in corn consists of particles significantly smaller than the kernels themselves. Most fine material in U. S. corn consists of broken pieces of corn, and has about the same nutrient quality as the whole grain. Spoutlines are the accumulations of this fine material beneath the spout where the grain is dropped into a container. Spoutlines in corn have been shown to contain five times or more fine material than grain in other parts of the mass.

***Screening*** Corn is passed over screens to scalp the material larger than the corn and remove most of the fine material. If corn is screened (cleaned) before storage, there is less fine material to accumulate in the spoutline, and storage management is simplified.

***Flow patterns*** If corn is not cleaned to remove the fine material, management of fine material depends on the type and configuration of the storage bin. Grain in upright concrete bins tends to exit the bin in a pattern called mass flow, wherein grain is discharged from the bin in about the same order it entered. Wide, short bins with flat floors, such as the corrugated metal bins common at feed mills in tropical countries, exhibit a pattern called funnel flow. In funnel flow, the column of grain immediately above the withdrawal port is the first to exit. Soon, grain at the surface above the withdrawal port exits, forming an inverted cone at the grain surface. In funnel flow, much of the last grain to enter the bin is the first to be withdrawn. In flat-floor bins, a large quantity of grain remains in the bins against the bin walls after the grain has stopped flowing by gravity.

**Coring** In bins with a center entry spout and a center discharge port, the “core” of grain should be removed shortly after the bin is filled. This leaves an inverted cone, rather than a peak, at the grain surface. This simple and inexpensive practice removes much of the spoutline and greatly facilitates maintenance of grain quality.

## Moisture

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**Condensation** When cold grain is moved through warm, moist air, liquid water sometimes condenses on the grain surface. This is sometimes observed when cold grain is unloaded in tropical ports. The grain quickly absorbs this moisture. If the grain remains cool for several days or weeks, the increased moisture content and inter-granular relative humidity have little negative effect, and the increase in moisture content is minor. However, this recently-absorbed water, held mostly in the outer layers of the kernel, may cause electronic moisture meters to overestimate grain moisture.

**Effect of moisture on rate of deterioration** High-moisture grain produces a high relative humidity in the air between kernels. This allows molds to grow and respire rapidly. Each percentage point of moisture greater than 14% increases the rate of grain respiration and deterioration by a factor of about two at the temperature range encountered in tropical storage.

**How moisture moves** Moisture may migrate and concentrate in one area of the grain mass. Moisture moves in vapor form along vapor pressure gradients produced by temperature differences from one part of the mass to another. Moisture can also move in air currents driven by wind and chimney effects. In tropical climates, moisture migration is most likely to be a result of one of the following.

**Aeration.** Poorly managed aeration is likely to cause moisture accumulation in parts of the grain mass. Examples of poorly-managed aeration include aerating cool grain with warm, moist air or maintaining grain temperatures above the average ambient temperature by aerating only during warm times of the day.

**Hot spots.** When molds begin growing rapidly in one area of the grain mass they generate heat, increasing the grain temperature and producing a “hot spot.” Moisture produced by the deterioration is carried by currents of rising hot air or along concentration gradients to cooler areas of the grain.

**Shade effects.** In tropical locations, the inner wall of shaded areas of the bin often develops layers of darkened, crusted grain that clings to the wall upon grain withdrawal. This spoilage is believed to be a result of the concentration of moisture in cooler areas of the bin.

## Temperature

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***Why temperatures change*** In tropical storage, the temperature of imported grain changes for two reasons. Either the grain arrived cooler than ambient conditions and is slowly warming to equilibrium with those conditions, or the grain is heating internally. The reason for the change can be discovered by observing the pattern of the temperature changes within the mass.

***Effect of temperature on rate of deterioration*** Above the threshold limits for mold growth, the rate of grain respiration and deterioration depends on grain temperature and moisture content. At common grain moistures, each 10 °C increase in grain temperature causes the rate of respiration and deterioration to increase by a factor of three.

***Temperature gradients*** Temperature gradients exist when the temperature of the grain is different from one part of the grain mass to another. Because grain is a poor conductor of heat, large differences in temperature may sometimes be found over just a few centimeters of grain. Temperature gradients are produced when one part of the grain mass is heating or when grain of two very different temperatures is placed in the same bin. Gradients also occur when cold grain is placed in a metal bin in warm climates. In this case, the upper and outer surfaces of the mass warm first, and the warmer temperatures slowly advance inward toward the center of the mass. This type of gradient is not a threat to grain quality in the short term because moisture tends to move toward the cooler areas that are protected from deterioration by their lower temperatures. However, the opposite type of gradient, where grain is warmer than the ambient temperature, often promotes deterioration within a few weeks.

## Grain Pests

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***Contamination caused by pests*** Insects contaminate grain with body parts and feces. Contamination with urine and feces of rodents, and the feces of birds may introduce disease organisms into the grain. These may be carried into the feed.

***Managing birds and rodents*** Rodents and birds are problems when grain is stored in open sheds. A barrier wherein vegetation is removed and water is not available should be maintained around the warehouse. Rodent and bird feces should be removed when possible so they do not contaminate the grain and carry into the feed. Birds are a special problem at ports, where they may contaminate the grain before it arrives at the warehouse. Routine feed analysis for *Salmonella* and other disease organisms is recommended.



**Managing insects** Feed manufacturers usually are not especially sensitive to insect presence in raw grain. However, many importers of U. S. corn produce flour, seed, or milled rice at the same location as the animal feed, so it is important to minimize infestations in raw feed ingredients, including corn. U. S. corn may contain no more than nine live insects per kilogram of sample without receiving the special designation “infested.” Most exported corn contains a much lower insect density. However, in a processing plant that is especially sensitive to stored-grain insects, it is best to limit infestation levels through contract specifications or by specifying in-transit fumigation. Once in-country, the most efficient method of managing insects includes a sound sanitation and monitoring program, use of aeration to maintain the grain temperature below the average daily ambient temperature, and limiting the amount of time the grain is stored under tropical conditions.

**Managing molds** Molds cause most of the heating, caking, and deterioration experienced in corn during tropical storage. They are managed by controlling the moisture content and temperature of the grain, thus limiting their ability to grow. Mold inhibitors are available in many countries and often are used to retard spoilage in the finished feed. The application of mold inhibitor to the grain before storage helps retard heating, reduce the rate of mold growth, and preserve dry matter. It is most cost-effective in cases where the mold inhibitor is added to the finished feed anyway or in the humid lowland tropics, where storage for longer than two months is especially difficult. Mold inhibitors should not be expected to kill all the molds or stop heating that has already begun. Mold inhibitors cannot destroy mycotoxins or remove them from the grain.

## **Mycotoxins**

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**Sources of mycotoxins** Mycotoxins are toxic substances produced by molds. Mycotoxins are sometimes found in cereal grains. All U. S. corn is tested at export for aflatoxin, the most common toxin in corn. Corn containing more than 20 parts per billion cannot be loaded.

**Field fungi toxins** Certain fungi, including those of the genus *Fusarium* commonly grow in corn plants. It is common and unremarkable to find these fungi in the outer tissues of freshly-harvested corn kernels. The continued presence of a high percentage of *Fusarium*-infected kernels usually indicates that the grain has been stored under good conditions. This is because the same storage conditions that promote the growth of storage fungi tend to cause the death of *Fusarium* fungi in the seed.

*Fusarium* fungi cause stem rots, ear rots, and other plant diseases, depending on environmental conditions. The growth of these fungi also can result in the contamination of the seed by mycotoxins. Deoxynivalenol (DON), fumonisin, T-2 toxin, and zearalenone are examples of this type of toxin and are sometimes found in the harvested grain. Contamination by mycotoxins usually is a localized phenomenon present in some crop years and not in others. Because nearly 80% of all U. S. corn is used domestically, the presence of these substances and location of problem areas typically is discovered long before any contaminated grain enters export channels.

***Storage fungi toxins*** Some fungi, principally *Aspergillus* spp. and *Penicillium* spp. specialize in attacking seeds in storage. Certain species of these genera can produce toxins under rare conditions. Well-managed storage prevents the production of mycotoxins. The same good storage practices that maintain grain quality prevent mycotoxin contamination.

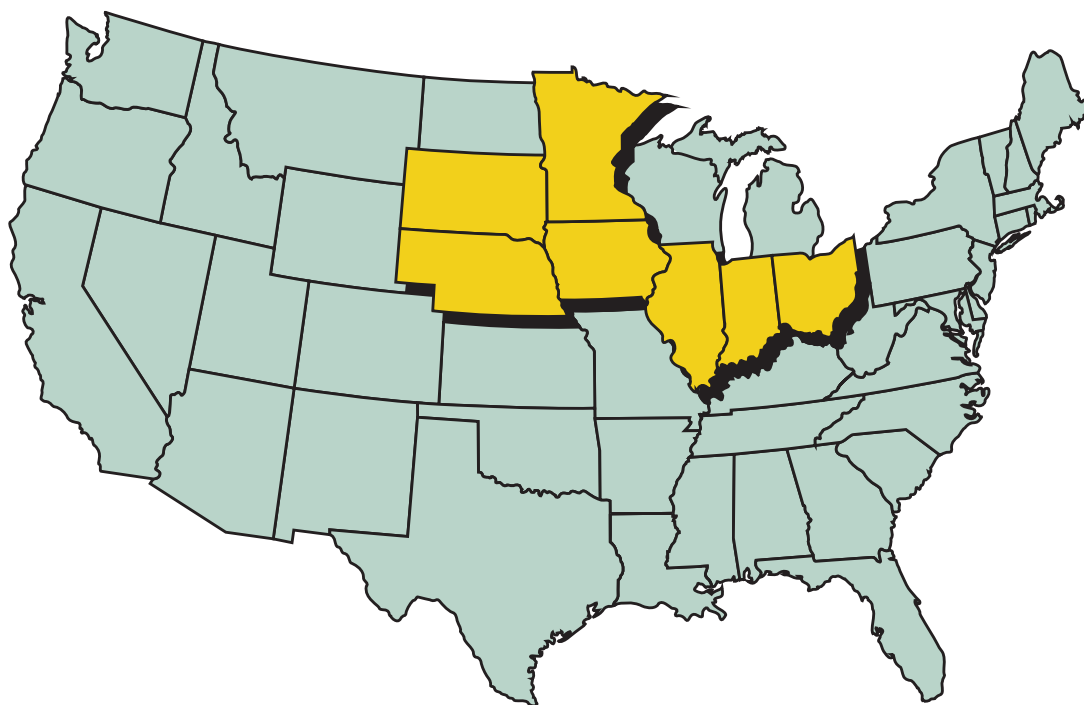
***Mycotoxin testing*** A variety of test kits are available commercially to analyze for mycotoxins in raw feed ingredients after storage. Routine sampling and testing help assure a toxin-free feed.

# *Characteristics of U. S. Corn*

## **Production**

Corn has been the largest crop in the United States for more than a century. More than 70% of all U. S. corn is grown in the temperate “corn-belt” states of Iowa, Illinois, Nebraska, Minnesota, Indiana, Ohio, and South Dakota (Figure 1). This part of North America is one of the world’s most productive agricultural areas because of its deep, fertile soil, flat or rolling topography, adequate rainfall, and long growing season. High-yielding, hybrid seed is planted early in the North American summer, and the crop is harvested as the cold, winter season begins.

**Figure 1. More than 70% of all U. S. corn is grown in these temperate-climate states.**



A vast network of resources is available to help U. S. corn producers maximize the yield and quality of their crop. Private and public entities annually invest millions of dollars in seed breeding programs. Private industry and the U. S. Cooperative Extension Service provide a variety of information related to tillage, fertilization, and pest control. Test fields allow farmers to observe side-by-side variety tests, and to review yield and quality data. Many of the world’s largest and most progressive manufacturers of agricultural machinery compete for the farmer’s business, offering the most advanced tillage, pest control, and harvesting technology.



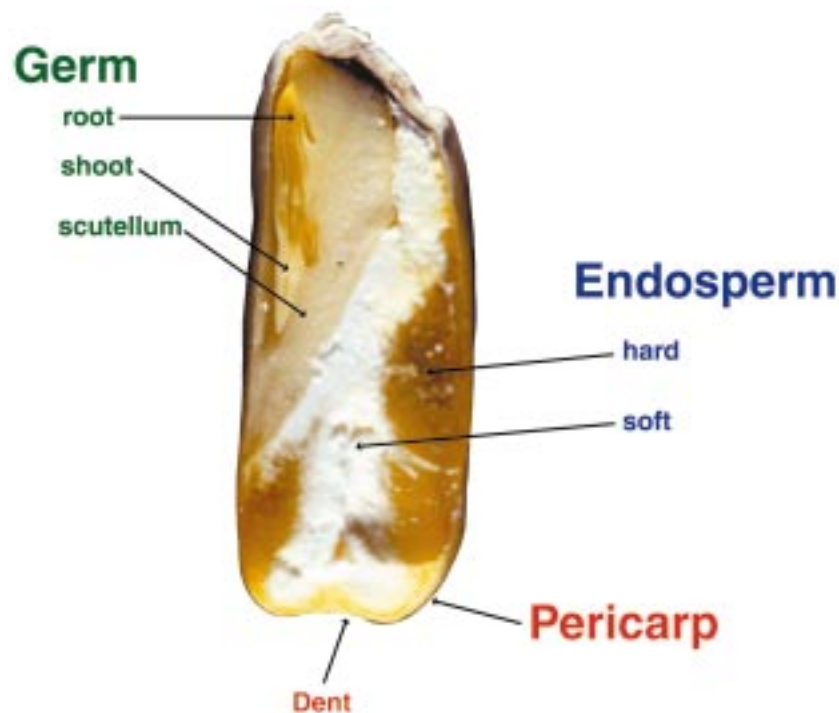
## Marketing

Some corn is transported directly from the field to grain elevators that provide drying and storage services. Other corn is stored on farms. Many farms have grain dryers and large grain bins. More than 20% of the U. S. corn production is exported. Most of this corn moves by river barge to export elevators on the Gulf of Mexico, but large quantities also are also transported by rail to export elevators on the east and west coasts of the U. S.

## Quality

Like other grasses, the corn kernel contains a pericarp, a fibrous outer covering produced by the mother plant to protect the seed (Figure 2). Inside the pericarp are the two most important structures of the seed, the germ and the endosperm. The endosperm contains the storehouse of energy-producing starches and other carbohydrates that the new plant requires when the seed germinates. The germ contains embryonic plant tissues, including a root and a shoot, and a structure called the scutellum that facilitates the supply of nutrients and cell-building materials to the new plant when the seed germinates.

**Figure 2. Internal structure of a kernel of U. S. corn.**



Because these structures have different purposes, they contain different kinds of nutrients. The pericarp represents only about 5% of the total weight of the corn kernel, but contributes almost all of the fiber. The germ represents about 13% of the weight of a kernel of commodity corn, but contributes about 85% of the lipids (fats and oils) and nearly one-quarter of all protein. The endosperm, which represents more than 80% of the total weight of a commodity corn kernel, consists almost entirely of starch and protein.

U. S. hybrid corn varieties produce kernels with two kinds of endosperm and a pronounced dent at the end opposite the germ. The endosperm consists of large cells with very thin cell walls. Inside the translucent (hard) endosperm cells, starch granules are tightly compacted. The compacted starch and the type of protein between the granules produce the glass-like appearance and the brittle texture. In the opaque (soft) endosperm, starch granules are more spherical, allowing for small air spaces between them. The tiny air spaces and the type of protein contribute to the opaque appearance and the softer texture.

The varieties used in the U. S. are developed for high yield potential, resistance to disease, and good nutritional quality. They are semi-soft types with a pericarp that happens to contain a relatively low concentration of yellow and orange pigments (carotenes and xanthophylls). The semi-soft endosperm and the relatively pale yellow color are of little consequence to the domestic market, but are of interest to many foreign buyers of U. S. corn. The endosperm type contributes to the tendency of U. S. corn to break during handling after high-temperature drying. This creates a challenge for importers because of the repeated elevations, impacts, and mechanical forces experienced by the grain during the handling required for export. Small pieces of the soft endosperm are ground into flour during export handling, creating the white dust familiar to importers. In some markets, the low carotene content means that additional pigments must be added to poultry feeds in order to produce the desired color of eggs and meat.

## **Export Condition**

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Several factors affect the storability of imported grain. Most importers of U. S. corn specify a maximum grain moisture content. This is a recommended practice because it provides a measure of control over one of the most important parameters affecting the rate of deterioration. In recent years, the average moisture content of exported U. S. corn has been about 14.3%, probably because of the 14.5% maximum moisture specifications in most contracts. Of all the corn grown in the U. S., the corn most likely to be exported is that grown near the rivers upon which it is transported to the export elevators. In this part of the corn belt, corn is likely to be harvested when it contains at least 20% moisture. Typically, the corn is dried in grain dryers and stored at 15–17% moisture. During subsequent aeration and storage through the cold, winter months, the grain dries further. Grain lots from various origins and having different characteristics are blended to meet the moisture content, bulk density, and other specifications of the export contract.

Other characteristics important to storability are the percentage of broken kernels and damaged kernels. The average broken corn and foreign material (BCFM) content of exported U. S. corn is 2.7%, and the average damaged kernel content is 2.7%. These quality factors are presented on the U. S. grade certificate.

Another parameter important to tropical storage of U. S. corn is the number of kernels infected by storage molds. This information is not provided on the grade certificate because the test requires several days. Mold infection is a function of the grain storage and handling history, including the length of storage, moisture and temperature during storage, and the blending that has occurred during export handling. Recent research shows that the percentage of kernels infected by the most important storage molds varies by season in exported U. S. corn (Figure 3). When the infection rate is high, successful storage under tropical conditions is more difficult. It appears likely that from January to June, U. S. corn will tend to be more easily stored under tropical conditions. From July or August through November or December, more precautions may be necessary for successful storage.

**Figure 3. Percentage of U. S. corn kernels infected with species of the storage mold *Aspergillus* at destination ports.**





# ***Corn Quality and Value***

## **Grades**

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The majority of U. S. corn is purchased as grade U. S. # 2. The grade certificate is the buyers' guarantee that the samples have been taken and analyzed by Federal Grain Inspection Service (FGIS) employees who are trained, certified, and supervised in their jobs; that the samples have been handled according to FGIS standards; that the apparatus used in grading has been certified and maintained; and a long list of further guarantees. The FGIS is part of a federal government agency called the Grain Inspection, Packers, and Stockyards Administration (GIPSA). The U. S. corn grades are well known and are shown in Appendix I.

Test weight is the weight of corn that occupies a standard volume. It is reported in pounds per bushel and can be converted to kg/hl by multiplying the lb/bu by 1.28. BCFM is the material that falls through a 12/64-inch (4.8 mm) round-hole sieve when a randomized sample of approximately 250 g is shaken on the sieve in the prescribed manner. It also consists of all pieces of stalk, cob, or other material that is not corn and that does not fall through the sieve. All corn kernels that remain on the sieve, even if they are obviously broken, are considered whole corn under the U. S. standards.

Damaged kernels have a long and very detailed definition given in the FGIS handbooks. Not every kernel that has an unusual, misshapen, or darkened appearance is considered damaged. Mechanical damage is not considered damaged. Some types of insect chewing are not considered damaged. Basically, only kernels deteriorated by molds or insects to a degree that might affect their nutritional quality are considered damaged.

Grade factors supply only limited information, especially in the case of corn. Test weight is a measure of compactness and kernel density, but is not necessarily an accurate predictor of milling characteristics or nutritional quality. BCFM conveys information about the amount of fine material but does not necessarily indicate storability. If a sample contains a large percentage of damaged kernels, it indicates that at some point in time, some deterioration occurred. However, a moderate level of damaged kernels (less than 10%) does not necessarily mean that the grain has inferior feeding value.

## Moisture Content

Moisture content is not a grading factor, but is given as an information factor on grade certificates. In general, there is an inverse relationship between moisture content and price. In order to evaluate the added value of a dryer commodity, the equivalent value may be calculated. Moisture adds weight without adding the proteins, starches, fats, vitamins and minerals that are the desired components of the corn. The equivalent value at any moisture content can be calculated by multiplying the price per ton by the dry weight ratio at the different moisture contents.

Consider the example of a buyer who is willing to pay \$120/ton for some commodity at 15% moisture. If he purchased the same commodity at 14% moisture content, he would receive more nutrients per ton. The dry weight ratio in this example is  $(100\% - 14\% \text{ m.c.}) / (100\% - 15\% \text{ m.c.}) = 1.01176$ . The equivalent value per ton of the commodity at 14% moisture content is  $\$120 * 1.01176$ , or = \$121.4/ton. In other words, at 14.0% moisture content and \$121.4/ton the buyer pays no more per kilogram of nutrition than at \$120/ton for the same commodity at 15% m.c.

## Nutritional Value

Typically, U. S. commodity corn contains 8–10% protein, about 3% fiber, 3–5% oil, and a net energy content for growth of about 2 Mcal/kg. High-oil corn and other specialty corns have a significantly different distribution of nutritional components. Screening (cleaning) before storage is recommended to minimize particle-size segregation and resulting accumulations of fine material. The nutritional value of various size fractions varies slightly (Table 1). In Table 1, the feed value of the whole corn is set to a value of 100 to demonstrate relative differences. Both broken kernels and corn dust are good feed ingredients. The dust contains nearly four times the amount of fiber and about 90% of the protein and energy compared to whole corn.

**Table 1. Nutritional value of BCFM and dust in U. S. corn as compared to whole corn.**

Size	Energy	Protein	Crude Fiber
Whole corn	100	100	100
BCFM (<4.8 mm)	95	105	155
Dust (<1.8 mm)	90	88	368

Adapted from Bern and Hurburgh, 1992

# **Tropical Storage of U. S. Corn**

The client who imports U. S. corn into a tropical environment faces a more difficult storage challenge than do his counterparts in the country of origin. This is because a) the repeated handling associated with exported grain has produced more breakage and dust, b) the ambient temperature is higher than in the country of origin, and c) the relative humidity is often higher in the tropics than in the U. S. To deal with these challenges, it is helpful to understand the physical, chemical, and biological factors that affect grain deterioration in storage.

## **Temperature, Moisture Content, and Deterioration**

In general, heat and water are the enemies of grain quality in storage. Even in temperate climates, grain temperature and moisture content dictate the rate of deterioration and loss. Table 2 shows that if 13% grain moisture content and 20 °C is taken as the reference condition, a hypothetical lot of exported corn is assumed to have 100 days of storage before a given amount of grain respiration and deterioration occurs. The numbers in the table are the equivalent days of safe storage for the same corn at higher temperatures and moisture contents. Increasing the temperature of the 13%-moisture corn to 30 °C reduces the number of safe storage days to 35 because the grain deteriorates three times faster at the warm temperature than at the reference conditions. The safe storage time at 25 °C is about 5 times less at 15% moisture content than at 13% moisture content

**Table 2. Days of safe storage time as affected by temperature and moisture content.**

Temperature (°C)	Grain Moisture Content (%)		
	13.0	14.0	15.0
20	100	41	20
25	59	24	12
30	35	15	7
35	21	9	4

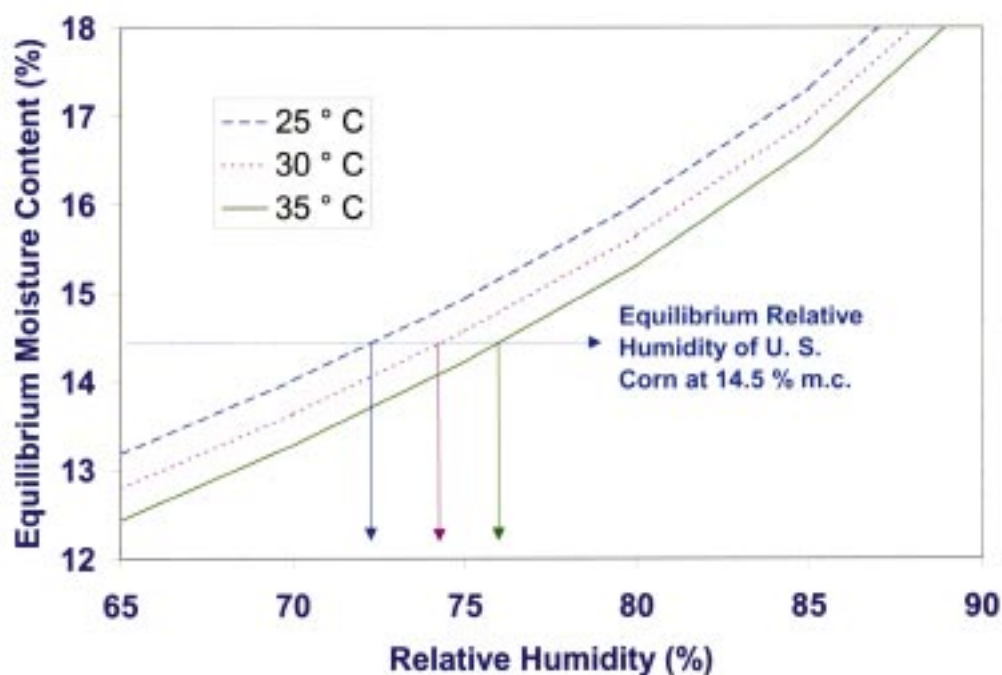
Adapted from Thompson, 1972



## Equilibrium Grain Moisture and Air Relative Humidity

Moisture in the air and grain affect several aspects of tropical handling and storage of exported U. S. corn. The American Society of Agricultural Engineers standard D245.4 for equilibrium moisture content is demonstrated in Figure 4. The equilibrium relative humidity for U. S. corn at 14.5% m.c. is shown. The higher levels of breakage present in exported corn would alter the relationship slightly, resulting in a lower equilibrium relative humidity at this moisture content.

**Figure 4. Equilibrium moisture contents, as estimated by the Chung-Pfost equation, for U. S. corn under tropical conditions.**



ASAE standard D245.4

Interpretation of the figure depends on the storage situation. Inside a grain mass where air does not move, such as inside an unaerated bin, the figure predicts the equilibrium relative humidity of the air between kernels. In contrast, when air movement is unrestricted, or if the amount of grain is small relative to the amount of air, tendencies in grain moisture change based on air relative humidity can be predicted.

For example, if corn containing 14.5% m. c. is stored in a bin with little air exchange, the relative humidity of the air between the kernels will be brought to about 73% if the grain and air temperature are 25 °C, and about 77% if the grain and air temperature is 35 °C. This is important because both high relative humidity and high temperature facilitate the growth of storage molds that deteriorate the grain. Also, if corn at 14.5% m. c. is in contact with large amounts of tropical air, such as at the surface of grain in a

flat warehouse, and if the air and grain are both 30 °C, then a relative humidity higher than about 74% will tend to wet the grain, and a relative humidity lower than 74% will tend to dry it.

These relationships relate to equilibrium conditions only. If the grain temperature is different than the air temperature, such as in the case of cool air used to aerate warm grain, the equilibrium curves do not apply. For example, it is false to conclude that, in order to cool corn with a temperature of 35 °C, air having a relative humidity of less than 77% must be used in order to avoid wetting the grain. Misinterpretations of this relationship are common, and often have led to unsound aeration practices. Examples of how to use information provided by equilibrium equations when aerating grain in the tropics are given in Appendix III.

## Condensation

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Knowledge of air relative humidity and grain equilibrium moisture relationships is also useful to understand condensation associated with the handling and storage of imported U. S. corn in tropical climates. Condensed water often is observed on grain transport equipment when cold corn is unloaded from vessels and transported under tropical conditions. In the North American winter, grain frequently is cooled to near zero °C during storage. Although it typically warms during domestic transport and ship-loading, it often arrives in tropical ports at a temperature at least 10 °C colder than the ambient air. Contact between this cold grain and metal machinery cools the metal until water condenses on its surface.

At the boundary between the grain and the tropical air, the relative humidity of the air increases as the air cools. Sometimes liquid water is observed on the grain. Even if liquid water is not seen, the nearly-saturated air of the cold boundary layer gives up water vapor to the grain. This water tends to be held in the outer layers of the grain, increasing the relative humidity of the inter-grain air even if it does not affect the moisture content of the grain. Recently-absorbed water is held in the outer layers of the grain causing electronic moisture meters to overestimate the grain moisture.

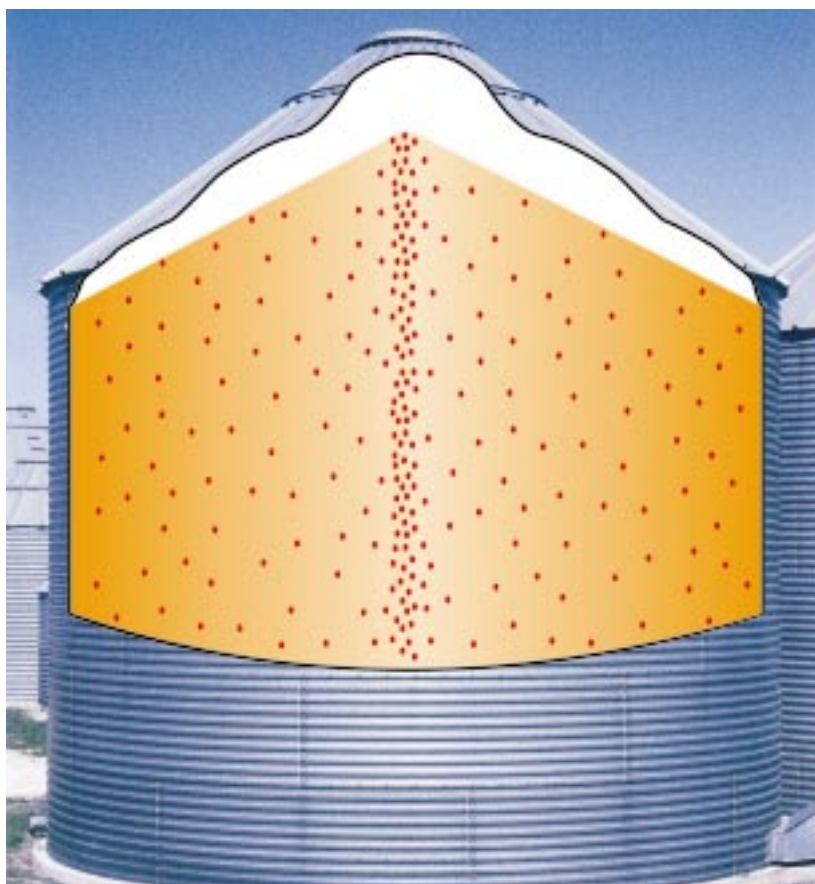
Another condensation phenomenon sometimes associated with imported U. S. corn is observed on the underside of the bin roof when grain is aerated. If a positive-pressure aeration fan is used to push air through warm grain toward the grain surface, condensation may occur on the bin roof, resulting in water falling onto the grain surface. This is most likely to occur in metal bins when the temperature of the grain is several degrees higher than that of the ambient air. The problem is resolved by installation of extraction fans that mix outside air with the air leaving the grain surface. This reduces the temperature and relative humidity of the air in contact with the cool metal surface.

## Fine Material

Although the fine material and dust in exported U. S. corn are good feed ingredients, their presence can cause problems in storage unless the condition is handled properly. When grain falls into a bin from an overhead spout, it creates a pile shaped like a cone with the peak approximately beneath the spout. Larger, denser particles tend to roll down the pile whereas small and less dense particles tend to be trapped between kernels near the peak. This creates an accumulation of fine material, called a “core” or a “spoutline,” beneath the peak.

Most grains produce pockets of fine material or light material when loaded into bulk storage bins. However, corn, because of its tendency to break, is likely to have a more pronounced concentration of fine material in the center grain column than other grains. The repeated handling associated with export accentuates the effect. Even in corn that was not exported, researchers have described cases in which the spoutline of corn contained six times the amount of fine material than the grain as a whole. In most metal bins, the spoutline is located in the middle of the grain mass because usually the bin loads from the center (Figure 5). In the upright bins of concrete elevators, which usually load close to the inside wall, the spoutline is located near the inside wall. In flat warehouses, a spoutline is located wherever the grain is peaked (Figure 6).

**Figure 5. Illustration of a spoutline in a metal grain bin.**





Spoutlines provide the ideal place for grain deterioration to start. The accumulation of broken kernels provides a very accessible source of food to the molds that cause heating and caking. The small particles are also densely packed, which traps within the spoutline the heat and moisture produced during mold growth. This additional heat and water promotes further mold growth and deterioration.

In addition to the increased natural tendency of spoutlines to foster deterioration, they also defeat aeration. Air forced through a grain mass by an aeration fan follows the path of least resistance. Therefore, it flows more easily through the cleaner grain where the spaces between kernels are not obstructed. Much of the space between the kernels in the spoutline is occupied by fine material, creating a greater resistance to airflow. In addition, the spoutline is located beneath the grain peak, where the distance that the air must travel to exit the grain is longest. The effect of spoutlines and peaked grain on aeration efficiency is more pronounced in larger bins. Research has shown that, in bins (14.5 m diameter), where the peak was about 2.5 m tall, the rate of airflow through the cleaner grain near the bin wall was 23 times that of the peak. Many examples have been described wherein grain in the spoutline and peak continued to heat and deteriorate during aeration with cool air. In these cases, it is likely that all of the air passed through the clean grain and none penetrated the compacted grain in the peak.

**Figure 6. Illustration of spoutlines in a flat store or warehouse.**



## Molds

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Field Fungi Molds are one of many types of microscopic organisms present in nature. Because stored grain is not a suitable medium for the growth of the other microorganisms (i.e. bacteria), only molds (fungi) will be discussed. Many types of molds live in soil and invade growing plants, hence the name “field fungi”. Some of these molds cause plant diseases, depending on environmental conditions, whereas others appear to cause no damage. Some live in the roots, stems, or leaves, whereas others also invade the seed.

It is common for various species of the *Fusarium* molds to invade corn plants in the field. These molds are routinely present in the roots and stems, and often are present in the reproductive organs where the seeds are formed. Usually, the molds do not interfere with the normal growth of the plant. However, some types of *Fusarium* cause blights or other diseases, depending on the weather during the growing season. These plant diseases occur when the molds synthesize a high level of certain chemicals that interfere with the functioning of the plant cells. In some cases, the substances produced by the molds in the plant tissues do not harm the plant. Rather, they produce sickness in animals that eat the contaminated plant part. Mycotoxins such as deoxynivalenol (DON, or vomitoxin), zearalenone, moniliformin, and fumonisins are produced by certain *Fusarium* species, and are deposited in the seeds. These toxins remain in the grain even if the mold dies or becomes dormant.

The field fungi, including *Fusarium* spp., *Alternaria* spp., and others, can grow only when the growth medium contains at least 20 to 25% moisture. Plants and developing seeds typically contain 50% or more water, making them excellent media for these microorganisms. Eventually, the corn plant dies and dries to a moisture content too low for the molds to grow. Corn seeds also dry until the field fungi can no longer grow. However, these fungi do not die. Rather, they produce various dormant structures that can survive for long periods under dry conditions.

Dormant structures of *Fusarium* and other field fungi often are present in the plant tissue that becomes the outside covering (pericarp) of the new grain kernel. When sound, recently-harvested corn kernels are analyzed in the laboratory for molds it is normal and common to find that most of the kernels contain viable structures of the field molds. Thus, the presence of a large number of *Fusarium* or *Alternaria*-invaded kernels does not indicate spoilage or poor storage conditions. Nor does it mean that enough toxin is present to cause feeding problems. Rather, it may indicate that the grain has been kept under good storage conditions. The dormant structures of field fungi remain viable inside corn seeds for long periods of time under cool, dry conditions. However, when subjected to poor storage conditions, e. g., warm temperatures and moist air, the field fungi and their dormant structures die. The same grain storage conditions that cause the disappearance of viable field fungi allow the storage fungi to thrive.

Storage Fungi The storage fungi, especially molds of the genera *Aspergillus* and *Penicillium*, are found widely in nature. They are common in soil and many other media. These fungi thrive in stored grain kernels that are too dry to sustain the growth of field fungi. The storage fungi are able to invade the seed directly. That is, they do not grow through the plant to reach the seed. Spores and other dormant structures of these molds are present nearly everywhere in nature and are especially abundant in and around grain handling equipment and facilities. The spores and other dormant structures germinate when the temperature and moisture conditions are favorable, and attack the stored grain kernels. Depending on the temperature, most species of storage molds grow at a specific moisture content within the range of about 12 to 19%.

*Aspergillus* and *Penicillium* molds are capable of infecting the grain in the field if damage to the husk allows them access to the kernels. However, most infections occur during handling and storage. Storage molds can produce mycotoxins under certain conditions. The most well-known mycotoxin produced by various species of *Aspergillus* is aflatoxin, but dozens of others, including ochratoxin and citrinin, have been described. *Penicillium* molds also produce toxins such as penicillic acid.

Storage molds are responsible for most grain deterioration in storage, including heating and caking. During grain deterioration, the proportion of kernels invaded by storage molds increases over time. Thus, the presence of large numbers of kernels invaded with *Aspergillus* spp. or *Penicillium* spp. indicates that the grain has been held under poor storage conditions that permitted the storage molds to infect and grow. To test grain for mold infection, randomly-selected kernels are washed with a bleach solution to kill mold spores, mycelia, and other mold structures on the surface of the kernel. The disinfected kernels are placed on an agar medium that promotes the growth of storage molds, and are incubated at warm temperatures for several days. Under these conditions, mold colonies grow out of the internally-infected kernels, and produce masses of spores. The colonies are identifiable by the color and shape of the spore masses. The level of infection is reported as the percent of the kernels infected with each species of mold. If the infection is advanced, the cumulative infections by several different species of molds may add to more than 100%.

Physical simulations of the storage of exported U. S. corn under tropical conditions showed that an increase in the level of infection by storage molds should be expected over a two-month period (Table 3). The increase was associated with the production of metabolic heat and a doubling of the percentage of germ-damaged kernels. In this experiment, the temperature of the environment was held at 30 °C. The temperature of the grain did not exceed 32 °C because the small size of the grain masses allowed metabolic heat to dissipate rapidly to the environment. Under these conditions, the increase in damaged kernels was not associated with a decrease in the nutritional value of the grain (see Appendix IV). Neither was it associated with a significant decrease in xanthophyll content.

**Table 3. Grain temperature, infection by storage molds, and kernel damage when export-condition U. S. corn was held for two months in a chamber with an air temperature of 30 °C.**

Weeks	Grain Temp. (°C)	Infection by <i>A. glaucus</i> (%)	Infection by All <i>Aspergillus</i> (%)	Damaged Kernels Total (%)
0	29.8	71.8	84.2	2.8
2	30.7	72.8	108.5	-
4	30.9	86.7	111.5	4.0
6	31.2	90.8	137.2	-
8	31.5	87.8	141.3	5.0

## Insects

A variety of small insects can infest U. S. corn. The genera and species of grain-infesting insects are similar throughout most of the world. Cosmopolitan beetles likely to be found in stored corn include the weevils (*Sitophilus* spp.), the lesser grain borer (*Rhyzopertha dominica*), the sawtooth grain beetle (*Oryzaephilus* spp.), flour beetles (*Tribolium* spp.), and flat or rusty grain beetles (*Cryptolestes* spp.). A few species of moths, psocids, and mites also inhabit stored corn. Grain held long-term in the dry tropics also is attacked by indigenous insects such as *Trogoderma granarium* and *Prostephanus truncatus*. Because nearly all importers of U. S. corn typically store the grain for two months or less, severe insect problems seldom are reported.

Insects can contribute to heating in corn stored under tropical conditions. The weevils often are associated with the production of large amounts of heat and metabolic water. This heat and water facilitates the growth of certain storage molds that greatly accelerate deterioration. *Sitophilus* weevils and *Rhyzopertha dominica* borers can cause major damage even without mold involvement because immature forms develop within kernels. The other cosmopolitan pests do not significantly damage the grain, but can cause contamination.

Stored grain insects require nearly a month to develop from the egg, through the larval and pupal stages, to emerge as adults under tropical conditions. Because only the adults reproduce, several months are required to develop damaging infestations if only a few are present at the start of the storage cycle. The time required to produce a new generation is directly related to temperature. Small reductions in temperature from the insects' optimum of about 35 °C result in longer generation times, providing a considerable measure of control in the short run.



The insect population density is low when U. S. corn is exported, as the grading system limits the number of live insects present without the special designation “infested” applied to the grade. Because most buyers would not accept infested grain, the grain is typically fumigated if this level is found. Many contracts specify shipboard fumigation regardless of the infestation level reported on the official grade certificate.

Infestation is likely to occur as the grain is discharged from the ship and passes through the grain handling and storage equipment in the tropical port. The majority of stored-grain insects found throughout the world are tropical in origin and are highly adapted to tropical conditions. Grain that has been held for more than a few days in port stores or that has been stored for any length of time in central warehouses is likely to be contaminated. If the grain is to be used only for animal feed, the tolerance for insect contamination is high, and light to moderate infestations are of little consequence. However, if the grain is to be used for human food or other infestation-sensitive uses, or if feed grain is stored or handled in the same location as grain destined for food uses, control of stored-grain insects is essential.



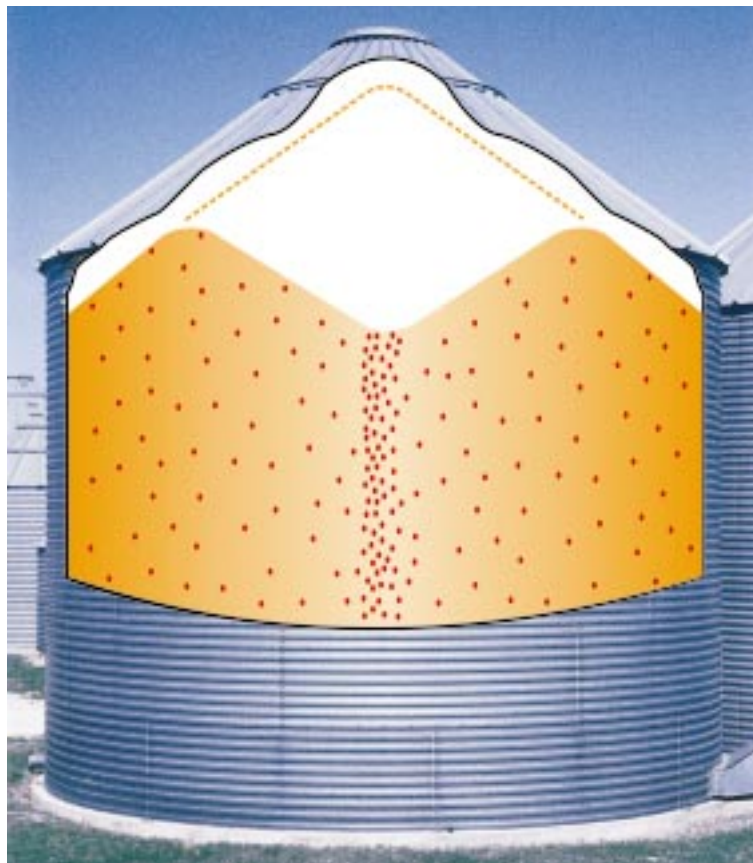
## **Quality Maintenance in Tropical Storage**

There are many factors that affect the quality of grain stored in tropical climates, and many techniques may be used to increase the chance of successfully maintaining quality. The following section provides information and recommended practices.

### **Coring and Leveling**

Coring refers to the practice of removing a small amount of grain after bin-loading is complete. It is used almost exclusively in cylindrical metal bins with a center fill spout, a center discharge port, and a diameter at least half as large as the grain height. The function of coring is to remove the center column of grain that contains a high concentration of fine material. In this process, the grain surface is partially leveled (Figure 7), and the grain peak, where heating and deterioration is most likely to occur, is removed and used first. The partial leveling of the grain surface also helps equalize airflow during aeration. In flat stores where the discharge spouts may not be located beneath the grain peaks, mechanical means can be used to partially equalize the grain height in order to facilitate airflow through the spoutlines.

**Figure 7. Illustration of a cylindrical bin that has been cored after filling.**

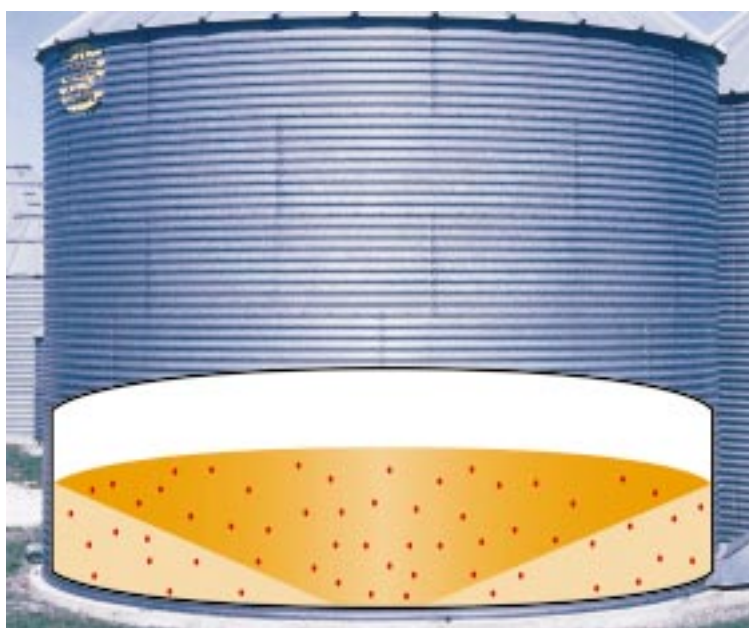


## Inventory Management

Because of the many challenges they face, importers in humid, lowland tropical areas have learned that two months is the maximum amount of time they can expect to consistently and successfully maintain the quality of U. S. corn. In the dry tropics and the cooler, upland tropics, importers have had greater success with longer storage times. This practical knowledge is consistent with scientific theory and the results of numerous experiments. The amount of deterioration that occurs in storage is known to be a function of initial grain condition, moisture content, temperature, and time of storage. If the other factors cannot be controlled, then the only way to avoid quality deterioration is to reduce the storage time by holding smaller inventories and scheduling more frequent deliveries.

In flat-bottom bins and warehouses, an important aspect of inventory control is the removal of the grain that remains in the bin after the grain stops flowing by gravity. In metal bins and other relatively wide structures, grain discharge is characterized by funnel flow. These are first-in, last-out structures. When discharge begins, the grain immediately above the discharge port exits, followed by the grain in the column above the port. Soon an inverted cone forms at the grain surface above the discharge port, as seen in Figure 7, and surface grain is carried down the slope of the cone and enters the moving column. The surface grain was the last to enter the bin but the first to be discharged. Only when the sides of the inverted cone reach the walls of the bin does grain located near the walls begin to exit the bin, beginning with the grain nearest the bin roof. The grain near the floor of the bin, which was some of the first grain to enter the bin, does not flow out of the bin by gravity (Figure 8). This grain constitutes the “grain bottom” that must be removed by mechanical means or by hand.

**Figure 8. Illustration of a bin containing a “grain bottom” after discharge by gravity has stopped.**





If grain is stored in a bin for a long period and then withdrawn over several days or weeks, the grain in the grain bottom may begin to heat and deteriorate because it has been subjected to tropical conditions for several weeks. This grain must be removed before the bin is refilled, as it is the “oldest” grain. Although production pressures may dictate otherwise, it is not cost-effective to allow this grain to remain in the bin through a second fill cycle. Under tropical conditions, it is likely to sustain damage if not removed and used before the bin is refilled.

Removing and using the corn in the grain bottom is necessary to follow the standard inventory rotation commonly known as “first in, first out.” This principle has long been the warehouseman’s standard operating procedure. However, it is sometimes advantageous to allow an exception to the rule. For example, if the corn in one bin or one part of a warehouse begins to heat, it may be advantageous to use it out of the standard rotation. This is often the simplest and least expensive way to deal with a storage problem.

## **Monitoring Grain Moisture**

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The moisture content of individual lots (trucks or railcars) should be tested when they arrive from the port. The moisture contents of individual loads may vary significantly from the average moisture content reported on the grade certificate. Individual lots with a moisture content greater than 14.5% should be segregated and used first.

## **Temperature Monitoring**

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The most direct method of monitoring grain condition is to collect and examine grain samples. The appearance, temperature, feel, and smell of the grain samples provides abundant information to the experienced grain manager. Grain samples must be sieved to detect insects or mites. However, in large grain masses, obtaining representative samples from deep within the grain mass is difficult, and many grain managers rely on the grain temperature as the principal monitoring tool. Careful monitoring of grain temperature is even more important for the grain manager in tropical climates than in temperate climates, as undesirable temperature changes and deterioration occur in the grain more rapidly under tropical conditions.

The best tool for this job is an installed temperature-monitoring system. For bulk warehouses, long rods with thermometers at the end are an inexpensive and practical alternative. Typically, thermocouple systems consist of braided-steel temperature cables supporting thin copper wires that terminate in contact with a wire made of a metal alloy called constantan. Where these dissimilar metals make contact, a thermocouple is formed and an electron current is generated. The current is carried by wires to a thermocouple reader, a device that measures the current and relates it to temperature. Most cables have these thermocouples at 2-meter intervals.

To most easily interpret grain temperature data, the data should be recorded in a way that facilitates comparing the same place in the bin at several sampling dates. Detailed instructions and examples of temperature logging and monitoring are presented in Appendix II.

## Drying or Chilling

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Grain dryers and chillers are available from several well-known suppliers. Chilling grain with refrigerated air or drying grain with high-temperature dryers are equally and greatly effective in preventing or arresting deterioration. Nevertheless, these options have not been of widespread interest to importers of U. S. corn because the equipment is expensive to purchase and operate.

## Aeration

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Definition Grain aeration refers to the forcing of air at low velocity through a static mass of grain to cool the grain. Grain aeration often is confused with grain drying, in which air is forced through grain to remove water, and which typically uses airflow rates at least an order of magnitude greater than those used for aeration. Typically, grain drying is done with heated air, and often is accomplished by moving the grain through a high-temperature grain dryer. In contrast, aeration must use air that is cooler than the grain.

Aeration Systems Grain aeration is accomplished by means of aeration fans. Both positive-pressure (push) systems and negative-pressure (pull) systems are common. The fans often are mounted at the base of the silo, but may be mounted on the bin roof. The fans force air through the void space between the kernels. The void space comprises about 40% of the volume of a grain mass. As air passes close to individual kernels, it exchanges heat, moisture, and gases with those kernels.

Power and Airflow Rate Grain provides resistance to airflow because the air must follow a tortuous path through small channels in order to exit the grain. The greater the resistance, the more powerful the fan motor required to deliver a given airflow rate. The amount of resistance per unit of grain depends on the air velocity, the size of the interseed air spaces, and the distance the air must travel to exit the grain mass. Air velocity and length of the air path have the greatest effect. In general, for a given size of bin and grain mass, a larger fan signifies higher capital and variable costs and a higher airflow rate, but a lower fan operation time requirement, than does a smaller fan. Literature from temperate climates typically recommends 0.08 m<sup>3</sup> of air per minute per m<sup>3</sup> of grain, (0.1 cubic foot of air per minute per bushel of grain) or less, but installed systems vary widely. Airflow rates of at least 0.3 m<sup>3</sup>/min/m<sup>3</sup> are recommended for the tropics.

Cooling Fronts and Wetting Fronts When air is passed through grain, both moisture vapor and heat energy are exchanged between the air and the grain. When cool air enters a warm grain mass, the air accepts heat from the grain until it warms to the grain temperature. This may occur as the air travels only a few centimeters, so only the first layers of grain are affected. Once the air is nearly the same temperature as the grain, it can no longer accept heat from the grain, and passes through the rest of the grain mass without affecting the grain temperature.

This produces a layer of cool grain in a mass of warm grain. The layer of grain in which the cooling occurs is called the cooling front. As more cool air passes through the grain, the cooled layer becomes deeper, and the front is farther from the air entry point. Thus, the front is said to “pass through” the grain. In order to complete the aeration cycle, the front must be “moved” all the way through the grain mass. The number of fan-hours required depends on the airflow rate, which is a function of the size and power of the aeration fan and motor compared to the amount of grain and length of the air path. Higher airflow rates are recommended for the tropics because cooling often must be accomplished faster in the tropics, with fewer hours of adequately cool air available.

Typically, a small amount of water is lost from the grain at the cooling front where the air comes to both moisture and temperature equilibrium. However, in the layers of grain that have already been cooled, the equilibrium conditions have changed and the cool ambient air encounters cool grain. If the cool air has a high relative humidity, a significant amount of grain rewetting may occur. Thermal fronts progress through the grain mass many times faster than moisture fronts, so rewetting can be minimized by stopping the aeration cycle as soon as the entire grain mass has cooled. In practice, well-monitored aeration seldom results in problems due to rewetting.

Uses of Aeration Aeration is used differently for imported U. S. corn in tropical regions than for local grain in temperate climates. In the unique case of U. S. corn stored in tropical climates, aeration should be employed only if one of the following is observed:

- Rapidly-heating grain, even in short-term storage
- Slowly-heating grain in long-term storage
- Deteriorated grain on bin walls.

**Rapid heating.** If a hot spot develops in the grain mass and the grain cannot be used immediately, it may be necessary to aerate in order to prevent severe damage or the production of mycotoxins. If a large portion of the grain mass has heated to several degrees above the mean daily ambient temperature, the fan should be operated whenever no rain is falling until the hot spot has been removed.

**Slow heating in long-term storage.** In some highland tropical areas, U. S. corn is stored for several months before use. In such moderate climates, quality can be maintained successfully by closely monitoring grain temperatures and using aeration. Aeration is applied only when the warm areas of the grain mass are at least 3 °C above nighttime temperatures. Then aeration is begun nightly whenever it is not raining. Usually, fans are operated less than six hours per night, during the coolest times. When the cooling front has been passed through the grain mass, the aeration cycle is complete and the fan is no longer operated.

**Deteriorated grain on bin walls.** In some bins, crusted, discolored grain remains in the bin each time the grain is discharged. This is most likely to occur in metal bins during storage longer than two months, and frequently manifests itself as crusted grain attached to a shaded side of the bin wall or in a ring near the floor. Sometimes this phenomenon is related to an obvious defect such as rain leaking into the grain at the wall-floor juncture, or the grain bottom not being removed before the bin is refilled. However, if the deterioration is not related to poor maintenance or poor practices, it often can be eliminated by nighttime aeration to reduce thermal gradients that cause moisture to migrate to cooler parts of the grain mass. To resolve this problem, the manager should operate the aeration fans for 1–2 hours every night when it is not raining.

Misuses of Aeration Aeration equipment and the electricity to power it require expenditure of company resources. The return on investment can be great if the aeration is managed correctly. The payback results from reducing and equalizing the grain temperatures or removing the heat and moisture produced by respiration in the grain mass. Therefore, air that is the same temperature or warmer than the grain should never be used for aeration. Aerating cool grain with warm, tropical air is certain to promote deterioration. It may create quality problems where none existed prior to the aeration. Another counterproductive practice is overaeration, that is, continuing to operate the fan after the cooling front has passed through the grain. This practice wastes electricity and can promote deterioration.

Headspace Ventilation In hot climates, it often is useful to control the temperature of the airspace over the grain surface (headspace), because the solar radiation on the roof causes this air to become much hotter than the ambient air. Extraction fans, located near the highest point on the bin roof, are used to force air out of the headspace. This creates a vacuum that draws ambient air through roof vents and the open spaces under the eaves of the bin roof. These extraction fans cool the headspace during the day, and are sometimes installed to resolve the problem of condensation on the bin roof during grain aeration.



**Benefits of Cooling** The advantages of aeration are demonstrated in Table 4. U. S. corn at export condition was stored under temperature and relative humidity conditions typical of tropical areas. In one case, the grain temperature at the beginning of the simulation trial was 25 °C. Because the quantity of grain in each replication of this trial was small (0.14 ton), the grain temperature was greatly affected by ambient conditions through the two-month storage period. This experiment simulated conditions in which the grain was maintained by aeration near the ambient temperature of many highland tropical areas. In the other trial, grain and air were initially brought to 30 °C, and the air was maintained at this temperature to simulate lowland tropical conditions. The initial mold and ergosterol numbers were arbitrarily set to 100% to demonstrate relative changes over time.

**Table 4. Effect of two storage temperatures, simulating aerated and non-aerated corn, on the rate of deterioration of U. S. corn at export condition. Changes are shown in relation to the original condition.**

Time (wk)	25 °C (simulates aerated)			30 °C (simulates non-aerated)		
	All <i>Aspergillus</i> (% of initial)	Ergosterol (% initial)	°C above Ambient	All <i>Aspergillus</i> (% of initial)	Ergosterol (% initial)	°C above Ambient
0	100	100	0	100	100	0
2	97	85	0	126	140	0.7
4	84	83	0.1	133	169	0.9
6	97	68	0.4	163	224	1.2
8	78	127	0.5	168	258	1.5

The lower rate of deterioration at 25 °C was demonstrated in a slower increase in the infection rate by *Aspergillus* molds. This was seen in both the percent of kernels infected with *Aspergillus* colonies compared to 30 °C and the lower amount of ergosterol, a chemical component of mold mycelia that is used as a measure of total mold biomass. No consistent increase was observed in either measure of mold growth at 25 °C. Rather, alternating high and low readings indicated random variations. In contrast, at 30 °C the percent infected kernels increased by about 70%, indicating that the infection spread to nearby kernels. The amount of mold biomass, as indicated by ergosterol, increased by a factor of 2.5.

A lower rate of respiration at 25 °C is suggested by the fact that the grain temperature increased little above the ambient temperature, indicating that the heat of respiration barely exceeded the rate of heat dissipation. In contrast, at 30 °C, heat energy accumulated within the grain mass, raising the grain temperature by nearly 2 °C. In summary, a grain temperature 5 °C lower was associated with a much slower growth rate of molds, and a much reduced respiration rate.

## Mold Inhibitors

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Commercial mold inhibitors available in many countries were originally tested for application to high-moisture corn (greater than 18% m. c.) immediately after harvest, and were developed to help the grain producer maintain quality when forced to hold the grain for some time before drying. Mold inhibitors have gained acceptance in many countries as additives to extend the shelf life of animal feeds. They are based on propionic acid, which is a well-accepted food and feed preservative. Neither propionic acid nor the formulations based upon it typically is applied to stored corn in the U. S., but they often are sold for application to exported U. S. corn in tropical countries.

The cost-effectiveness of mold inhibitor application depends on several variables. If mold inhibitors are added routinely to the finished feed, then the cost of applying them to the grain before storage depends on how much of the inhibitory power is lost during the storage period and when the grain is ground and made into feed. Vendors may be contacted for this information. In contrast, if the mold inhibitor is added for the sole purpose of retarding grain deterioration in storage, then its cost-effectiveness depends on the extent that deterioration is delayed. The following information relative to the effect of propionic-acid mold inhibitors applied to export condition U. S. corn was developed from laboratory simulation trials and limited commercial trials under tropical conditions.

Kernel Damage An increase in the level of damaged kernels indicates that deterioration has occurred. To assess the effect of a mold inhibitor on increases in damaged kernels, laboratory simulation trials were conducted. Mold inhibitor was applied at the rate of 1 kg/ton and the grain was stored at either 30 °C or 25 °C. The grain treated with the mold inhibitor was compared to cleaned grain and to grain to which no treatment was applied.

The damaged-kernel content was too variable throughout the trials to show definitive results at either temperature (Table 5). The initial percent damaged kernels in the export-condition U. S. corn was set to 100 to demonstrate relative changes thereafter. Because the damaged kernel content cannot decrease, values smaller than 100 indicate random variability, not the disappearance of damage kernels. Cleaning did not show an advantage over no treatment. Rather, the highest damaged kernel content was observed in the cleaned corn after six weeks at 30 °C. The damaged kernel content of corn treated with mold inhibitor appeared to vary less than the other treatments. Despite an apparent increase in damaged kernels in the untreated corn, no differences in feed value or pigment content were observed (see Appendix IV).

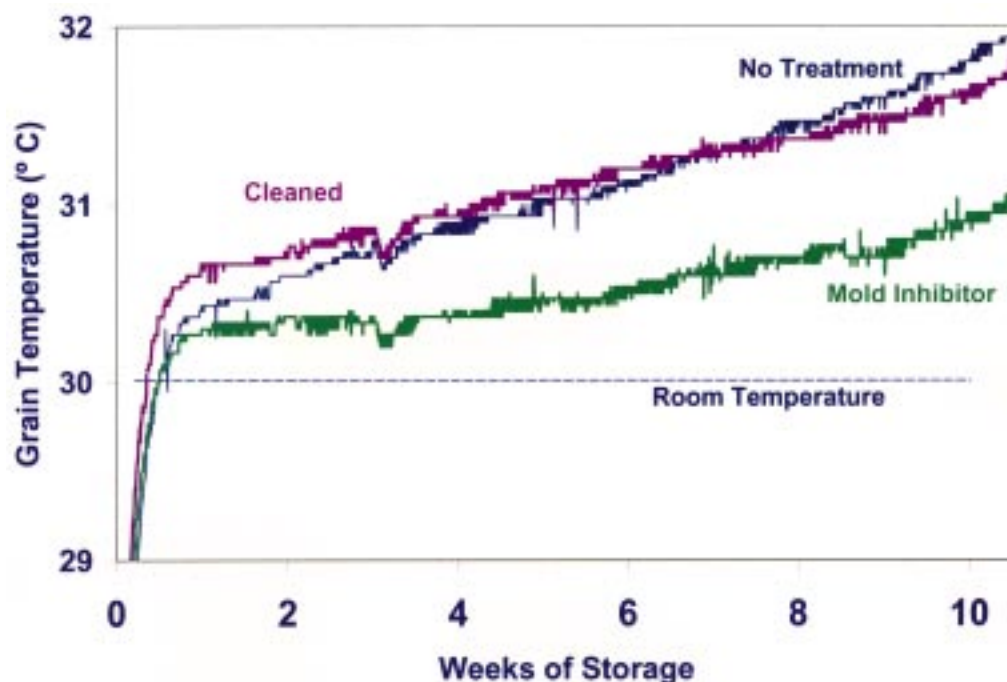
**Table 5. Changes in percent damaged kernels in simulations of export-condition U. S. corn stored for two months at 25 °C or 30 °C. Changes are shown in relation to the initial damaged-kernel content.**

Weeks	25 °C			30 °C		
	No Treatment	Cleaned	Mold Inhibitor	No Treatment	Cleaned	Mold Inhibitor
0	100	100	100	100	100	100
2	40	50	50	100	60	100
4	120	80	50	130	80	80
6	100	40	80	120	150	120
8	200	140	90	110	160	100

Grain Heating The production of heat in the grain mass is another indicator of deterioration. Corn treated with mold inhibitor heated less when stored at 30 °C (Figure 9). Because the grain masses were small (0.14 tons of grain), metabolic heat generated within the grain masses was able to dissipate rapidly to the atmosphere. Constant generation of metabolic heat was required to maintain grain temperatures warmer than the environment. Therefore, the fact that the grain treated with mold inhibitor accumulated heat at a slower rate than the other grain indicates that the treatment suppressed respiration significantly.

In trials at commercial feed mills, lots of imported U. S. corn (about 125 tons each) were stored for at least two months at an average ambient temperature of 29.8 °C and average relative humidity of 64%. Individual lots were stored as received (no treatment), cleaned before storage, or stored after 1 kg/ton commercial mold inhibitor was applied. In these trials, two of the masses, one treated with mold inhibitor and one not treated or cleaned, deteriorated much more than the others. Both heated to an average of 42 °C, and both suffered deterioration that produced about 40% damaged kernels.

**Figure 9. Grain temperatures over time in export-condition U. S. corn stored at 30 °C.**



Dry Matter Loss These trials showed that in export-condition corn stored under tropical conditions, the application of mold inhibitor helped reduce heating and kernel damage in some cases. Another important component of the cost of deterioration under tropical storage conditions is the amount of dry matter lost during storage. Dry matter loss refers to loss of weight other than water due to respiration. During aerobic respiration, carbohydrates, fats, and proteins are consumed. The value of dry matter lost is directly related to the price of the grain. For example, if the total value of imported corn, including the port warehousing costs and the in-country transportation costs, is \$125/ton, then a loss of 0.5% of the dry matter of the grain costs the buyer \$0.625/ton ( $\$125 \times 0.005$ ).

When export-condition corn was stored at 30 °C for two months in a laboratory respirator, the observed dry matter losses were 0.22%, 0.18%, and 0.09% for untreated corn, cleaned corn, and corn treated with mold inhibitor, respectively. In this case, the mold inhibitor preserved 0.22–0.09%, or 0.13% of the dry matter of the grain. If, for example, the grain cost \$125/ton, then the value of the preserved weight was \$0.16/ton ( $\$125 \times 0.0013$ ). The value of cleaning in this case was 0.04% (0.22–0.18). Thus, cleaning would be cost-effective only if it cost less than 0.04% of the price of the grain. Obviously, the economic value of the weight of grain preserved by the application of mold inhibitor or cleaning would vary with the grain price.



## Cleaning

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The effect of cleaning, i.e., the removal of fine material by screening before storage, on the respiration of stored grain is discussed above in relation to mold inhibitor application. Little benefit of cleaning was observed in laboratory simulation trials. However, many grain storage phenomena are observed only in large scale, and cleaning may help resolve common storage problems. For example, if imported U. S. corn must be stored for several weeks in a warehouse, especially under lowland-tropical conditions, and especially during the months when heating is most likely, then screening may help minimize the development of hot spots. In general, cleaning before storage will help reduce the fine material concentration in spout lines, and facilitate the cooling action of aeration. If fumigation becomes necessary, pre-storage screening would be helpful to minimize the compacted areas where the fumigant gas might not otherwise penetrate.

## Fumigation

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U. S. corn is an infestible commodity and may require fumigation if held for several months under tropical conditions. Fumigation is expensive and potentially hazardous. Consistently safe and effective grain fumigation requires trained personnel. The following is intended as general information, not as a substitute for proper fumigator training.

Both methyl bromide ( $\text{MeBr}_2$ ) and phosphine ( $\text{PH}_3$ ) grain fumigants sometimes are used in tropical countries. Although both fumigants kill insects and disinfest grain, they have very different characteristics (Table 6).

**Table 6. Characteristics of phosphine and methyl bromide grain fumigants.**

<b>Phosphine Fumigants</b>	<b>Methyl Bromide Fumigants</b>
Traditionally, are supplied as flasks of pellets or tablets or as powder incorporated into packs or sachets. New formulations generate $\text{PH}_3$ on-site or carry $\text{PH}_3$ in compressed carbon dioxide	Are supplied as a compressed gas
Require several days of exposure to insects	Require a few hours of exposure to insects
Require a sealed structure	Require a vacuum vault, gas-tight tarpaulin, or recirculation
Produce $\text{PH}_3$ , with a molecular weight similar to that of air, so it moves with air currents	Are much heavier than air and migrate downward unless recirculated
Leave no significant phosphine residue in grain	May leave objectionable residues of inorganic bromine if the fumigation technique is not adequate
Typically are used in raw grain storage	Typically are used in grain processing areas or equipment, or in warehouses
Sorb slowly to grain	Sorb quickly to grain
Currently are not threatened by international agreement	Currently are scheduled to be phased out because of their potential destructiveness to the earth's ozone layer

Except for fumigation of small quantities of grain or grain product in bags under gas-tight sheets in warehouses, fumigations with methyl bromide are likely to be conducted by fumigation companies. In contrast, phosphine fumigations often are conducted by employees of the grain-handling company. Solid phosphine fumigants are easy to handle and apply, and provide an additional measure of security because large quantities of the toxic gas are not generated for several hours.

Phosphine fumigants (solid formulations) must react with the water in the air to generate the toxic gas. The rate at which  $\text{PH}_3$  generates from the fumigant placed in the grain mass depends on the grain temperature and moisture content. In general, the warmer and wetter the grain, the faster the phosphine generates. The gas generation rate is unrelated to short-term changes in ambient conditions.

Fumigations are successful only if a gas concentration high enough to kill all stages of the insects is maintained long enough to be lethal. This can occur only if the fumigated area is well sealed. Leaks are the most common cause of fumigation failures, and also put employees at risk. Phosphine migrates through plastic, porous concrete, and small openings in metal bins. Plastic and tape, which are porous to phosphine, often are used as sealing materials to retard air currents that would carry the gas out of the fumigated grain.

The lethal dose depends on the insect species, temperature, length of exposure, and life stage. Higher temperatures (25–35 °C) often are associated with successful fumigations, other factors being equal, because all life stages and species are more susceptible to phosphine at these temperatures. Also, resistant life stages (eggs and pupae) develop into more susceptible stages more rapidly at the higher temperatures. However, if a portion of the grain mass is 40 °C or warmer, it may be difficult to hold the gas long enough to effect a complete kill.

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Sutherland, J.W., Banks, P.J., and W. B. Elder. 1983. Interaction between successive temperature or moisture fronts during aeration of deep grain beds. Journal of Agricultural Engineering Research 28:1-19.

## **Recommended Reading**

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Drying and Storage of Grains and Oilseeds. Brooker, D. B., Bakker-Arkema, F. W., and C. W. Hall. 1992. Van Nostrand Reinhold, New York, New York.  
ISBN 0-442-20515-5.

Quality Maintenance in Stored Grains and Seeds. Christensen, C. M., and R. A. Meronuck. 1986. University of Minnesota Press. Minneapolis, MN  
ISBN 0-8166-1453-9.

Storage of Cereal Grains and Their Products. D. B. Sauer, Ed. 1992. American Association of Cereal Chemists. St. Paul, MN  
ISBN 0-913250-74-0.

## **Appendix I. U. S. Grades for Corn.**

Grading Factors	Grades U. S. Numbers				
	1	2	3	4	5
Test Weight					
Minimum per bushel (pounds)	56.0	54.0	52.0	49.0	46.0
Damaged kernels					
Heat	0.1	0.2	0.5	1.0	3.0
Total	3.0	5.0	7.0	10.0	15.0
Broken corn and foreign material	2.0	3.0	4.0	5.0	7.0

U. S. Sample grade corn is corn that:

- a) Does not meet the requirements for U. S. Nos. 1, 2, 3, 4, or 5; or
- b) Contains 8 or more stones that have an aggregate weight in excess of 0.2% of the sample weight, 2 or more pieces of glass, 3 or more crotalaria seeds, 2 or more castor beans, 4 or more particles of an unknown foreign substance or a commonly recognized harmful or toxic substance, 8 or more cockleburrs or similar seeds singly or in combination, or animal filth in excess of 0.2% in 1000 g; or
- c) Has a musty, sour, or commercially-objectionable foreign odor; or
- d) Is heating or of distinctly low quality.

For further information, downloadable publications, and the e-mail address, access the Federal Grain Inspection Service (FGIS/GIPSA) website at: [www.usda.gov/gipsa](http://www.usda.gov/gipsa).



## **Appendix II Grain Temperature Monitoring**

To most easily interpret grain temperature data, the data should be recorded in a way that facilitates comparing the same place in the grain mass at several sampling dates. For example, consider a facility with three storage bins, each having four cables, where each cable has eight thermocouples (sensors). Temperatures were recorded last on 29 December. The most useful way of constructing the temperature log is to place readings from the same cable close to one another, as follows:

Date	Bin	Cable	Sensor							
			1	2	3	4	5	6	7	8
5 Dec	1	1	24	22	22	22	21	21	22	23
11 Dec	1	1	25	22	22	22	21	21	22	24
17 Dec	1	1	25	23	22	22	21	21	23	25
23 Dec	1	1	25	23	23	22	21	21	24	26
29 Dec	1	1	25	23	23	22	21	22	24	28
5 Dec	1	2	24	23	23	23	22	22	22	23
11 Dec	1	2	24	Etc.	Etc.	Etc.	Etc.	Etc.	Etc.	Etc.

The above example illustrates that grain in contact with the # 1 and # 8 sensors, near the top (# 8) and bottom (# 1) of the grain mass, is slowly increasing in temperature, whereas deep within the grain that surrounds cable #1, temperatures are not changing. It is usually helpful to compare temperature profiles over at least a one-month period in order to interpret the data.

An alternative, but less helpful method of recording the same readings is to place all the temperature data from the same day together, as follows:

Date	Bin	Cable	Sensor							
			1	2	3	4	5	6	7	8
5 Dec	1	1	24	24	24	25	24	25	30	30
	1	2	24	26	26	27	29	24	24	30
	1	3	24	23	22	22	21	22	22	29
	1	4	24	23	22	22	22	21	22	29
	2	1	26	22	21	22	21	20	25	27
	2	2	24	23	23	22	22	21	21	24
	2	3	24	22	23	23	24	24	25	25
	2	4	24	22	23	23	24	24	24	25
	3	1	26	26	24	25	22	23	23	25
	3	2	27	26	25	26	23	25	24	24
	3	3	27	25	25	24	23	23	25	25
	3	4	27	25	25	24	23	23	25	25
11 Dec	1	1	27	24	24	25	25	22	24	24
	1	2	Etc.	Etc.	Etc.	Etc.	Etc.	Etc.	Etc.	Etc.

Here, the manager cannot immediately determine whether the high temperatures indicate deterioration or the effect of ambient conditions. The high temperatures at the top sensors (#7 and 8) on cable #1 in bin 1 may lead the manager to believe there is a hot spot. (In this case the high temperature simply indicates that the thermocouple is not covered by grain.) Similarly, it is not possible to determine whether the grain near the 5th position on cable #2 of bin #1 is heating or whether the cable has been displaced close to the outside wall.

### Examples of Grain Temperature Records

The sensors nearest the roof often are not covered by grain. They detect the temperature of the air in the headspace above the grain. Sensors not covered or barely covered by grain are characterized by fluctuating readings that vary depending on the time of day when the temperatures are recorded. This results in records showing alternately higher or lower readings. A typical example in which the top two sensors are not covered by grain is:

Date	Bin	Cable	Sensor							
			1	2	3	4	5	6	7	8
5 Dec	1	1	26	26	27	27	25	27	32	32
11 Dec	1	1	26	25	26	27	27	27	25	26
17 Dec	1	1	27	25	27	28	27	28	34	34
23 Dec	1	1	27	26	27	27	27	29	32	33

In the following example, the temperature line has been displaced to near the bin wall, exposing sensors #4, 5, and 6 to near-ambient conditions. Note that the temperatures at these points are alternately higher and lower, depending on ambient conditions when the temperatures were recorded.

Date	Bin	Cable	Sensor							
			1	2	3	4	5	6	7	8
5 Dec	1	1	24	24	24	28	31	29	25	26
11 Dec	1	1	25	25	26	27	29	29	25	28
17 Dec	1	1	25	25	25	26	29	27	25	27
23 Dec	1	1	25	25	26	29	30	30	24	28

True “hot spots” create a different pattern, one of steadily increasing temperatures. The rate of increase usually is moderate and usually only one or two sensors are affected at first. This differentiates a hot spot from surface warming, where sensors on several lines are affected equally. An example follows.

Date	Bin	Cable	Sensor							
			1	2	3	4	5	6	7	8
5 Dec	1	1	29	28	29	30	31	30	31	32
11 Dec	1	1	29	28	29	32	31	31	32	29
17 Dec	1	1	30	29	30	33	32	31	33	32
23 Dec	1	1	31	29	30	35	32	31	33	35

In this case, the grain temperature deep within the grain mass (# 4) increased by 3 °C in only 12 days while temperatures at other points closer to the surface (# 7) gained only two degrees and those at most positions remained relatively stable (sensor # 8 is out of the grain). This point is beginning to heat and deteriorate. An experienced grain manager will monitor this bin very closely and will take action if the temperature continues to increase at the rate of more than one degree per week.

## **Appendix III. Aeration in Tropical Climates**

### **When to Aerate**

In general, cool grain stores better and deteriorates less than warm grain. Both insects and molds grow faster and cause more damage at higher temperatures. Therefore, grain should be maintained as cool as possible. In temperate climates, this is relatively simple and inexpensive. However, in warm climates, and especially in the humid, low-land tropics, it may not be feasible without chilling equipment. An inexpensive and reasonable alternative is to store grain for short periods only, monitor it closely, and consume grain that is heating or in marginal condition before using the more storable grain. However, there are many circumstances in which aeration is useful under tropical conditions.

When Grain Is Warming at the Surface If the grain is warming to above ambient temperature because of the hot air between the bin roof and the grain, extraction fans may be helpful. In warm climates, the sun heats metal bin roofs, causing the air over the grain to become much warmer than the ambient air. Because nighttime air in the tropics is also warm, much of this heat does not escape during the night, so the grain surface is exposed constantly to air warmer than ambient temperatures.

Small extraction fans (usually 0.5 to 1 HP) should be positioned near the peak of bin roofs. As they remove the hot air from the headspace, cooler outside air is pulled into the bin beneath the eaves and through roof vents. The function of these fans is twofold. When the grain is not being aerated, they help prevent the daytime temperature of the headspace air from becoming excessively warmer than the ambient temperature. When the grain is being aerated by aeration fans that move air upwards through the grain mass, extraction fans mix ambient air with the hot, moist air leaving the grain mass, thus avoiding condensation on the metal roof at night. Extraction fans can be connected to automatic controllers that activate them whenever the aeration fans are turned on or whenever the headspace temperature is above a predetermined limit.

When Cool Air Is Available In the highland tropics and dry tropics, cool air may be available during nighttime hours. This cooler air may be used to extend the safe storage time of grain, sometimes for several months. After the bins are filled, the grain temperature is monitored closely as explained in Appendix II. Aeration fans are not activated unless the temperature of a significant portion of the grain mass exceeds the daily average temperature. If aeration is required, fans are activated during the night except during rain. Fans often are operated only during the coolest 3 to 4 hours, because the ambient temperature must be at least 3° C cooler than the warm grain for cooling to be efficient. When the cooling front has exited the grain, nightly aeration is stopped. This practice eliminates temperature gradients within the mass and brings the bulk of the grain mass to a temperature below the daily average ambient temperature.

When Grain Arrives Cold During the North American winter, grain sometimes arrives at the receiving port much cooler than the ambient air. When cool grain is placed in storage bins, the pattern of temperature change may indicate that the cool grain is coming to equilibrium with the environment at the storage site. The manager knows this is happening if the top, bottom, and outside are steadily warming and the inside of the grain mass is warming much slower. In this case, the best management decision is to “keep the cold in” by not operating aeration fans and by covering ground-level openings. Extraction fans could be operated on warm afternoons because they do not pull air through the grain.

When the Grain Is Heating due to Molds or Insects In the worst case, it is hot spots produced by mold or insects that cause the grain temperature to change. The best management strategy in this case is to use the grain immediately, before it heats to above 30–35 °C, at which point deterioration takes place more rapidly and the possibility of mycotoxin formation is greater. It is more important to use the heating grain immediately than to follow the standard warehouseman’s rule of “first in—first out.” One of the advantages of metal bins is that the grain at the peak and top center, where hot spots are most likely to occur, usually exits the bin soon after discharging begins. Therefore, it may be necessary to use only 15 or 20% of the heating grain out of turn.

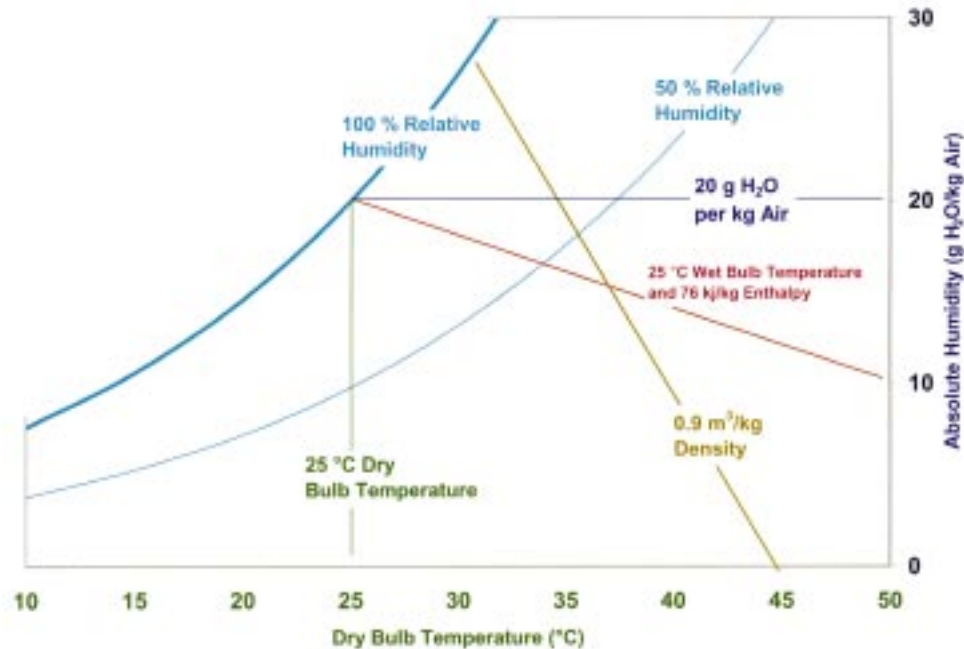
During the grain movement, samples should be taken, sieved, and examined for evidence of insects. If large numbers of *Rhyzopertha dominica* borers or *Sitophilus* weevils are observed, the heating can be stopped by fumigation. If few insects are present, and if the grain cannot be consumed immediately, aeration may be the only way to minimize grain damage. When aeration is required to control hot spots, ambient air is used to carry the excess heat and moisture from the grain, thereby maintaining the grain temperatures no more than a few degrees above the ambient temperatures. Outside air should be at least 3 °C cooler than the hot spot before this will be successful, and the fans should be left on continuously for several days, long enough for the heat and moisture to be carried all the way out of the bin. Operating the fans for just a few hours will result only in the movement of the heat and moisture to other grain.



## Psychrometrics of Aeration in Tropical Climates

**The Psychrometric Chart** A psychrometric chart is a useful tool in understanding grain aeration under tropical conditions because it illustrates in graphic form the relationships between temperature, moisture content, and various other characteristics of the air. Figure 1 illustrates the components of one common type of psychrometric chart at sea level.

**Figure 1. Components of the Psychrometric Chart.**



**Dry Bulb Temperature** On the horizontal axis, in green ink, the air temperature is presented as commonly measured with a standard mercury thermometer. A green line extends vertically upward from the 25 °C point on the horizontal axis to illustrate that all points on that line represent conditions associated with air at 25 °C.

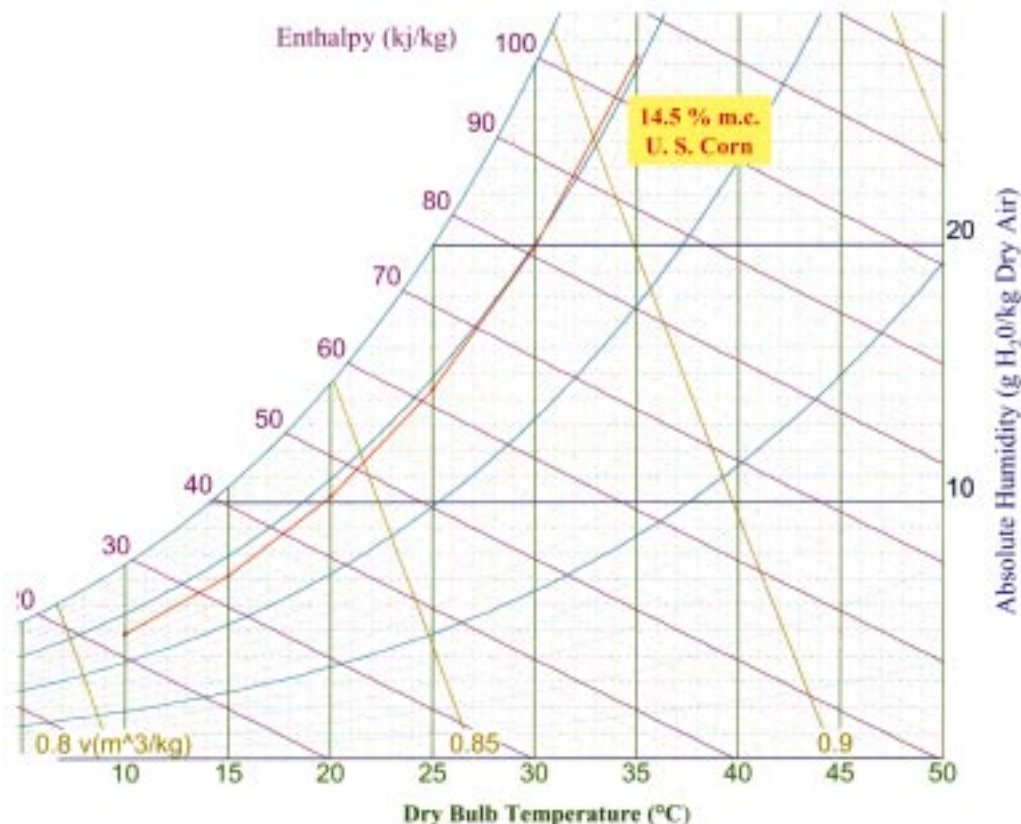
**Wet Bulb Temperature and Constant Enthalpy** The 25 °C line terminates at the curved line in the upper left-hand portion of the chart that illustrates conditions associated with saturated air (100% relative humidity). On the complete chart, numbers in red ink are printed on this line, representing the enthalpy (total heat energy) associated with various points on the saturation line. The inclined line in red ink represents air conditions associated with a constant enthalpy as other air characteristics vary. The red line also adequately represents the constant wet bulb temperature. The wet bulb temperature of air is measured with a standard thermometer whose bulb end is covered with a cloth wick. Measurements are taken by wetting the cloth and passing air across it. Evaporative cooling reduces the temperature measured by the thermometer to an extent dictated by the dry bulb temperature and the moisture content of the air.

**Relative Humidity** The curved lines in aqua-blue ink represent relative humidity. Relative humidity is defined as the ratio of the water vapor pressure in the air and that of saturated air. It can be thought of as the percent of water vapor in the air compared to the maximum capacity of the air at the same temperature and barometric pressure. It is often calculated from the difference between the dry bulb temperature and the wet bulb temperature.

**Absolute Humidity** The vertical axis on the right-hand side of the graph presents numbers in dark blue ink describing the water content of the air in grams of water vapor per kg of dry air. The dark blue, horizontal line (indicating 20 g/kg) intersects the vertical, green line (representing 25 °C) at the saturation line. This indicates that saturated air at 25 °C contains 20 g/kg of water. At the intersection of the 25 °C temperature line with the 50% relative humidity line, the absolute humidity is 10 g/kg, indicating that the air contains 50% of saturation, i.e. 10 g of the 20 g maximum capacity for that temperature and pressure.

**Density** The inclined line in gold ink is an example of a constant density line. The density of air is reported in m<sup>3</sup> air per kg.

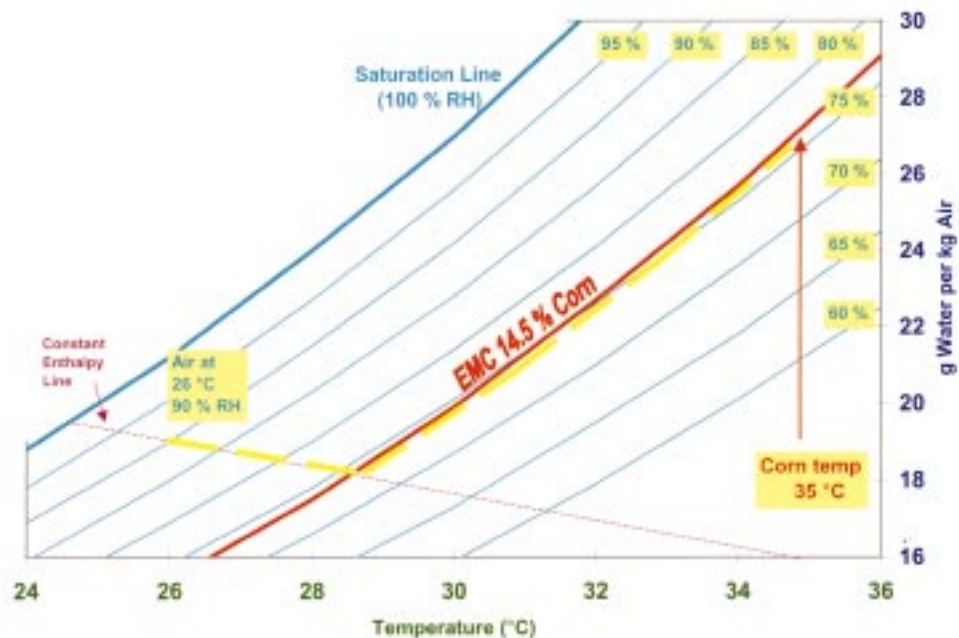
**Figure 2. Psychrometric chart at sea level, with the equilibrium moisture content line for 14.5% m. c. U. S. corn overlaid.**



Example of Grain Cooling The psychrometric chart illustrates properties of air only. In order to relate the air conditions to equilibrium grain conditions, a line representing the equilibrium conditions of the grain at the moisture content in question must be plotted at several temperatures, as shown in Figure 2. The points defining the red line for U. S. corn at 14.5% moisture content were calculated from the same ASAE equation as the lines shown in Figure 4, page 16.

An example of how the interaction between air properties and equilibrium grain conditions describes grain cooling by aeration is shown in Figure 3. Here, air at 26 °C and 90% relative humidity is used to cool corn at 14.5% m. c. and 35 °C. As the air is slowly passed through the grain, heat and water are exchanged. This process is described by the dashed, yellow line parallel to the constant wet bulb line. According to grain drying theory, the characteristics of air passing through grain are defined by the constant wet bulb temperature line. This is based on the assumption that the enthalpy of the air in the system cannot experience a net change in total energy. Rather, any change in sensible heat content (heat detected by the thermometer) is offset by an equal change in the non-sensible forms of heat energy associated with the states of the water in the grain-air system.

**Figure 3. Properties of ambient air at 26 °C and 90% relative humidity as it passes through U. S. corn with 14.5% m. c. at 35 °C.**



The changes in the properties of the air are described by a line connecting the point corresponding to the initial air characteristics and the point where the constant wet bulb line intersects the grain equilibrium moisture content line. At this intersection, the air temperature (dry bulb) has increased to 28.7 °C and the relative humidity has been reduced to 74% as 1.1 g water/kg is given up by the air and accepted by the grain. This process, wherein air and grain moisture comes to equilibrium, is thought to occur very rapidly. Thereafter, the air properties are described by the equilibrium moisture content line until the air temperature reaches the grain temperature. This is represented by the dashed, yellow line parallel to the equilibrium moisture line. As the air reaches thermal equilibrium with the grain, the relative humidity comes to about 77%, the temperature (dry bulb) is 35 °C, and the air gains water until it contains nearly 27 g/kg. Thus the air, which contained 19.2 g/kg before it was passed through the grain, accepted 7.8 g water per kg of dry air from the grain. Because the air density was 0.875 m<sup>3</sup>/kg initially, this represents a water loss from the grain of 8.9 g/m<sup>3</sup>, or about 0.6 percentage points of grain moisture, assuming a typical aeration rate and cycle duration.

Grain Rewetting The above example demonstrates how moist air can dry the grain if the air is several degrees cooler than the grain. However, this grain drying occurs at the thermal front only. Behind the thermal front, that is, in the layer of grain that has already cooled, ambient air entering the grain mass encounters grain that is slightly drier, but much cooler than before aeration began. Near the air entry point, changes in air properties are represented by the linear portion of the dashed yellow line, the portion parallel to the constant enthalpy line. In this phase of the process, the grain is wetted slightly as the air comes to moisture equilibrium. The second phase of the process, in which the air increases to the temperature of the uncooled grain, does not occur until the air reaches the thermal front, which may be several meters from the air entry point. Therefore, re-wetting of the grain can occur concurrently with grain drying, in different parts of the grain mass.

In practice, significant rewetting is seldom observed unless the grain is significantly overaerated. If the aeration is closely monitored and the process is stopped as soon as the thermal front has been passed completely through the grain, little re-wetting occurs. This is due to various phenomena. First, in the example above, the temperature and relative humidity of the ambient air are presumed to remain constant. In real life, air temperature and relative humidity change constantly, and it is likely that some of the air used for aeration will be represented by points below or to the right-hand side of the equilibrium moisture content line. When this occurs, the air accepts small quantities of water from the grain in the moisture-equilibration phase, resulting in drying of the rewetted grain. Second, the ambient air usually is warmed and its relative humidity is reduced as it passes through the fan and the plenum chamber. Finally, the rewetting process takes place much slower than the cooling process. According to the model of Sutherland et al. (1983), the rewetting front would “move” at a rate from 65 to 75 times slower, depending on the temperature, than the cooling front under the conditions described in the example above. Only if the aeration was continued long after the cooling front had exited the grain could significant rewetting occur.

## **Appendix IV. Feed value and xanthophyll content of U. S. corn at export condition.**

**Table 1. Feed value \* after 8 weeks of storage at 30 °C.**

<b>Sample</b>	<b>Wks Storage</b>	<b>Crude Protein (%)</b>	<b>ADF (%)</b>	<b>NEG (Mcal/lb)</b>	<b>NEM (Mcal/lb)</b>	<b>TDN (%)</b>
No Treatment	0	8.75	3.01	0.70	1.02	87.70
	2	8.67	3.63	0.69	1.01	86.80
	4	8.48	3.71	0.69	1.01	86.80
	6	8.49	2.93	0.70	1.02	87.70
	8	8.67	3.39	0.69	1.01	86.80
Cleaned	0	8.75	2.89	0.70	1.02	87.70
	2	8.92	2.99	0.70	1.02	87.70
	4	9.01	2.67	0.70	1.02	87.70
	6	8.63	2.82	0.70	1.02	87.70
	8	8.63	2.78	0.70	1.02	87.70
Mold Inhibitor	0	8.77	3.26	0.69	1.01	86.80
	2	8.92	3.07	0.70	1.02	87.70
	4	9.16	2.63	0.70	1.02	87.70
	6	9.05	2.76	0.70	1.02	87.70
	8	8.89	4.05	0.69	1.01	86.80

**Table 2. Feed value \* after 8 weeks of storage at 25 °C.**

<b>Sample</b>	<b>Wks Storage</b>	<b>Crude Protein (%)</b>	<b>ADF (%)</b>	<b>NEG (Mcal/lb)</b>	<b>NEM (Mcal/lb)</b>	<b>TDN (%)</b>
No Treatment	0	8.32	2.97	0.70	1.02	87.70
	2	8.42	2.55	0.70	1.02	87.70
	4	8.48	2.30	0.70	1.02	87.70
	6	8.73	2.62	0.70	1.02	87.70
	8	8.74	3.77	0.69	1.01	86.80
Cleaned	0	8.49	2.81	0.70	1.02	87.70
	2	8.42	3.28	0.69	1.01	86.80
	4	8.29	3.34	0.69	1.01	86.80
	6	8.17	3.64	0.69	1.01	86.80
	8	8.34	2.56	0.70	1.02	87.70
Mold Inhibitor	0	8.45	2.45	0.70	1.02	87.70
	2	8.62	3.56	0.69	1.01	86.80
	4	8.19	3.42	0.69	1.01	86.80
	6	8.28	3.29	0.69	1.01	86.80
	8	8.70	2.72	0.70	1.02	87.70



No significant change was observed in the nutritional content of the export-condition U. S. corn stored in laboratory simulations at 30 °C and 25 °C, as seen in Tables 1 and 2 above. The xanthophyll content was not changed in any consistent pattern by storage under tropical conditions (Table 3).

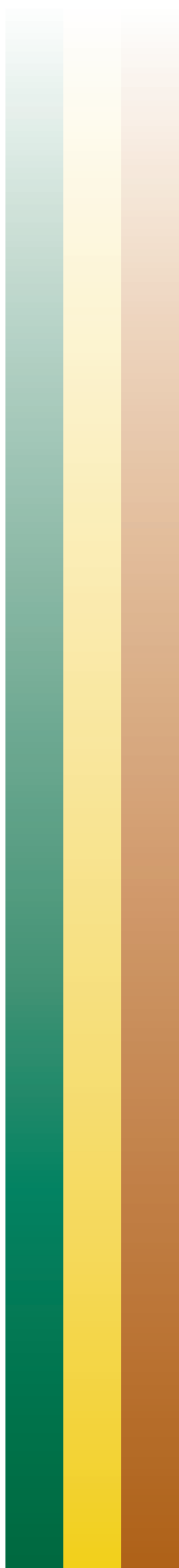
**Table 3. Changes in Xanthophyll content of export-condition U. S. corn stored at 25 or 30 °C.**

	25 °C			30 °C		
	No Treatment (mg/kg)	Cleaned Only (mg/kg)	Mold Inhibitor (mg/kg)	No Treatment (mg/kg)	Cleaned Only (mg/kg)	Mold Inhibitor (mg/kg)
Initial	12.8	15.6	13.2	14.7	11.0	17.4
Final	11.4	13.6	13.6	12.3	13.2	10.1

\* ADF = All Digestible Fiber  
 NEG = Net Energy for Growth  
 NEM = Net Energy for Maintenance  
 TDN = Total Digestible Nutrients

## **Appendix V. Summary of Recommendations**

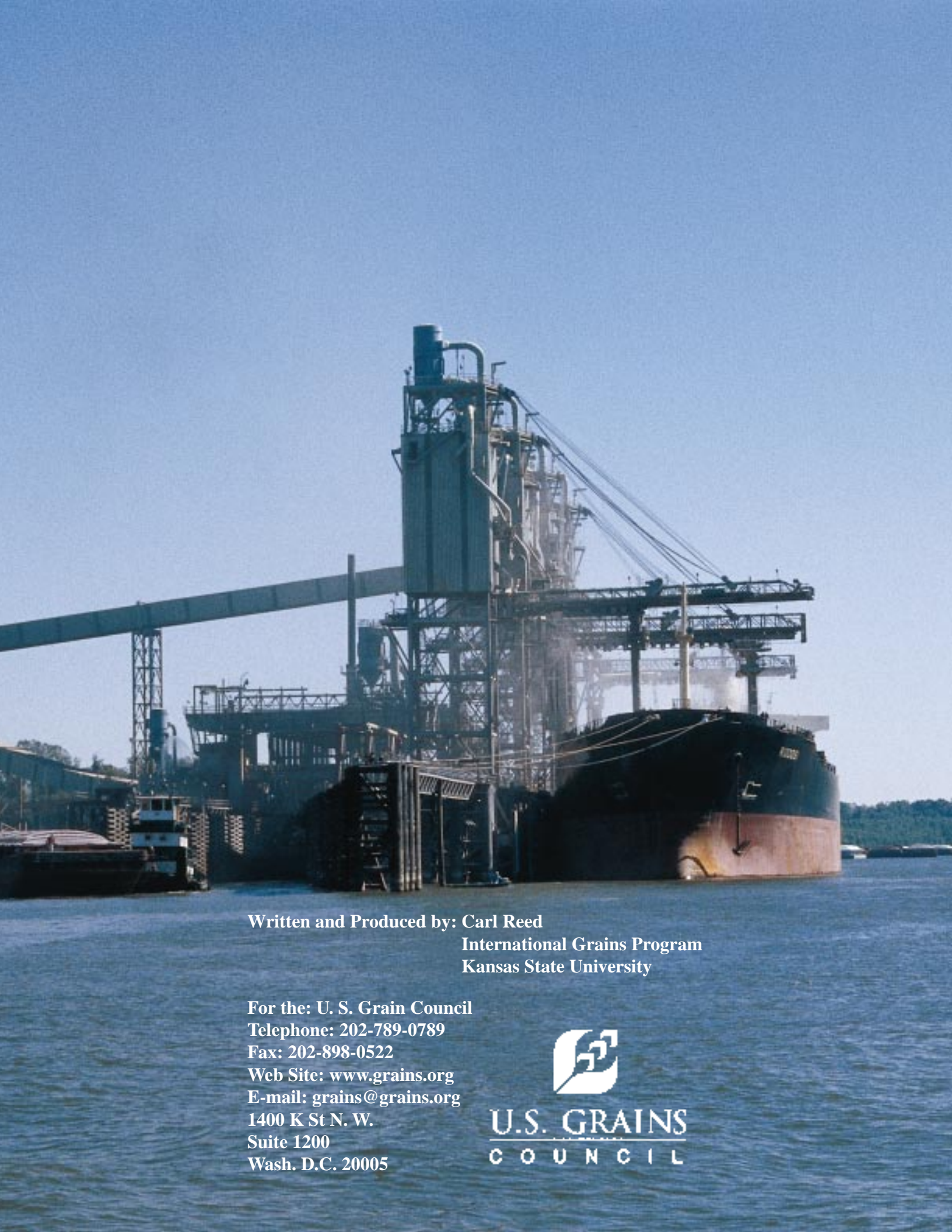
- |   |  |
|---|--|
| 1. <b><i>Contracting</i></b>            | Specify a maximum moisture content (14.0–14.5%).   |
| 2. <b><i>Cleaning</i></b>               | Clean (screen) the corn to remove fine material  |
| 3. <b><i>Inventory Rotation</i></b>     | Use the oldest grain first unless other grain is heating. Proper rotation includes removing all the grain from the bin before refilling the bin.   |
| 4. <b><i>Coring</i></b>                 | Core the grain before storage to remove spout lines and equalize the grain height for efficient aeration.  |
| 5. <b><i>Sanitation</i></b>             | Clean bin bottoms and handling equipment, and remove accumulations of grain material.  |
| 6. <b><i>Moisture Monitoring</i></b>    | Segregate corn containing more than 14.5% moisture content and use it first.   |
| 7. <b><i>Temperature Monitoring</i></b> | Monitor grain temperatures with installed temperature cables, push rods, or by grain sampling.   |
| 8. <b><i>Aeration</i></b>               | <ul style="list-style-type: none"><li>• grain temperature should be monitored to determine when to begin aeration</li><li>• the grain temperature also should be monitored to determine the location of cooling front</li><li>• aeration should be used to control grain temperatures, not to dry the grain</li><li>• aeration should begin only if the grain temperature exceeds the average daily temperature, or if a part of the mass begins to heat</li><li>• unless there is a hot spot, fans should be operated when the air temperature is less than the average daily temperature</li><li>• airflow rates of no less than 0.3 m<sup>3</sup>/min/m<sup>3</sup> are recommended for the tropics</li><li>• small extraction fans (roof fans) may be used to cool air above the grain</li></ul> |











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