23 Temperature Monitoring

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Grain moisture content and temperature are the two most critical factors for maintaining grain quality during storage. Under unsafe grain temperatures and moisture content, cereal grains and oilseeds deteriorate and produce heat, water, and carbon dioxide (CO_2). Most, if not all, processes by which stored crops deteriorate are exothermic. Measuring increase in grain temperature, moisture content, and CO_2 are effective for detecting incipient deterioration. Studies have shown that measuring CO_2 concentrations in the intergranular air can faciliate early detection of spoilage in storage grain bulk (Muir et al. 1980, 1985, Singh et al. 1983, Sinha et al. 1986a, b, c). Using CO_2 sensors to monitor grain quality is still under investigation (Maier et al. 2010). Researchers are developing an inexpensive, highly accurate CO_2 sensor (Neethirajan et al. 2009, 2010). A device to measure grain moisture content in-situ is not commercially available.

Compared to CO_2 and moisture content, continuous temperature monitoring within grain masses is relatively easy and inexpensive using thermocouples. The accuracy of temperature sensors sold on the market is about 0.5℃. Measured temperature and relative humidity (RH) can be used to predict grain moisture content based on equilibrium moisture content (EMC) equations. The predicted EMC can differ by more than 0.25 percentage points with grain moisture contents (dry basis) measured using the oven method (Uddin et al. 2006).

Although measuring grain temperature has limitations and drawbacks; it is an effective, commercially practicable, reliable, common, and traditional method of detecting incipient grain deterioration and monitoring grain quality. One important advantage of temperature monitoring is that it provides information on a wide range of grain quality parameters when the measured grain temperatures are correctly interpreted. For example, measured grain temperatures and grain moisture contents can be used to estimate storage life of grains and oilseeds.

Heat Produced by Living Organisms

All living organisms in a grain bulk respire, including grain, insects, mites, and microorganisms. During respiration the carbohydrates, fats, or proteins in the grain or in the living organisms are oxidized. The general respiration process is described approximately by the formula:

$$C_6H_{12}O_6 + 6\ O_2 = 6\ CO_2 + 6\ H_2O + 2870\ kJ$$

Applying this formula, 15.7 kJ of heat is produced for each gram of $C_6H_{12}O_6$ broken down (Zhang et al. 1992). The amount of heat released is 3946 kJ per gram of lipids and 15.7 kJ per gram of glucose (Multon 1988). Glucose fermentation usually occurs when oxygen is limited or absent – under airtight conditions, for example. The heat released under fermentation conditions is about one-tenth of that released under aerobic conditions (Multon 1988). The total respiration of the living organisms increases with temperature, grain moisture content, infestation level, and degree of fungal spoilage (White et al. 1982 a, b).

The heat produced by grain normally is not an important factor in the grain storage ecosystem because, under safe storage conditions, grain has negligible respiration rate (Hummel et al. 1954). There is no evidence that respiration of the seeds themselves is a major factor in total respiration, heating, or other deteriorative processes in stored grain. The heat produced by the dry cereal grain itself may be about 0.01 W/t (Zhang et al. 1992). Respiration rates of molds and bacteria are usually much higher than that of the dry grain except when moisture content rises rapidly and germination occurs (Sauer et al. 1992). Consumption of dry matter by respiration and heat produced by the grain itself under safe storage conditions usually can be ignored.

The peak rate of heat production by molds and moist grain at 45°C and 27% moisture content is 150 mW/kg of wheat (Zhang et al. 1992). The average rate of heat production (mW/kg) over the initial storage period until 0.1% dry matter loss has occurred in wheat is 2 for 20°C and 17% moisture content; 7 for 30°C and 17%; and 36 for 30°C and 25% (White et al. 1982 a, b).

When moisture is high, it is difficult to separate the respiration between grain and mold. Actually, mold is the more important contributor of the heat produced in damp or wet grain (about 85 to 95%). For example, wheat stored at 24% moisture content can rapidly deplete oxygen to 0% in two to three days, while CO_2 continually increases. At 17% moisture content, it takes 70 days for the oxygen to drop to near 0%. At 14% moisture and 15°C there is less than 2% reduction of oxygen in 18 months (Bell and Armitage 1992).

The rate of heat production by adult rusty grain beetle is 4 to 20μW per insect (Cofie-Agblor et al. 1996) and 66 to 81 μW per insect by granary weevils (Cofie-Agblor et al. 1995). Heat production (or rate of respiration) increases with temperature and moisture content of the wheat and changes only slightly with age and population density. Grain stored at safe moisture content and in otherwise safe storage condition, except for the presence of insects, can develop hot spots. This heating, which can only be attributed to heat released by the insects, is termed dry grain heating.

Postharvest maturation of grain may affect respiration and the amount of heat produced. Grain, such as wheat, might follow a complex series of biological and chemical changes immediately after harvest (Sinha 1973). Seed germination at the beginning of this period is low and increases over several weeks. Moisture content of the grain and temperature can influence the length of this period. This may explain why freshly harvested grain passes through a sweating period when grain temperature rises, and spoilage may occur (Muir 1999).

Water and heat produced during respiration increases moisture content and product temperature. Such increases may increase the growth rate and respiration of pests and microorganisms. A succession of organisms can occur. For example, insects in dry grain can produce sufficient moisture that fungi can begin to grow. This results in grain deterioration within hot spots, while grain outside the hot spot is still at safe storage moisture content. The heat produced and the increased grain temperature are the reason grain temperatures should be measured to detect deterioration.

Temperature monitoring cannot detect all of the mold and insect infestations even though the temperature cables are located at the infestation locations. In wheat and corn at 14.0 to 14.5% moisture and 10 to 25°C, *Aspergillus restrictus* grows so slowly that it causes no detectable rise in temperature (Sauer et al. 1992). Blue-eye of corn is produced by spore masses of fungi without a temperature rise in the grain. Insects at low density will produce a certain amount of heat, which is undetectable using temperature sensors currently on the market.

Heat Transfer and Temperature Gradients in Stored Grain Bulks

Inside the mass of stored grain, heat can be transferred by conduction, convection, and radiation. During storage without aeration, the grain temperature is mainly influenced by conduction (Smith and Sokhansanj 1990, Jayas 1995, Jian et al. 2005). The thermal properties (such as thermal conductivity and thermal diffusivity) of the stored grain influence heat transfer. Thermal conductivity is used to calculate the rate at which heat moves through a material. Thermal diffusivity is used to calculate the rate at which the grain will change temperature. The faster heat is conducted through a material, the more rapidly its temperature will change. The more the heat required to change the temperature of a given volume of material, the slower the temperature will change. Grain with low thermal diffusivity will change temperature slowly. Although glass wool (a common insulation material of buildings) has a lower thermal conductivity than wheat, the temperature of a bin of glass wool changes about 22 times faster than that of a bin of wheat because wheat has a higher density and specific heat than glass wool, which results in lower thermal diffusivity. But glass wool is a better insulator because it transfers heat at about one-third the rate for wheat. Compared with wheat, rapeseed (canola) has a low thermal diffusivity mainly due to its low thermal conductivity. Wheat cools faster in fall and warms faster in spring. This is one of several reasons it can be more difficult to safely store canola than wheat. Low thermal conductivity and diffusivity of the grain are the main reason heat produced inside a hot spot is prevented from dissipating.

Freshly harvested grain loaded into an unaerated bin in the fall will cool by conduction toward the bin's periphery. Grain temperatures near the walls (within 15 cm) are mainly influenced by seasonal weather temperatures (Figure 1). Solar radiation causes the temperatures at the south and west walls to be higher than at other locations from August to March in the Northern hemisphere. Bin wall and grain temperature is also influenced by bin surroundings. For example, if the bin is under the shadow of a structure, the bin under the shadow will not receive solar radiation. Jian et al. (2009) found that temperatures at the north wall of the tested bin were not the lowest temperatures during winter, and temperatures at the east wall were the highest temperatures from the March to August. They suspected that the dyke to the east and the identical silo north of their test silo might have influenced wind speeds and directions that cause the temperatures on the east wall to have the largest fluctuations. Montross et al. (2002) also found that pilot bins were more heavily influenced by wind than conventional-sized bins.

There are different temperature gradients at different sides of bins due to the differences of wind speed, solar radiation, and surroundings of the bins. The temperature gradients in uninfested steel bins of farm-stored wheat or barley (39 to 217 t) in the autumn and winter range from 1.2 to 15.3°C/m and from 3.1 to 20°C/m, respectively, in infested steel bins 1 m below the top of the grain bulk in Manitoba, Canada (calculated from the data of Loschiavo 1985). In the United States, temperature gradients in farm-stored wheat often reach 7 to 10°C/m in the

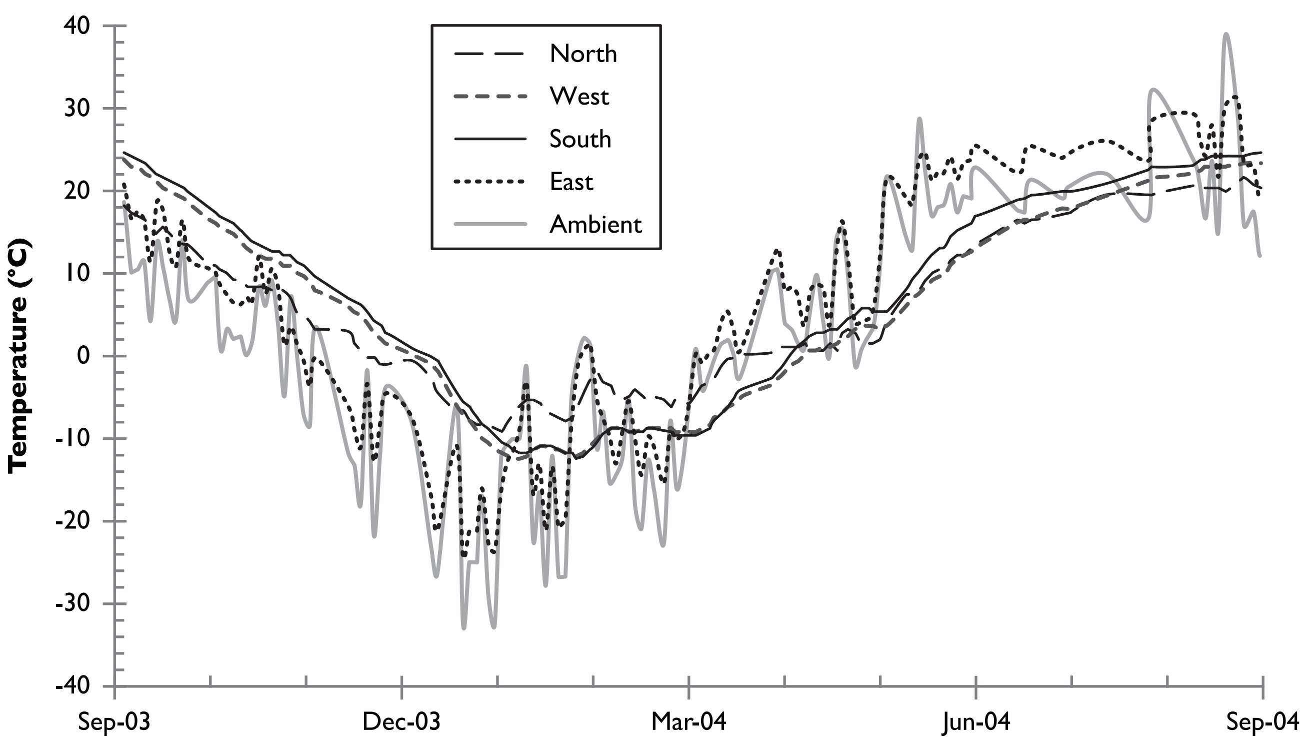

Figure 1. *Hard red spring wheat temperatures at 15 cm away from the walls and 1.0 m depth in a flat-bottom steel bin (3.7 m diameter, 5.7 m high) near Winnipeg, Manitoba, Canada (49°54'N, 97°14'W).*

autumn and winter months (Hagstrum 1987). In a galvanized steel silo located near Winnipeg, Manitoba, Canada, the highest temperature gradient was 32.4°C/m, and it was located at 0.0 to 0.90 m from the center. At this location, the average temperature gradient was 10.8°C/m during the 15-month experimental period (Jian et al. 2009).

The directions of the temperature gradients also vary depending on location and time. During summer, the wall temperature might be higher than at other locations, while in winter it will be lower. Temperatures of the grain at the top and bottom of flat bottom silos are mainly influenced by the headspace and soil temperatures, respectively. This causes the complex distribution of temperature gradients inside silos. The following factors also influence grain temperatures and temperature gradient distribution: initial grain temperature, grain moisture contents, bin wall materials, bin structures (shapes and bottom configurations), bin diameters, grain and bin heights, geographical locations, grain types, storage times, and operations (such as grain turning and aeration). The interpretation of temperature data should be based on temperature distribution patterns and heat transfer theories.

Methods of Temperature Measurement

Temperature measurement methods can range from persons feeling stored-crop temperatures with their hands, to using a computer to control temperature measurement and fans automatically. For example, if devices for measuring temperature are not available, a metal rod can be used to estimate the grain heating and spoilage using following procedure: 1) Insert a metal rod at least 1 m into the grain mass; 2) Leave the rod for approximately 30 min; 3) Remove the rod and, with the palm of the hand, test it for warmth and wetness at various points of the rod. Any section of the rod that feels warm or wet to the touch is an indication of heating and grain spoilage.

Harner (1985) described temperature monitoring systems that were commercially available before 1985. Temperature measurement devices commercially available now include temperature probes, temperature cables with handheld monitors, personal computer (PC)-based temperature monitoring systems, and computer control systems.

Temperature Probe

A temperature probe is made of a 1- to 4-meter steel rod with one to three sensors. If the probe has only one sensor, it will be located at the tip. Manufacturers also make probes longer than four meters and more than four sensors along one metal rod, if asked. The thermocouples, thermistors, or digital temperature sensors inside the rod can be connected to a digital handheld reader at any time. This handheld reader can be a single probe or up to several probes (multi sensors) connected to a monitor with LCD display. Models made by some companies can store the temperature data for a year or more and graphically display the history of the measured grain temperatures.

A temperature probe usually is not permanently installed in a grain silo. It is carried around, pushed into the grain mass and left for at least a half hour to measure temperature. During grain loading and unloading, temperature probe(s) should be taken out of the silos. The data stored inside the handheld monitor can be transferred into a PC so temperatures can be displayed. Probes also can be directly connected to a PC. This connection is similar to PC-based temperature monitoring system.

PC-Based Temperature Monitoring System

Even though different manufacturers have different PC-based temperature monitoring systems and use different terms, the system usually consists of hardware (suspension, anchor, and accessories), temperature cables, connector (lead wire), RTU (remote terminal unit) box (central reading station, remote scanner), power supply, wire (communication cable), converter, and PC (Figure 2). The communication cable can be replaced by one pair of radios.

The temperature cable may comprise an inner sensing element and outer cable jacket. The sensing element (sensors and conductors) is housed inside a protective cable jacket, which can be a tube or a layer of coating over the sensing element. The tube or cable jacket is fastened to the roof and floor of the silo. For ease of maintenance and repair, the sensing element can be removed from the tube. (This is called a retractable cable). Companies try to make small cables because a smaller diameter cable jacket reduces the pulling force on the cable during grain

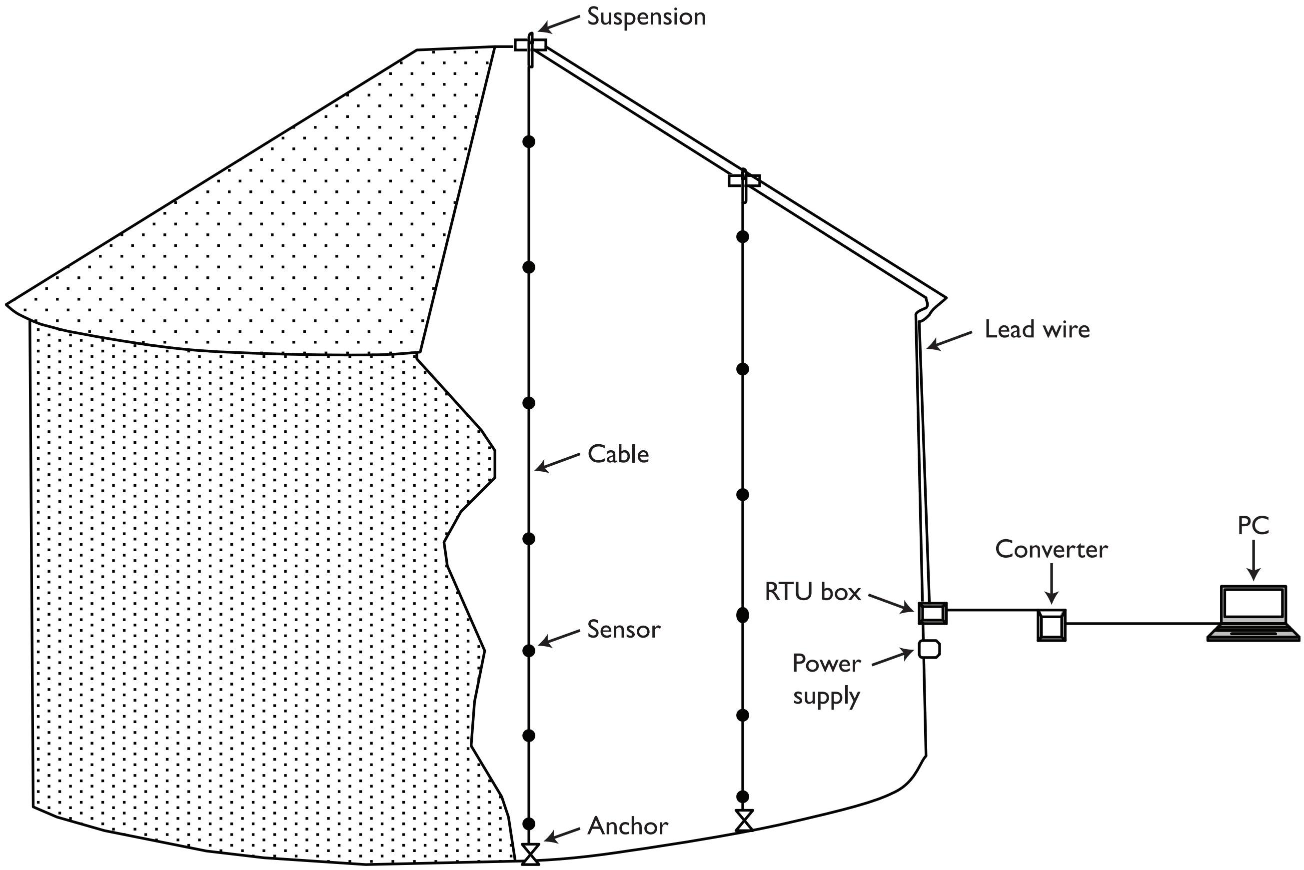

Figure 2. *Schematic presentation of a PC-based temperature monitoring system.*

unloading. To reinforce the retractable cable, which bears the pulling force, the tube is coated and lined with high-strength steel wire. Retractable cables allow the sensors to be changed without removing the cable tube, even if the silo is full of grain.

Because the temperature in the grain mass varies, the sensors must be adequately distributed throughout the stored mass. The number of sensors in a cable mainly depends on cable length and distance between sensors. Companies usually recommend that the maximum length between sensors is 5 meters. The best result is achieved if the distance between the sensors is kept around 1.2 to 1.8 meters or less. The temperature cable can be installed permanently or temporarily. From an economic and practical viewpoint, the cable should be installed permanently.

The sensing element can be a T-type thermocouple, high-impedance thermistor, or digital temperature sensor. The digital temperature sensor provides the highest accuracy reading. Multiple sensors per cable and multiple cables per bin can be interconnected inside the RTU box to form one simple two-wire connection (the communication wire). If the cable does not contain digital sensors, addressing sensors and converting analog signal to digital signal will be completed in the center reading station (remote scanner). The signal transmitted via the communication wire or the pair of radios is read by the software installed in the PC.

The PC-based software of the temperature monitoring system usually provides the following basic functions: field input and site configuration, site and structure navigation, and statistics of the measured grain temperatures. Field input and site configuration let the user enter information about the structure, such as grain type, moisture content of the grain, and grain loading date. Site and structure navigation let the user find the right cables and sensors to view the measured grain temperatures. Temperatures can be reviewed using graphs or tables. The graph or table can show the history of the grain temperature in time scale or current temperatures inside the entire structure. The views of grain temperatures provide statistical information associated with the measured grain temperatures, such as the average, maximum, minimum grain temperatures at one cable location or inside the entire structure.

Some companies also incorporate several advanced functions such as level, reports, printing, and alarm. The level function estimates the grain depth at each cable location. Based on the estimated grain depths, the total volume of the grain inside the silo is estimated. Report and printing functions help the user document the measured grain temperatures. Based on the user setting, such as the high limit temperature and the rate of rise in grain temperature, the system can generate alarms. Alarm output can be on-screen and on-site (audible or visual) or delivered via text messaging and email if the system is connected to the Internet.

Computer Control Systems

The computer control system connects the PC-based temperature monitoring system with fans and other measurement and control devices. For example, the Intergris pro developed by OPIsystems (Calgary, Canada) connects the temperature-monitoring system with temperature cables, Insectors, moisture cables, fans, heaters, and roof ventilation fans. The system measures temperatures, relative humidities, pressures inside silos (including grain mass, plenum, and headspace), and the ambient air. The measured temperatures and relative humidities are used to calculate grain moisture content. The Insector system classifies captured insects into species groups and estimates the insect densities at each Insector location. Based on this data and user setting – such as aeration, natural air drying, and drying with heater – the software can do calculations and make decisions. The PC sends control signals to field devices to prompt starting and stopping of aeration fans and roof ventilation fans, for example. This system is fully modular and can adapt to any storage configuration and still allow for expansion. Computer control systems make automatic multiple silo control possible.

Location of Temperature Sensors

To detect spoilage spots in the early stages, the ideal distance between two temperature sensors and between two cables must be within about 0.5 meter (1.64 ft) (Singh et al. 1983) and temperature must be measured on a closely spaced grid. This distance might be impractical because too many cables would increase cost, roof loading, and increase the difficulty of grain loading and unloading. To measure temperature economically, measurements should be taken at locations where spoilage is expected, rather than on a grid of measurement points. For example, cable should be installed at locations where dust and dockage (broken kernels, weed seeds, etc.) accumulate. At least some sensors should be located at the center of the silo because the largest moisture accumulation in non-aerated grain storage usually is at the top center of grain bulk. The center of a grain silo without aeration usually can maintain high temperatures that allow insects to survive and multiply. Insects enter the silo from the top and gradually move down into the grain. Warmer temperature in the headspace will help insects multiply at the top center of the silo. Also multiplication of insects at the top of the grain mass might also initiate hot spots there.

Cables are installed before grain loading and will be used for several years. The grain silo might store various grain types at different depths. This increases the difficulty of predicting spoilage locations. Usually, cables are installed with equal distance between them. Some companies consider possible spoilage locations when making recommendations.

Temperature Measurement Frequency

Measurements should be taken consistently and frequently because temperature change is more significant than the temperature itself at any given time. During spring in Manitoba, temperatures of a fungus-induced hot spot rose from 20 to 65°C, and then cooled back down to 30°C within about two weeks. If the interval between readings is more than two weeks, such a hot spot may not be detected by temperature measurement. With PC prices decreasing and CPU processing ability increasing, temperature measurement in less than a half hour over the entire storage period is possible. In some measurement situations, the larger distance between sensors might be remedied by increasing measurement frequency.

Even though well-designed software can expedite the process, monitoring temperature consistently and frequently takes time. The amount of time should be based on grain storage and weather conditions. For example, temperature should be checked more frequently during hot weather. If grain moisture content is higher than recommended for safe storage, temperature measurement and review frequency should be increased. The common practice is that if grain is not under safe storage condition (because of warmer temperature, damp grain, and possible insect infestation), temperature should be measured at least every three hours, and reviewed every one to two days. If grain is under safe storage condition, measurements can be taken daily and reviewed biweekly.

Interpretation of Temperature Readings

Temperature measurement is not only used to detect active deterioration but also to indicate, along with moisture content and infestation information, potential for deterioration (or safe storage time). Each spoilage process has temperature ranges in which the rates of deterioration are rapid, slow, or prevented. For example, optimum development of the granary weevil (*Sitophilus granarius* L.) occurs at 26 to 30°C; for the saw-toothed grain beetle (*Oryzaephilus surinamensis* L.) it occurs at 31 to 34°C (Loschiavo 1984). Magnitudes of measured temperatures, temperature differences among locations in the stored bulk, temperature gradients, and changes in temperatures over time must be correctly interpreted. Correct interpretation requires a general knowledge of storage ecosystems and experience with specific types of grain, grain bins, and climate. Grain physical properties (such as thermal conductivity and thermal diffusivity) and heat and mass transfer theory should be used to interpret temperature readings. For example, wheat and canola stored inside the same structure and at the same geographic location would have different temperature gradients. Compared with canola, wheat cools faster in fall. It also warms faster in spring because wheat has higher thermal diffusivity than canola. Hot spots might be more difficult to detect in canola than in wheat.

To correctly interpret the temperature reading, the more information that is collected the better. Information should include history of the temperature reading, pattern of temperature distribution, temperature difference between sensors, and temperature rise rate at a particular location, grain infestation and insect species, grain moisture content and distribution, structure and surrounding of the silo, weather data, and history of the operation inside the silo. For example, fungi can grow at temperatures as low as -5°C, and mites can continue reproducing at 5°C. A low-level infestation or infection undetectable by temperature measurement can do considerable damage over a long storage time. Also, such a situation can rapidly develop into a major problem when conditions in the bulk move into optimum ranges for the pests. This information should be used to detect major problems as early as possible.

Temperature Patterns of Stored Grain Without Aeration

In Canada, wheat is normally harvested in late summer or early fall when the outside air temperature is decreasing. The newly harvested wheat usually has a higher temperature than the outside ambient temperature due to the solar radiation on the heads of the grain swath. On sunny days the temperatures of wheat heads on the top of the swath and in standing crop are about 7°C above the ambient air temperature (Williamson 1964, Prasad et al. 1978). The grain kernels maintain this increased temperature as they move through the combine to the truck and into the storage bin.

At all North American latitudes in an unventilated bin, wheat begins to cool at the bin's periphery. A few days after grain loading, temperature gradients develop from the bin center to the periphery of the bin. From the beginning of the grain loading until the ambient weather temperature begins to rise in spring, the warmer grain in a bin will be at or near its center.

In spring and summer, the bin warms along with the ambient temperature. Temperatures of the grain near the walls rise above the temperatures of the grain at the center. Grain near the walls and the headspace will be warmer than in other places.

Bin diameter and grain depth are two main factors that influence the temperature pattern inside the bin. As bin diameter increases, center temperature changes more slowly. Small bins cool most rapidly in the fall and warm most rapidly in the spring. Increasing bin diameter will decrease the difference between maximum and minimum temperatures. Grain loading time and initial temperature and storage time also influence the temperature pattern in bins (Jayas et al. 1994).

Monitor Grain Temperature in Bins Without Aeration

For economic reasons, there are usually no cables at or near the walls. This increases the difficulty of identifying the temperature distribution pattern. Daily average of the ambient temperature (or weather station data) could be used to approximate the grain temperatures within 15 cm away from the walls. Grain temperature distribution pattern and temperature fluctuation should be monitored at least biweekly.

During spring and summer, grain temperature at the center of silos is cooler than the ambient temperature. If fan ducts located at the bottom of the silo are not properly sealed, the dense air at the center of the silo will leak out through the unsealed fan ducts. This moving air will drive warmer air inside the headspace down to the grain mass. Daily monitoring of grain temperature and rate of temperature increase at the locations close to the headspace can detect this problem.

Temperature Patterns of Grain Bulks with Hot Spots

Hot spots refer to small patches or pockets of grain that are warmer than surrounding grain in the bin of sound grain (Sinha and Wallace 1965). Insects and mold can initiate hot spots. After a hot spot is initiated, heat and moisture produced by biological respiration will speed the rate of grain temperature increase because the heat-insulating properties of the grain prevent heat from dissipating. For example, the temperature in a developing hot spot in a wheat granary increased 10°C from 0°C in three weeks, and then increased a further 54°C to a maximum temperature of about 64°C in only 10 more days (Sinha and Wallace 1965). When active spoilage is localized in a bulk, a sharp temperature gradient can develop. For example, the temperature only 45 cm from the 64°C grain was still at the normal grain temperature of 10 to 15°C (Sinha and Wallace 1965).

The size of hot spots depends on the amount of moist grain and moisture content around the hot spot. It can be as small as 50 cm in diameter. Small spoilage pockets may die out as the heat produced causes convection currents and moisture diffusion that dry out the moist spoiling grain. It is not clear when and how the small spoilage pocket dies out. A large hot spot may continue to increase its size with accompanying increases in temperature, moisture content, and deterioration of the grain. When the grain temperature reaches above 60°C, biological respiration of the grain might cease and chemical oxidation may continue. Grain temperature can reach 380 to 400°C after oxidation (Muir 1999), and this high temperature can cause the entire bin to catch fire if enough oxygen is available.

Hot Spot Detection

When there are hot spots inside the grain mass, determination of the temperature distribution pattern (including seasonal pattern and the temperature distribution pattern around the hot spot) and rate of temperature increase at a given location are important. For example, a temperature at the center of a bulk that is higher than the ambient temperature can mean either the grain is spoiling or the grain has not cooled from its initial storage temperature. Yaciuk et al. (1975) reported that the temperature at the center of an unaerated, 8-meter diameter bin of sound wheat stored at 25°C at harvest time in Canada can still be at 25°C on January 1, four months after harvest, when the ambient temperature is below –20°C. Without the history of measured grain temperature at the center location, it can be mistaken as a hot spot.

Because of the low thermal diffusivity of grain, hot spots affect the temperature of the grain only a short distance from the center of the hot spot. Detection of a small hot spot requires temperature measurements in less than one week and at intervals of less than 50 cm apart. The distance between cables is usually larger than this recommended distance. If measurement intervals are less than one day, temperatures associated with larger than 50 cm distance might be used to detect some hot spots (if not all).

Based on the temperature distribution pattern and temperature increase rate, at least two hot spots could be identified in a flat bottom bin located in the U.S. Midwest (Table 1). One hot spot is located

Table 1. *Locating hot spots in a 140-foot (43 m) diameter flat-bottom bin with corn 70 feet (21 m) deep in the US Midwest, using 36 cable Integris^Pro system developed by OPIsystems Inc., Calgary, Canada.*

Grain depth (ft)	Selected Cables									
	C1	C2	C3	C5	C6	C9	C10	C23	C28	C33
80	48.0	89.4	53.8							
76	53.3	57.7	56.9	51.0	53.4					
72	61.1	55.9	55.8	49.8	55.0	49.8	51.3			
68	71.2	57.0	54.3	49.3	54.9	45.5	51.6	50.2		
64	73.1	56.0	54.3	51.0	54.3	41.3	51.1	47.3	19.1	45
60	69.4	52.0	53.1	52.9	52.2	41.5	49.6	42.5	9.0	36.6
56	52.5	41.6	52.5	53.8	48.6	41.9	45.0	39.6	0.8	29.3
52	54.6	35.1	53.1	52.9	45.8	40.3	38.9	33.1	-2.9	21.9
48	54.1	24.1	55.2	52.3	43.0	38.9	31.9	31.7	-2.9	14.6
44	53.9	16.7	54.5	50.2	38.1	36.7	24.2	26.1	-1.5	4.9
40	52.2	8.5	53.1	49.2	34.9	33.6	15.6	19.1	2.8	1.3
36	51.5	4.9	53.0	47.9	34.0	30.6	4.5	9.2	13.9	1.9
32	50.4	5.6	51.6	45.7	27.4	26.5	0.8	3.0	31.0	4.3
28	47.1	12.8	50.5	41.3	20.1	24.5	2.7	1.7	31.8	9.0
24	31.1	28.7	46.6	40.1	11.7	22.9	9.1	2.8	25.5	18.0
20	19.9	31.0	43.8	36.7	3.1	21.5	28.2	21.1	23.9	28.7
16	29.6	27.7	25.6	34.4	4.0	24.2	32.2	28.3	26.9	29.5
12	25.1	30.8	6.7	41.4	20.9	19.3	26.1	29.2	28.3	26.4
8	20.6	26.5	6.2	46.0	33.4	16.2	26.5	28.9	27.2	28.3
4	19.3	24.3	31.9	17.5	26.2	31.4	27.8	27.9	27.3	25.6
0	18.8	19.7	26.3	12.9	27.9	32.3	17.9	27.5	27.4	24.1

at the center of the bin and 8 feet down from the surface of the grain mass (C1 in Table 1). The size of the hot spot might be 16 feet in diameter. The second hot spot is located at the C2 and at the surface of the grain mass. There might be other hot spots at the surface of the grain mass and at the locations C3, C5, C6, C9, C10, and C23. The hot spots might connect with each other. After sampling and further monitoring, it was confirmed that there were at least two hot spots at the center location. The hot spots at C3, C5, C6, C9, C10, and C23 were a thin layer (less than 1ft), and the grain in this layer spoiled and sprouted because of water dripped on grain from condensation on the bin ceiling.

Temperature cables also can be used to monitor aeration and drying (see chapters 10 and 11). Drying fronts can be located because of evaporative cooling during drying.

Prediction by Temperature Models

Grain temperatures and moisture contents inside grain silos can be predicted by published mathematical models (Jayas 1995). Even though the mathematical simulation is less accurate than actual tests, calibrating and validating models can verify and improve their accuracy. Mathematical models are used by some companies for customer consulting, management strategy planning, fan selection, and storage structure design. Using a mathematical model to control grain aeration (without measurement of grain temperatures) is marketed and practiced by one Australian company (Aeration Control Australia, Joondalup WA).

If a mathematical model is combined with a PC-based temperature monitoring system, the predicted temperatures can be checked and corrected frequently by the measured grain temperatures. The advantage of this combination is that the model can show the right pattern and possible trend of the temperature distribution. Also, the model can warn users of impending storage problems. By comparing the pattern predicted by the model with that of measured temperatures, hot spots can be easily detected at the early stage. For example, when the fungus-induced hot spot was at 3°C, the temperature of the hot spot began to rise above the temperature of the control bin, indicating active spoilage (Sinha and Wallace 1965). But this temperature rise due to biological deterioration would not be readily apparent if a control bin was not available for comparison.

Future Research and Application

Even though temperature monitoring can be conducted by using inexpensive and simple methods, new technology will be developed and the measurement technique will be continuously updated. There might be an opportunity to increase the temperature sensor accuracy because the sensor accuracy on the market is about 0.5°C. Reducing the distance between cables and sensors is one of the methods for an early detection of grain spoilage. Decreasing cable diameter without losing load-bearing capacity might help make this possible. Mathematical models with a high accuracy will play a role in grain temperature monitoring and storage management. To decrease the costs of grain temperature monitoring, mathematical simulation without temperature measurement might make grain storage management possible.

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