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Abstract. *The primary objective of this study was to determine the effectiveness of detecting a hot spot primarily due to spoilage of high moisture corn in a stored grain bulk with a CO_2 sensor installed in the headspace of the bin compared to detecting with temperature cables. Three experimental trials were conducted in a 12.5-t pilot-scale bin from September 2001 to March 2002. A hot spot in the grain bulk was initiated by dripping a controlled amount of water into a confined grain mass held in five layers of cylindrical mesh trays within the grain bulk. Temperature sensors in the core of the hot spot formation monitored its progress and confirmed biological activity, which paralleled the increasing CO_2 concentration recorded by the CO_2 sensor in the headspace of the bin. CO_2 concentrations in the bin headspace rose from the initial base level of 500 to 1500 ppm for Trial 1, 1700 ppm for Trial 2, and 2300 ppm for Trial 3 and were recorded after 400, 600, and 1800 h, respectively. There was a strong positive linear correlation between the rise in headspace CO_2 concentration and the parallel rise in temperature recorded by sensors in the core of the hot spot during all three trials. Field tests of spoilage detection with a CO_2 sensor conducted in 33,000- to 51,000-t grain piles and a 12,500-t cylindrical steel tank with stored corn indicated that a CO_2 sensor was effective in detecting the occurrence of spoilage in the stored grain and detected spoilage earlier than temperature cables. Spoilage detection was effective either by measuring CO_2 concentration of the air stream from a negative draft aeration duct with a handheld CO_2 sensor, or by installing a wall-mounted CO_2 sensor in the tank headspace. Our results show that temperature cables alone might not be a reliable indicator of stored grain conditions and CO_2 sensors could be used as an additional complimentary tool for stored grain management.*

Keywords. *Carbon dioxide, CO_2 detection, CO_2 sensors, Hot spot, Grain spoilage, Stored grain, Corn.*

The grain industry standard method for monitoring stored product deterioration utilizes temperature cables in storage structures and probing of grain for moisture content. To detect a pocket of spoiling grain, commonly referred to as a hot spot, moisture content or temperature must be measured in or near the spoilage because moisture and heat do not diffuse outward readily (Sinha and Wallace, 1965). In principle, the detection of metabolic heat produced by harmful organisms is a sound procedure because the existence of a hot spot in a grain bulk indicates that the grain in the affected area is in an advanced stage of decay (Singh et al., 1983). However, because of the low thermal diffusivity of bulk grain, a single temperature measurement must be within about 0.5 m (Sinha and Wallace, 1965) or less of an active spoilage spot to detect the self-heating. This means that deterioration occurring in the stored grain over 0.5 m away from the temperature sensor could proceed into advanced stages before any noticeable rise in temperature is recorded. Hence, alternative methods of detection need to be developed and incorporated into stored grain management protocols that enable detection of onset of biological activity in a more timely manner. The early detection of grain spoilage will limit product damage, help prevent dangerous mycotoxins in the food chain, and avoid financial loss due to the application of timely, appropriate, economical, and sustainable control measures that utilize temperature management (aeration, chilling), stirring and turning bins, ozonation, alternative residual stored grain protectants, and predatory insects using an integrated pest management approach.

Early studies by Bailey and Gurjar (1918) and Bailey (1921, 1940) showed that respiration of dormant seeds as estimated by laboratory techniques was closely related to the tendency of the grain to spoil and heat when stored in a bulk under unfavorable moisture conditions. Studies conducted in the 1940s and ’50s indicated that wheat stored below an equilibrium moisture content of 14.5% did not produce measurable CO_2 (Christensen, 1957). However, when wheat was stored at 18% moisture, CO_2 production was detectable in 5 days due to fungal growth, and the rate of CO_2 production increased rapidly over the next 10 days (Milner et al., 1947). This increase in CO_2 was detected before the temperature increase was detectable and was also greater than that of temperature.

In the late 1950s and ’60s, corn storability was determined as the rate of dry matter loss by measuring carbon dioxide given off when fungi metabolizes the carbohydrates in corn (Saul and Steele, 1966; Steele, 1967; Steele et al., 1969). They used the complete combustion of a typical carbohydrate represented by:

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$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + Heat(677.2\,kCal) \quad (1)$$

Equation 1 translates into 1.47 g of CO_2, 0.6 g of H_2O, and 677.2 kCal of heat produced for each gram of carbohydrate that is consumed (Thompson, 1972). The grams of carbon dioxide produced per kg dry matter under reference storage conditions (15.6°C, 25% moisture content, and 30% mechanical damage) was found to be related to storage time (Steele et al., 1969). Saul and Steele (1966), Steele (1967), and Steele et al. (1969) conducted the foundational work that led to the development of the shelled corn storage time (SCST) model which has since become the standard (*ASAE Standards*, 2005) used to calculate the storability of corn under conditions of temperature, moisture, mechanical damage, etc. Storability tests conducted by tracking the dry matter loss from small samples of corn have been perfected over the years and determined quite accurately in laboratory experiments (Fernandez et al., 1985; Wilcke et al., 1993; Dugba et al., 1996). Even though the measurement of CO_2 as a reliable indicator of the stored grain condition is well established, the tracking of CO_2 in a grain bin has not been developed as an additional tool for monitoring spoilage and/or dry matter loss.

Muir et al. (1985) investigated the use of carbon dioxide as an early indicator of stored cereal and oilseed spoilage. They measured the concentration of carbon dioxide in interseed air in 39 farm-stored bulks of wheat, rapeseed, barley, and corn stored mainly in galvanized steel bins and a flat shed in Manitoba, Canada and Minnesota, United States. Spoilage was confirmed by analyses of the probed grain samples in 97% of the 34 bins having CO_2 concentrations greater than ambient air CO_2 concentration (»400 ppm). They stated that the best sampling point for measuring CO_2 concentration was in the spoilage pocket but when its location was unknown, the next best point was at the center of the bin about 1 to 2 m below the grain surface. Despite the fact that their results showed that active spoilage of stored cereal and oilseed crops by insects, mites, fungi, and a combination of these pests can be detected in farm granaries by measuring the concentration of CO_2 in the interseed air (Muir et al., 1985), the practical application was not feasible at the time. Their method required that the position of the hot spot within the grain mass was known in order to take a reading of the CO_2 concentration of the interseed air within the deteriorating grain pocket or close to it. Even though hot spots normally occur at the center of grain bulks, their development in other regions is a possibility and the location is generally not known.

In spite of the promising results obtained by Muir et al. (1985) for measuring CO_2 concentrations in stored grain to monitor grain deterioration and infestation, its use in the grain storage industry was never practically implemented. The major limiting factor was the equipment and laborious methodology used to obtain CO_2 data by previous researchers. Most researchers quantified gas concentrations in bins by first withdrawing samples of air with tubes from various depths of the grain bulk then analyzing them with a portable gas analyzer (Muir et al., 1985). Of the five CO_2 gas-sensing devices presented by Singh et al. (1983), none were suitable at that time for on-farm or commercial use in storage structures. This was due to their cost and non-portability (for gas chromatographs), instability (for leakseeker gas sensors), expensive operational cost (Draeger tube gas sensors), and inadequate resolution (Frite gas analyzer). Also, these were not instruments that could be placed in the storage structure for continuous CO_2 monitoring. Thus, laborious sampling would have been involved in collecting gas samples from grain bulks, which is impossible to implement due to worker safety standards that limit entry into confined spaces (OSHA Standard, 2005). Therefore, the reasons for the present non-utilization of CO_2 monitoring for on-farm and commercial grain quality management are quite evident.

Most biological organisms produce carbon dioxide, heat and water as by-products of their metabolism. Biological activity by insects, mites and fungi in a deteriorating grain mass increases the rate of carbon dioxide, heat and water production (hot spot). Of these three by-products of deterioration, carbon dioxide diffuses most readily from the source of generation. Thus, sensors located away from the deterioration pocket should be able to detect increases in CO_2 gas concentration. For example, the diffusion coefficient of heat in wheat is 0.000414 m^2/h (*ASAE Standards*, 2004) while that of CO_2 in wheat is 0.0134 m^2/h (Singh et al., 1983, Singh, 1982). Thus, CO_2 diffuses about 30 to 40 times faster than heat in a grain bulk. Additionally, a CO_2 sensor is most likely to detect any changes in concentration in the grain mass much faster than a temperature sensor placed at the same position would detect changes in temperature. Therefore, we hypothesize that we should be able to detect the onset of critical biological activity that results in grain deterioration with CO_2 sensors earlier than with temperature sensors, which is the currently "best available technology" on U.S. farms and in the U.S. grain storage industry. Early detection of a problem in these stored food products would allow stored grain managers to apply more timely and appropriate control measures to maintain quality, prevent economic loss, and ensure a safe product to the food supply chain.

Objectives

The primary objectives of this study were to:

- create and monitor CO_2 evolution from a developing hot spot primarily due to fungal growth caused by a small quantity of deteriorating high moisture corn in the grain mass,
- compare the effectiveness of tracking stored grain deterioration in a grain bin with a headspace CO_2 sensor and temperature sensors on cables located in the stored grain, and
- implement the use of a CO_2 sensor in the bin headspace and/or fan exhaust for early detection of grain spoilage in commercial storage structures such as bins, tanks and grain piles.

Materials and Methods

Pilot-Bin Experiments of CO_2 Detection from a Developing Hot Spot

A developing hot spot primarily due to fungal growth on the deteriorating corn mass was simulated in a corn bulk of about 9.6 t stored in a 12.5-t capacity pilot scale bin of 3.1-m eave height × ∅2.7 m with a 30° roof slope. The hot spot was initiated by automatically dripping water into a confined part of the grain bulk at the center, which gradually increased the grain moisture content to optimum conditions that permitted fungi spores to thrive and colonize the affected corn mass

creating a localized hot spot. The water drip apparatus delivered a given amount of water (about 125 to 250 g per day) to the surface of the confined grain mass via a solenoid valve. In Trial 1, a drip rate of 125 g was used at the beginning of the experiment and this was later adjusted to 250 g per day when the ambient temperature began to cool down. In Trials 2 and 3, the higher drip rate of 250 g per day was used throughout the experiment in order to compensate for the cooler fall/winter temperatures which prolonged mold development more than in Trial 1, which was conducted in early fall. The confined part of the grain bulk where water was dripped into was termed the hot spot module. It consisted of five cylindrical trays (16.5 cm height × ∅31.8 cm diameter) made from stainless steel mesh material and stacked in layers one on top of the other after they had been filled with corn from the bin. The hot spot module was confined and held in place in the corn bulk by extracting grain from the center with a shop vacuum while placing a perforated cylinder through the bulk such that the top of the cylinder aligned with the grain surface. The cylindrical mesh trays with corn were stacked in the perforated cylinder and designated from the top most layer of the stack as layer 1 to the bottom-most layer of the stack as layer 5. Figure 1 shows a comprehensive schematic diagram of the experimental set-up.

Temperature sensing thermocouples (three per layer) were placed at the center of the corn mass in the mesh cylinder layers. Because of cost, only one relative humidity probe each was placed in layers 1 and 3 to monitor interstitial relative humidity as the hot spot developed due to moisture increase of the grain. These sensors monitored the changes in temperature and relative humidity occurring during hot spot development due to fungi colonization in the corn mass. Temperature and relative humidity sensors were also installed in the headspace of the bin, and a CO_2 detector (Valtronics, Model 2156-R, Valley Springs, Calif.) was installed in the headspace above the hot spot module just below the roof to monitor headspace CO_2 concentrations during the experiment. A wind vane was mounted on the roof just by the side of the bin to monitor ambient wind conditions. A LabVIEW Virtual Instrument program was developed to control the drip apparatus and record data from all sensors via an I/O data logging system (FieldPoint, Model FP-1000, National Instruments, Inc., Austin, Tex.). The bin had five temperature cables with the center cable having six sensors and the other cables in the four cardinal directions having five sensors each. The center cable was the closest to the hot spot module and about 0.15 m (0.5 ft) from the periphery of the hot spot module. The other four cables were about 0.3 m (1 ft) from the bin wall and 1.2 m (4 ft) from the periphery of the hot spot module. Data of the grain bulk temperature at various points were recorded at 15-min intervals by the sensors mounted on the five cables. During the experiment, the bin was aerated for 20 min once every 3 to 4 days with an airflow rate of 0.15 m^3/min/t. The purpose of aeration was to

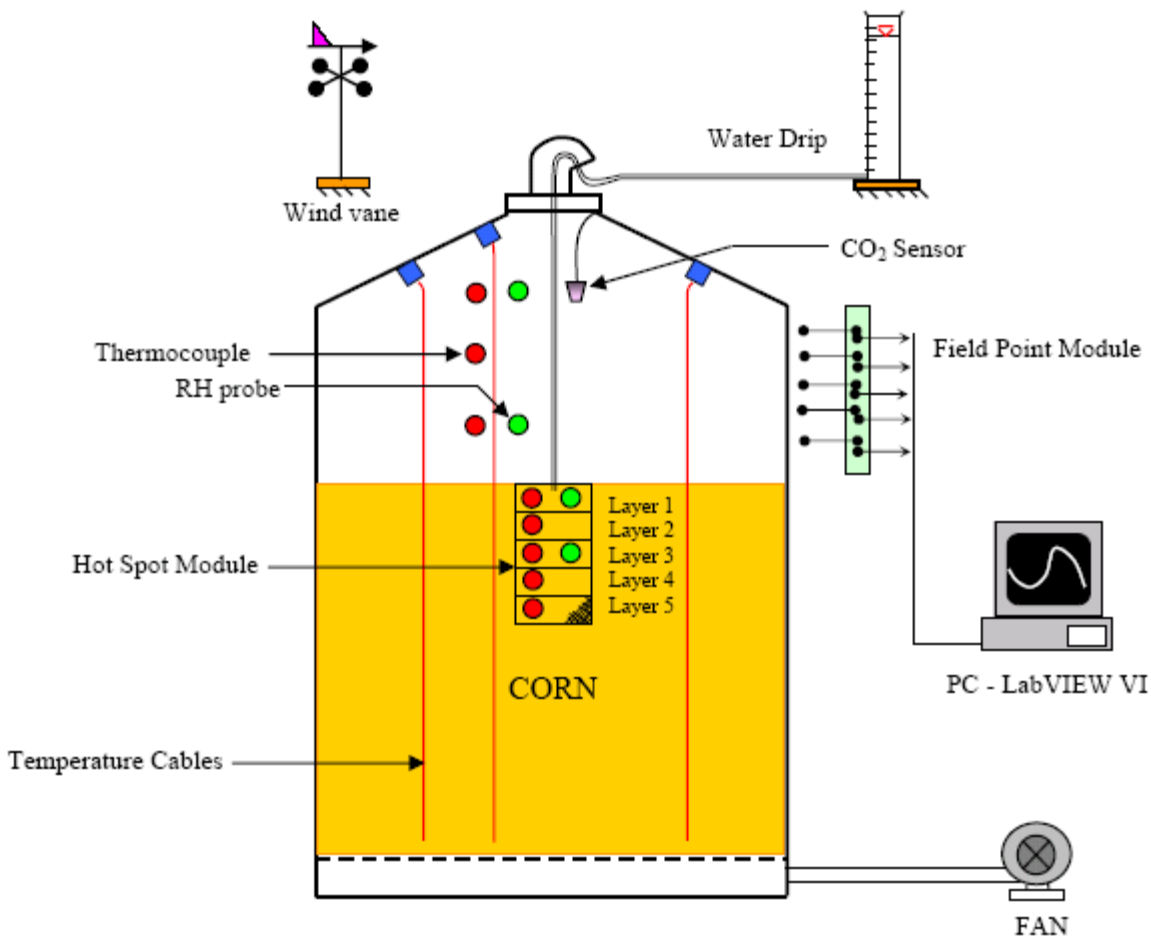

Figure 1. Schematic diagram of the experimental set-up of the in-bin drip experiment.

push CO_2 generated in the hot spot module to the headspace where the CO_2 sensor was mounted. Data was recorded every 0.3 s during this aeration phase. The data recorded during a trial were temperature at three points per layer in the hot spot module, bin headspace CO_2 concentration, grain bulk temperatures, bin headspace temperature and relative humidity, relative humidity and equilibrium moisture contents in layers 1 and 3 of the hot spot module, and ambient temperature, relative humidity and wind speed. The aforementioned data were recorded at 5-min intervals. An experimental trial was stopped when we positively confirmed a hot spot had been formed in the module as indicated by the increased temperature recorded by temperature sensors in the hot spot core (the center of the hot spot module) and CO_2 concentration recorded by the CO_2 sensor in the headspace.

Before the experimental trials, the stored grain bulk was monitored for insect pests and then fumigated appropriately. This was to safely attribute any CO_2 concentration recorded in the bin headspace as generated mainly by seed respiration and/or fungi growth alone in the grain bulk versus the possibility of CO_2 generation from other stored-ecosystem organisms such as insect pests. In addition, the grain surface was treated with a Diatomaceous Earth (DE) product to prevent any immigrant insects from thriving in the grain bulk. Trials 1, 2, and 3 were conducted from 9 September to 19 October 2001, 31 October to 10 December 2001, and 19 December to 18 March 2002, respectively. These periods covered hot spot development in the range from early fall warm weather conditions to winter cool weather conditions. The experimental set-up and trial runs were not replicated in other bins due to the cost involved in the experimental set-up and data collection. Thus, the three trial runs conducted in sequential order from Trial 1 to 3, with just 12 days between Trial 1 and 2, and 9 days between Trial 2 and 3, will be analyzed to prove the concept of spoilage detection with a headspace mounted CO_2 sensor, as well as compare their reliability and versatility with the method of using temperature cables alone for grain spoilage detection. Linear correlation analysis was conducted between the headspace CO_2 concentration recorded due to the developing hot spot and the temperatures in layers 1 to 5 in the hot spot module, the cable nearest to the hot spot module and the average grain temperature from all five cables in the bin using Microsoft Excel Analysis ToolPak (Microsoft, 2003).

The experimental trials were conducted in a pilot bin exposed to real environmental conditions at various periods of the year (fall to winter). The vent was left open and no additional measures were undertaken to seal the bin except for sealing the plenum fan during the non-aeration periods. Leakage of CO_2 through the bin wall seams, plenum and vent, weather-induced variation of temperatures and wind velocity, and a relatively large headspace volume compared to grain volume all affected our ability to detect CO_2. However, no determination was made to quantify the gas-tightness of the bin. Moisture content of the corn mass in the module was determined at the beginning and end of each trial by the air-oven method (*ASAE Standards*, 2003). Moisture content data reported were calculated on a percentage wet basis. Because the overall goal of the experiment was to determine the effectiveness and reliability of detecting grain spoilage from a developing hot spot with a headspace mounted CO_2 sensor versus detection with temperature cables and not grain storability, corn kernels were not plated before and after each trial to determine the number of colonies of fungi, bacteria, and yeasts.

Field Application of CO_2 Sensors for Spoliage Detection in Commercial Grain Structures

Trials 1, 2, and 3 showed that monitoring the CO_2 concentration in the headspace of stored grain in a bin gave a good indication of spoilage within the grain bulk. Therefore, we measured CO_2 concentration in commercial grain storage structures to explore whether this was possible outside of controlled experimental conditions. The storage structure types were: a 12.5-t cylindrical steel bin, 33,091- and 50,909-t corn piles, and a 12,500-t cylindrical steel grain tank.

Spoilage Detection in a 12.5-t Cylindrical Steel Tank

The first exploratory trial was in one of the 12.5-t pilot-scale tank of the Post-Harvest Education and Research Center (PHERC) in West Lafayette, Indiana, where the drip experiments were conducted. The odor of spoiling grain from a hot spot was discovered during a routine check of about 9.6 t of corn stored in the bin. Although this bin was equipped with five temperature cables with a total of 26 sensors (only 15 sensors were located within the grain bulk), spoiling grain that was caused by water entering the bin from a leak in the bin roof, was not detected by any of the sensors on the cables. Subsequently, a CO_2 sensor was mounted at different times in several locations in the bin (headspace or embedded in the grain surface above the hot spot) and the data of CO_2 concentration were collected in the following sequence:

1. bin was unsealed and the CO_2 sensor was mounted in the bin headspace,
2. bin was sealed at the roof vent and fan air intake with a heavy-duty plastic garbage bag secured in place with duct tape and the CO_2 sensor was mounted in the bin headspace,
3. bin was sealed as in (2) but the CO_2 sensor was embedded in the grain surface above the hot spot,
4. bin was unsealed with the CO_2 sensor still embedded in the grain surface above the hot spot,
5. the spoiling grain (hot spot) was removed by unloading the bin and loading the grain back into the bin with the bin unsealed and the CO_2 sensor mounted in the headspace,
6. bin was sealed as in (2) after removal of the spoiled grain and the CO_2 sensor was mounted in the headspace, and
7. bin was sealed as in (2) and the CO_2 sensor was embedded in the grain surface.

Spoilage Detection in 33,000- to 51,000-t Corn Piles

Compact and durable hand-held CO_2 sensors (fig. 2) that measure CO_2 in the range of 0 to 5000 ppm are now commercially available and currently used by the fruit and vegetable industries. These sensors are small infrared adsorption analyzers that continuously sample the air. Once a baseline is established, the sensors can measure any changes in CO_2 levels that occur (Maier, 2004). Unlike temperature, CO_2 is a gas that diffuses throughout the grain

bin and can be pushed by aeration fans or by natural convection currents from the source (spoiling grain mass) to the top of the bin or exhaust vent where the CO_2 monitor can be easily positioned.

During the winter of 2002 and 2003, a handheld CO_2 sensor (Telaire® 7001, Telaire®, Goleta, Calif.) was used to periodically monitor CO_2 concentrations in the exhaust air stream of fans holding down tarps on ground piles of corn ranging from 33,000 to 51,000 t (1.3 to 2 mil bu) located at four country elevators in Indiana. CO_2 sampling was coordinated to fit the elevators' operations, minimizing disruptions to daily operations and meeting their safety requirements. Thus, as few as one sampling to as many as four samplings within a two-week interval were obtained from these outdoor piles. This also depended on the scheduled dates for piles to be picked up for shipment.

Fans (negative draft) installed along the base of the grain piles pulled air through the grain from ducted vents that ran along the pile floor and through the top of the pile. They were normally kept running to hold the tarp down and preventing it from blowing off the grain surface, as well as keeping the grain cool. At one location, the fans were controlled by a wind sensor mounted on the loading leg above the pile peak. The number of fans that were kept running depended on the wind speed and direction.

To sample the fan exhaust for CO_2 concentrations, the sensor was held in front of the fan exhaust in the air stream and the fan was turned on (fig. 2). CO_2 concentrations were collected from all of the operational fans that were kept running to hold the tarp down and those that could be turned on at the time of data collection. Particular attention was paid to those fans that were turned on at the time data was collected because we expected that some CO_2 produced from active spoilage might still be retained around locations where the fans had not been running prior to data collection. A higher concentration of CO_2 than what would normally be expected from grain in good storage condition was expected when the rate of CO_2 diffusion out of the pile in that region was much slower than the rate of CO_2 production by spoiling grain. The grain moisture data were obtained from the elevator's scale tickets of corn loads transferred to the pile.

Spoilage Detection in a 12,500-t Cylindrical Steel Tank

The detection of spoilage in stored corn in 12,500-t cylindrical welded steel tanks was explored in the spring of 2002, 2003, and 2004. The stored grain was from the fall 2001, 2002, and 2003 harvest seasons, respectively, and binned from delivered loads of corn. CO_2 samples were collected from tanks containing corn, wheat and soybean, although our primary interest was stored corn. The grain moisture data was obtained from the elevator's scale tickets.

CO_2 samples were collected from four tanks twice in March 2002, thrice from four tanks in 2003 (January and February), and nine times from one tank in 2004 (March to June). For 2002 and 2003, a handheld CO_2 sensor (Telaire® 7001, Telaire®, Goleta, Calif.) was used in collecting data of CO_2 concentrations from the exhaust of all four fans in a 12,500-t steel tank (downdraft aeration) containing about 10,000 t of grain. At the time of data collection, the sensor was placed in the fan exhaust as shown in figure 2, and the fan was manually turned on. Data were read off the digital display on the sensor after a maximum CO_2 concentration was recorded and the next fan was sampled in sequence until all the fans had been sampled. In 2003, data collection at a fan exhaust was stopped after the respective readings of CO_2 concentrations had stabilized as observed on a laptop computer installed with a CO_2 data acquisition software (CO_2 View®, Telaire®, Goleta, Calif.) for automated data logging and visualization. The software enabled CO_2 concentration vs. time to be recorded from which the total CO_2 sucked from the tank could be calculated as the integration of the curves of CO_2 concentration versus time. Data collection from the other fans were conducted in this manner in sequence one at a time with no particular order, but at the discretion of the elevator's operations manager. Sampling periods ranged from 30 min for the first fan sampled to 10 min for the last fan sampled, as less CO_2 was sucked out of the tank with fans turned on sequentially.

In addition to sampling the exhaust air in 2004, one wall-mounted CO_2 sensor (Ventostat® 8002, Telaire®, Calif.) was installed in a fixed location in the headspace of a 12,500-t steel tank filled with about 10,000 t (400,000 bu) of corn. Hourly automatic monitoring of the CO_2 readings was recorded with a data logger (Fluke Hydra 2625A, Fluke Corporation, Everett, Wash.) throughout the winter and spring 2004. A second wall-mounted CO_2 sensor (Ventostat® 8002, Telaire®, Calif.) was installed in one of the four fan exhausts (downdraft aeration) and controlled with a data logger (Fluke Hydra 2625A, Fluke Corporation, Everett, Wash.) that turned on whenever a trigger sensed airflow in the fan exhaust. The exhaust fans were set by the elevator manager to cool the grain bulk to below 15.6°C and the control input was from temperature sensors mounted on cables. The tank had a total of 25 cables installed in four rings with cables 1 to 3 in the center ring of about 2.4- to 3-m radius, cables 4 to 9 in a 6-m radius, cables 10 to 16 in a 9-m radius, and cables 17 to 25 in a 13.5-m radius. The tank radius was 34.2 m.

Results and Discussion

Moisture Content Profile in the Hot Spot Module of the Pilot Bin Experiments

Table 1 shows the final moisture contents measured in the core and periphery of the layers in the hot spot module. The average initial moisture content of the corn bulk before

Figure 2. Handheld sensor measuring CO_2 concentration in the exhaust air stream of a fan on a ground pile.

Table 1. Moisture content (% wet basis) of corn in the core and periphery of the hot spot module.

	Trial 1		Trial 2		Trial 3	
Layer	Core	Periphery	Core	Periphery	Core	Periphery
1	60.9	20.0	25.7	16.9	21.8	13.5
2	49.8	14.8	23.8	14.7	19.6	13.4
3	39.9	11.4	24.9	13.2	21.6	12.8
4	25.2	13.3	27.4	13.8	23.4	13.4
5	19.8	10.5	28.3	12.7	21.2	13.9

Trials 1, 2, and 3 were 13.5%, 13.7%, and 13.3%, respectively. The total water dripped into the hot spot module for Trials 1, 2, and 3 were 5325, 7265, and 5510 g, respectively (Maier et al., 2002). The total water dripped was not the same in the three trials because the water drip rates were adjusted during the course of the experiment for Trials 2 and 3 so as to promote more rapid fungi development in inclement cool weather conditions that slowed down hot spot formation. At the end of the trials, the maximum final moisture contents of the deteriorated corn mass at the core were 60.9% for Trial 1, 28.3% for Trial 2, and 23.4% for Trial 3. The moisture content of the corn mass in the core of the hot spot module layers were more than those in the periphery in all three trials (table 1). Thus, in all three trials, spoilage occurred mainly at the core of each layer, while the grain at the periphery of the hot spot module layers still remained loose and in fairly good condition (fig. 3). We can safely conclude that the moisture movement through the layers of corn as water dripped directly in the center of the hot spot module, first moved vertically down, and then slowly moved laterally outward from the center as the core became saturated from the top to the bottom layer. Thus, the topmost layer had the largest diameter of moldy grain and the bottom layer had the smallest diameter of moldy grain. There were other factors that might have interfered with this pattern such as inclement headspace conditions, which is in direct contact with the topmost layer.

Variation in moisture contents of the corn mass was observed from layer to layer, and the variation was more in Trial 1 than Trials 2 and 3. The moisture profile of the layers indicated that layer 1 absorbed more water than the other four layers in Trial 1, while layers 5 and 4 absorbed more water in Trials 2 and 3, respectively. The different profiles observed were due to the ambient conditions at the time of the trial and the water drip rates applied, which was adjusted from 125 to 250 g per day. Trials 1 and 2 were conducted in the fall to early winter and took about 38 days on average to completion. Trial 3 took about 102 days due to the cold winter ambient temperatures, which prevented early fungi growth even though the corn mass moisture content was favorable.

Figure 3. Hot spot formation in one of the layers in the hot spot module.

Detection of Spoilage (Hot Spot) in the Grain Mass of the Pilot Bin

Figures 4, 5, and 6 show the CO_2 concentration in the headspace, the profiles of temperatures in the core of layers 1 (TempL1), 2 (TempL2), 3 (TempL3), 4 (TempL4), and 5 (TempL5), the temperature of the sensor on the cable closest

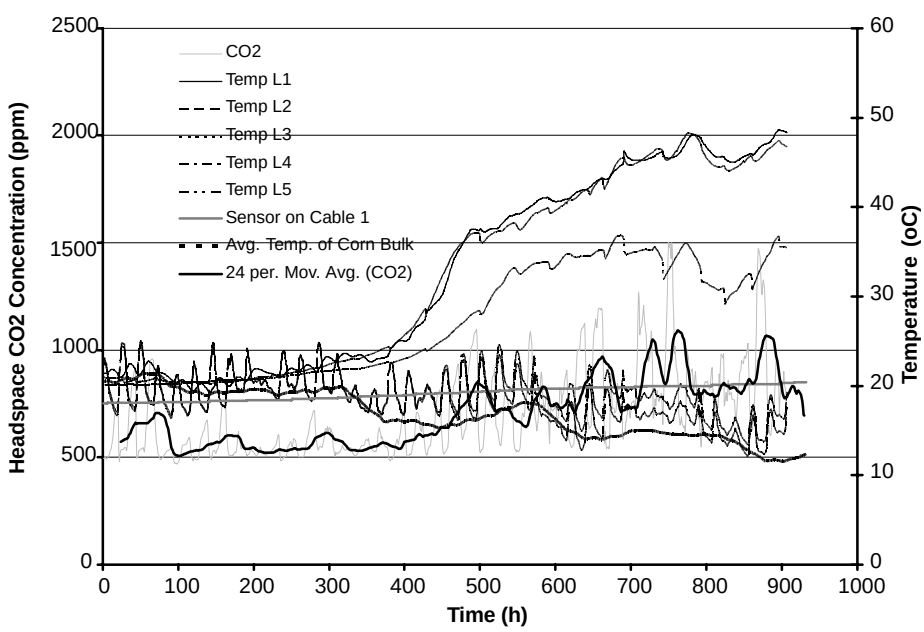

Figure 4. Temperature and CO_2 profiles measured during the hot spot development in Trial 1.

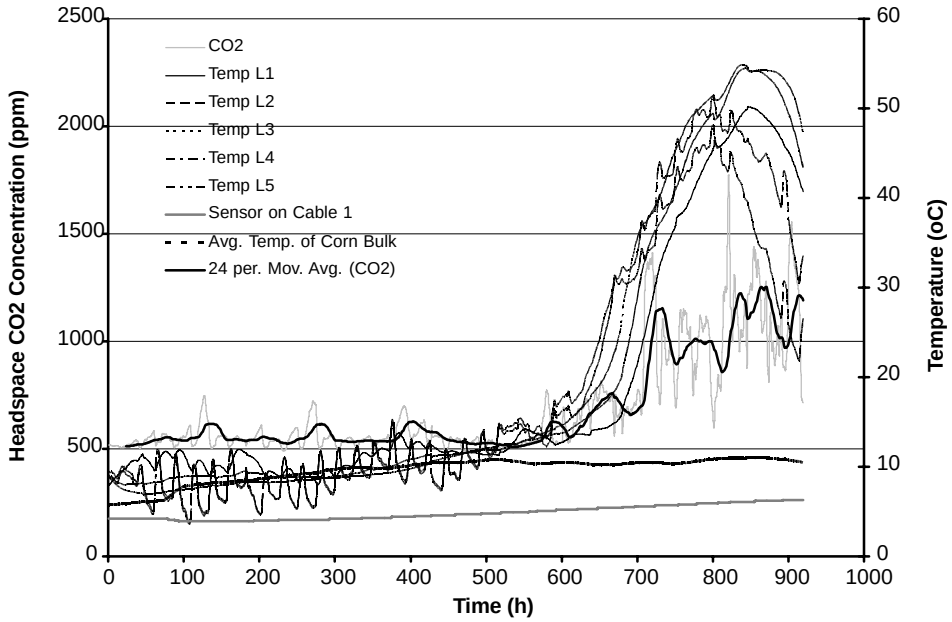

Figure 5. Temperature and CO_2 profiles measured during hot spot development in Trial 2.

to the hot spot module (about 0.15 m), the average temperature of the grain bulk (from 15 sensors on five cables), and a 24-h moving average of headspace CO_2 concentration during experimental Trials 1, 2, and 3, respectively. The base level of CO_2 concentration in the headspace was 500 ppm, about 100 ppm above the atmospheric CO_2 concentration. This was the approximate base level recorded in the three stored grain structures of this study. In all three trials, the rising temperatures at the center of the grain mass in the hot spot module after about 400, 600, and 800 h were parallel to the rising CO_2 concentrations recorded by the CO_2 sensor in the headspace. The 24-h moving average confirmed the trends. This was an indication of hot spot formation and progression in the confined grain mass within the hot spot module.

In Trial 1, a strong positive correlation was observed between the headspace CO_2 concentration and temperatures in layers 1, 2, 3 (table 2). During this period, the CO_2 concentration increased from a base level of about 500 ppm to as high as 1500 ppm, while the temperatures in layers 1, 2, and 3 in the hot spot module increased from about 21°C to 49°C, 47°C, and 37°C, respectively. The cable sensor closest to the hot spot module appeared to show a positive correlation, but the temperature only increased from 18°C to about 20°C. This indicated that the sensor did not really sense the hot spot development. Temperatures in the hot spot module layers 4 and 5, and the average temperature of the grain bulk showed a strong negative correlation. These temperatures decreased from 21°C to 16°C and 12°C for the module layers and grain bulk temperatures, respectively.

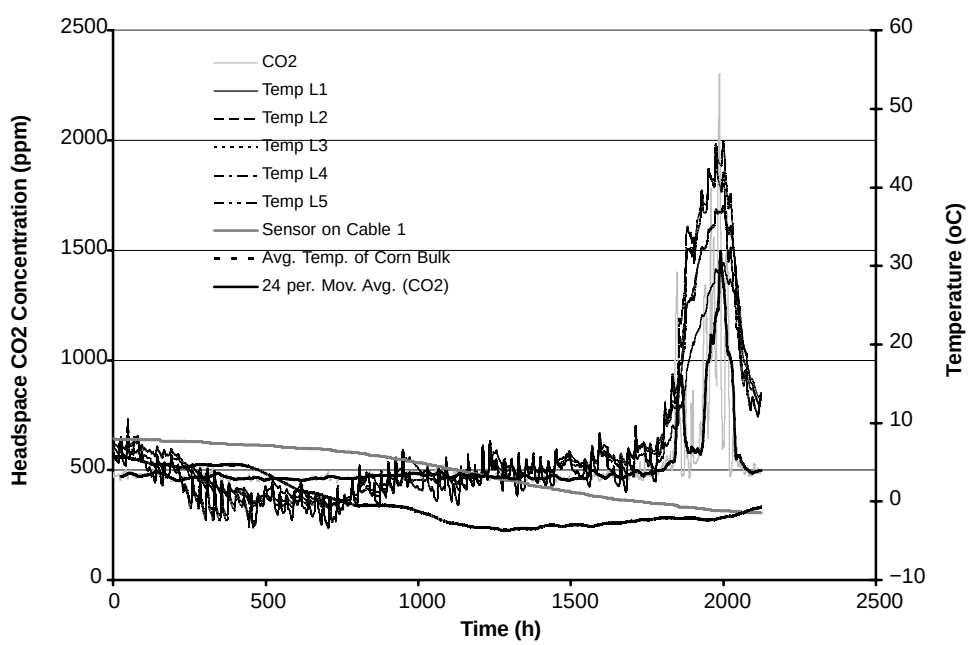

Figure 6. Temperature and CO_2 profiles measured during the hot spot development in Trial 3.

Table 2. Coefficient of determination for linear correlation between headspace CO_2 concentration (ppm) and temperatures in the hot spot module (layers 1 to 5), the nearest cable sensor to the hot spot module, and the average grain bulk temperature.

Trials	CO_2 (ppm)	TempL1 (°C)[a]	TempL2 (°C)	TempL3 (°C)	TempL4 (°C)	TempL5 (°C)	Cable S (°C)[b]	Bulk (°C)[c]
1-CO_2	1	0.66	0.66	0.62	-0.60	-0.70	0.62	-0.57
2-CO_2	1	0.86	0.87	0.87	0.82	0.76	0.79	0.43
3-CO_2	1	0.65	0.65	0.68	0.69	0.68	-0.37	-0.16

[a] TempL1 to L5 is the temperature recorded by thermocouples located at the center of layers 1 to 5 within the hot spot module.
[b] Cable S is the nearest cable sensor (center cable) located about 0.15 m (0.5 ft) from the hot spot module.
[c] Bulk temperature was calculated as the average of 15 sensors on 5 cables located at the bin center and four cardinal directions about 0.304 m from the bin wall.

A strong positive correlation was observed between the CO_2 headspace concentration and the temperatures in all five layers of the hot spot module (table 2). While the headspace CO_2 concentration increased from 500 ppm to about 1700 ppm, the temperatures in all the hot spot module layers increased from 8°C to over 50°C. The temperatures of the cable sensor closest to the hot spot module and the grain bulk increased from 4°C and 6°C to 6°C and 11°C, respectively, which did not appear to correspond substantially to the hot spot development.

A similar trend of headspace CO_2 concentration and temperatures in the hot spot module layers was also observed in Trial 3. Headspace CO_2 concentration increased from the base level of 500 ppm to a peak of about 2300 ppm after about 1800 h. Sensors in the core of all five layers of the hot spot module increased from 6°C to as high as 30°C to 45°C, while temperatures for the cable sensor closest to the hot spot module and the grain bulk decreased from 8°C to -1.4°C and -0.8°C, respectively.

Table 2 shows a strong positive correlation between the headspace CO_2 concentration and the temperatures in the top three layers of the hot spot module for Trial 1 and all five layers of the hot spot module in Trials 2 and 3. Temperatures for the cable sensor closest to the hot spot module had a positive correlation for Trials 1 and 2 and a negative correlation for Trial 3. The grain bulk temperature had a negative correlation with the headspace CO_2 concentration for Trials 1 and 3, and a positive correlation for Trial 2.

Trials 1, 2, and 3 showed a strong positive correlation between increasing headspace CO_2 concentrations and increasing temperatures in the core of the hot spot module especially in the top three layers. The three trials were conducted in sequence at different time periods, which had different prevailing ambient conditions that would have affected the rate of hot spot development and the levels of CO_2 concentration detected. The hot spot in Trial 3 took a much longer time to develop (1800 h) compared to that in Trials 1 (400 h) and 2 (600 h). The longer hours for hot spot formation from Trial 1 to 3 was most likely due to the cooler prevailing ambient temperatures as the trials progressed into the peak winter season. In all the trials, the average temperature of the grain bulk recorded by 15 sensors on five cables as well as the sensor on the cable about 0.15 m from the hot spot module did not detect the spoilage activity occurring in the hot spot module. In a real scenario, an undetected hot spot could spread and cause substantial damage to a large portion or even the entire grain bulk. On the other hand, if hot spot development were detected early, appropriate control measures (e.g., aeration cooling, partial unloading) could be applied to prevent its progression.

Figures 7, 8, and 9 show headspace CO_2 concentration and headspace temperature during Trials 1, 2, and 3. A cyclic pattern of CO_2 concentration similar to diurnal temperature fluctuations was observed in all three trials. Peak concentrations of CO_2 occurred during the lower night temperatures

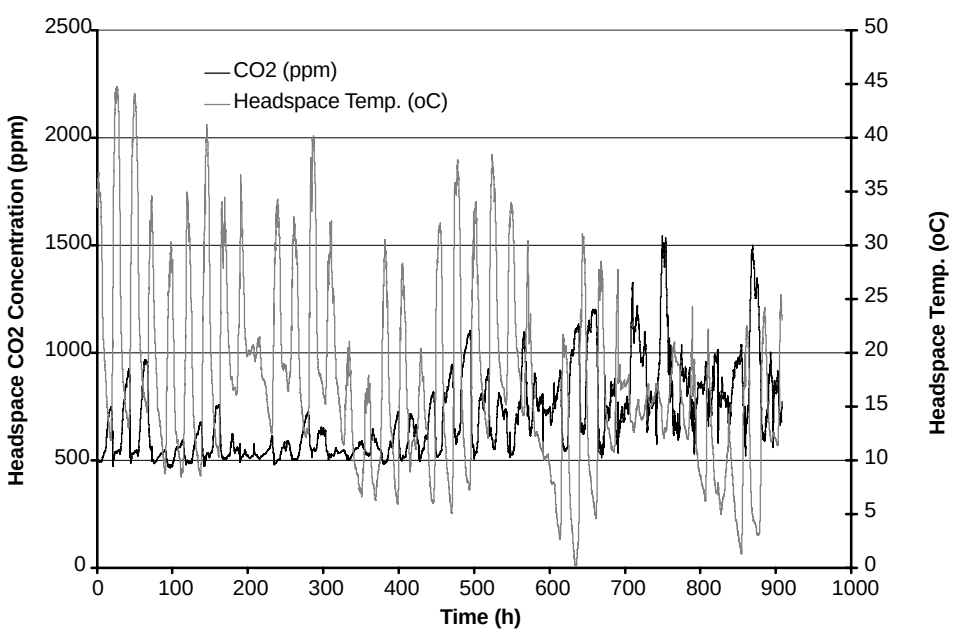

Figure 7. Headspace CO_2 concentration and headspace temperature during Trial 1.

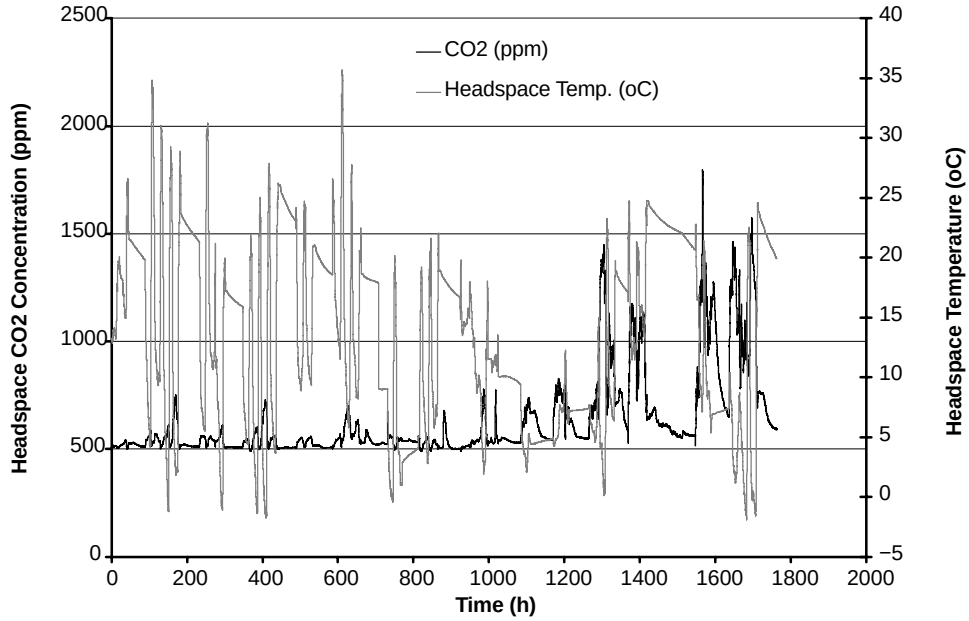

Figure 8. Headspace CO_2 concentration and headspace temperature during Trial 2.

and vice versa. This was supported by a negative correlation between headspace CO_2 concentration and temperature, with Trial 1 having the strongest negative correlation (-0.57) and Trial 3 the weakest (-0.107). This phenomenon can be explained by pressure differences between the headspace and external ambient environment caused by diurnal temperature fluctuations. The resulting effect causes more air movement and thus CO_2 loss from the headspace to the ambient environment during higher daytime temperatures, which results in lower CO_2 concentrations. During cooler nighttime temperatures, the air movement slows, which results in less CO_2 loss and thus higher CO_2 concentrations. This is of course also influenced by wind effects on the roof eaves and vents of the bin, though no consistent correlation could be determined for these experimental trials (Maier et al., 2002).

Figures 10 and 11 show headspace CO_2 concentration and headspace relative humidity for Trials 1 and 2. Trial 3 is not shown due to faulty sensor readings. The headspace relative humidity showed a strong positive correlation (about 0.5 for both trials) and followed a pattern parallel to the CO_2 concentration and opposite to the headspace temperature as would be expected, because higher headspace temperatures result in lower relative humidities.

Application of CO_2 Monitoring for Early Detection of Spoilage

Detection of Spoilage in a 12.5-t Pilot Bin with a Fixed CO_2 Sensor

A hot spot was discovered in a 12.5-t pilot bin with 9.6 t of yellow-shelled corn during a routine check when one of

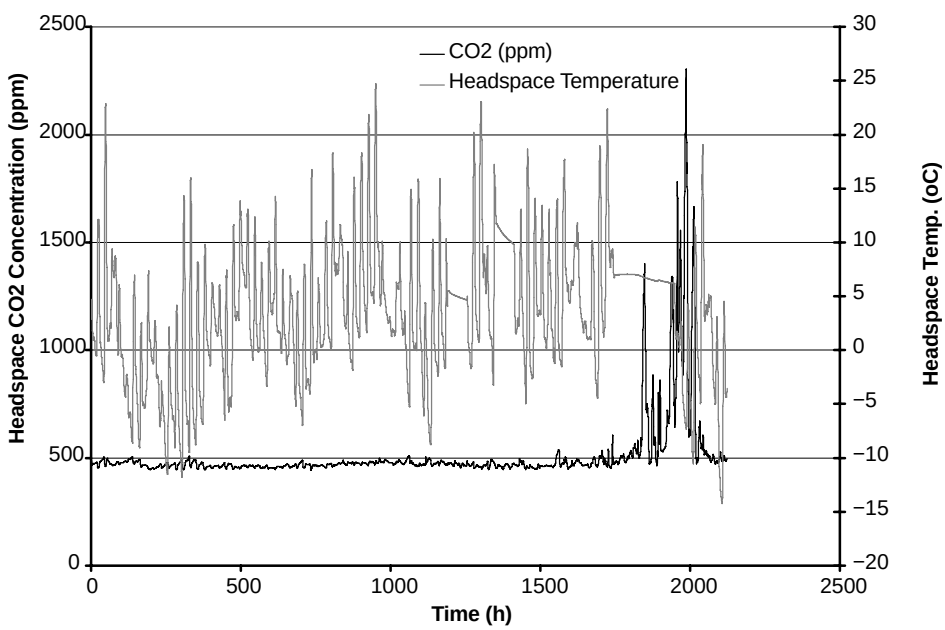

Figure 9. Headspace CO_2 concentration and headspace temperature during Trial 3.

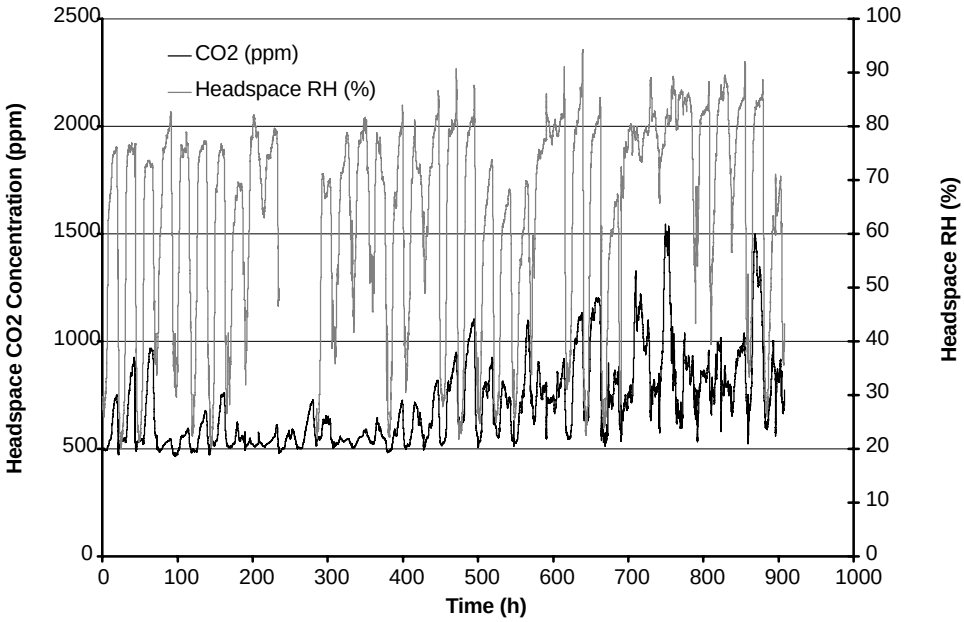

Figure 10. Headspace CO_2 concentration and headspace relative humidity during Trial 1.

the authors noticed a musty smell in the bin headspace (fig. 12.). Further investigation by hand probing the grain surface located a hot spot at the center of the bin that was caused by water leakage through the bin manhole cover located at the bin roof peak directly above. Figure 13 shows that the temperature profile of the center cable (average of three sensors) prior to 27 October 2001 when the hot spot was discovered did not indicate the presence of a hot spot or spoilage problem. The center cable, which was previously located about 0.3 m from the hot spot core, was probed into the hot spot core after 27 October (fig. 12), when the hot spot was discovered. The resulting temperature rise after 27 October (fig. 13) is indicative of heating due to spoilage.

Figure 14 shows CO_2 concentration over the period after which the hot spot was discovered (from 27 October 2001). CO_2 levels were monitored with a CO_2 sensor (Valtronics, model 2156-R, Valley Spring, Calif.) and logged hourly with a data logger (Fluke Hydra, model 2635A, Fluke Corporation, Everett, Wash.). Data was collected in sequence (fig. 14) with the CO_2 sensor installed in two locations (headspace and grain surface) and the bin under unsealed and sealed conditions. The initial CO_2 concentration in the headspace was twice higher (1000 ppm) than what was normally observed as the base level headspace CO_2 concentration (500 ppm) in bins with stored grain without spoilage as reported earlier in the drip experiment. Headspace CO_2 concentration rose to 5000 ppm, the maximum reading for the sensor, when the bin was sealed (manhole and fan inlet sealed with high-grade plastic but not air-tight). The CO_2 concentration remained at 5000 ppm when the bin was sealed and then unsealed while the sensor was embedded above the core of the hot spot at the grain surface. After about

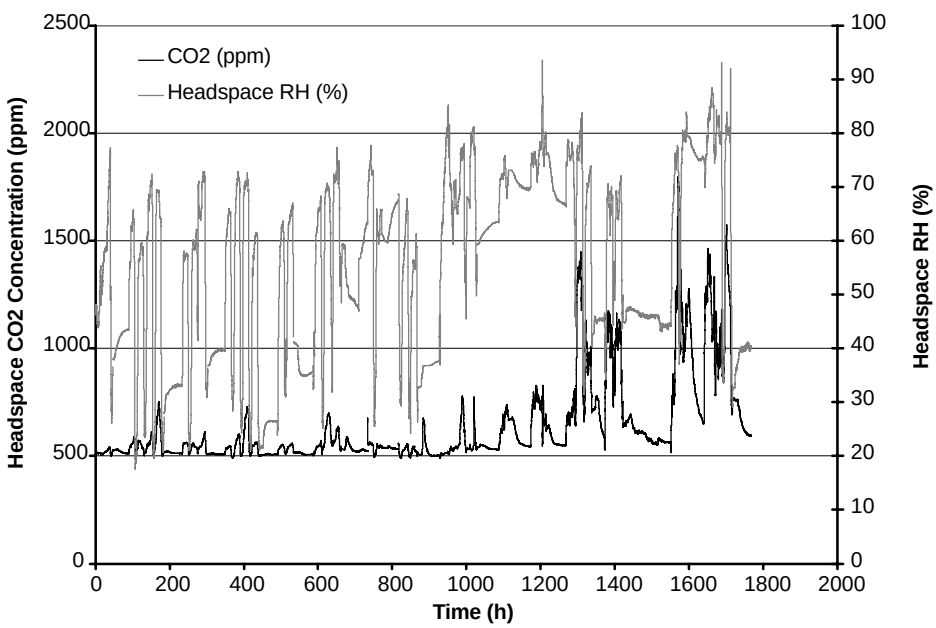

Figure 11. Headspace CO_2 concentration and headspace relative humidity during Trial 2.

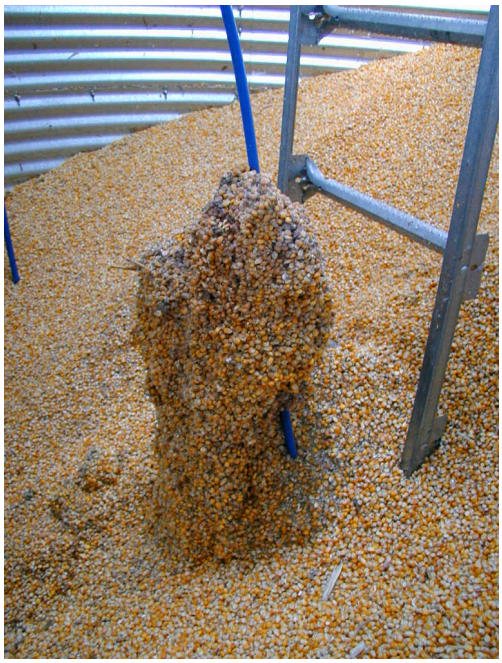

Figure 12. Hot spot detected at the center of the stored grain bulk (temperature cable in the hot spot was previously located 0.3 m away but probed in after the hot spot was detected due to musty smell in the headspace).

one month of data collection, the stored corn in the bin was emptied to remove the hot spot and turn the grain. Headspace CO_2 concentration dropped to the base level of 500 ppm (unsealed bin) after the good grain was loaded back into the bin. However, the headspace CO_2 concentration and grain pocket CO_2 concentration (with sensor embedded in the grain surface) was about 1000 ppm when the bin was sealed after removal of the hot spot and turning the grain. This indicated that the air exchange through the bin floor (full perforated floor), vent, walls, and other leakage locations did cause substantially more CO_2 loss from the bin than would have been recorded if the bin had been sealed airtight. Nevertheless, CO_2 concentrations in the headspace above the 500-ppm base levels gave an indication of on-going biological activity and hot spot development in the stored grain. Biological activity was not only caused by a hot spot due to grain spoilage, but also by an insect-induced hot spot. This example also showed that a hot spot will only be discovered in a timely manner by temperature cables located within the hot spot core. Thus, temperature cables cannot be exclusively relied upon for stored grain quality management.

Detection of Spoilage in Grain Piles and 12,500-t Steel Tanks with a Handheld CO_2 Sensor

During the winter of 2002, we used a handheld CO_2 sensor (Telaire® 7001, Telaire®, Calif.) to periodically monitor CO_2 concentrations in the exhaust air stream of fans holding down tarps on 33,000- to 51,000-t (1.3 to 2 mil bu) ground piles, and of downdraft aeration fans installed on 12,500-t (500,000-bu) welded steel tanks. In 2003, we continued this practice into the late spring.

About every two weeks, one exhaust fan at a time was turned on and the change in CO_2 concentration over time in the exhaust air stream was recorded. Figure 15 shows the CO_2 curves for four fans installed on one 12,500-t tank holding semi-wet corn (average 17% moisture content, wet basis) that was collected in June 2003. The integration of these curves gave the total CO_2 that was pulled out of the tank during data collection.

Figure 16 shows the total CO_2 pulled from the tank during the period of April through June 2003. Initially, only a slight upward trend in the total CO_2 concentration was observed in late April through May 2003 that might have indicated the onset of some grain spoilage or poor storage conditions (fig. 16). This was followed by a sharp increase throughout June that indicated increased self-heating in some portion of the grain mass. The location of the hot spot could not be confirmed until the middle of June when finally an increase of temperature was observed on one set of cable sensors. As confirmed when the tank was unloaded, the extent of spoilage

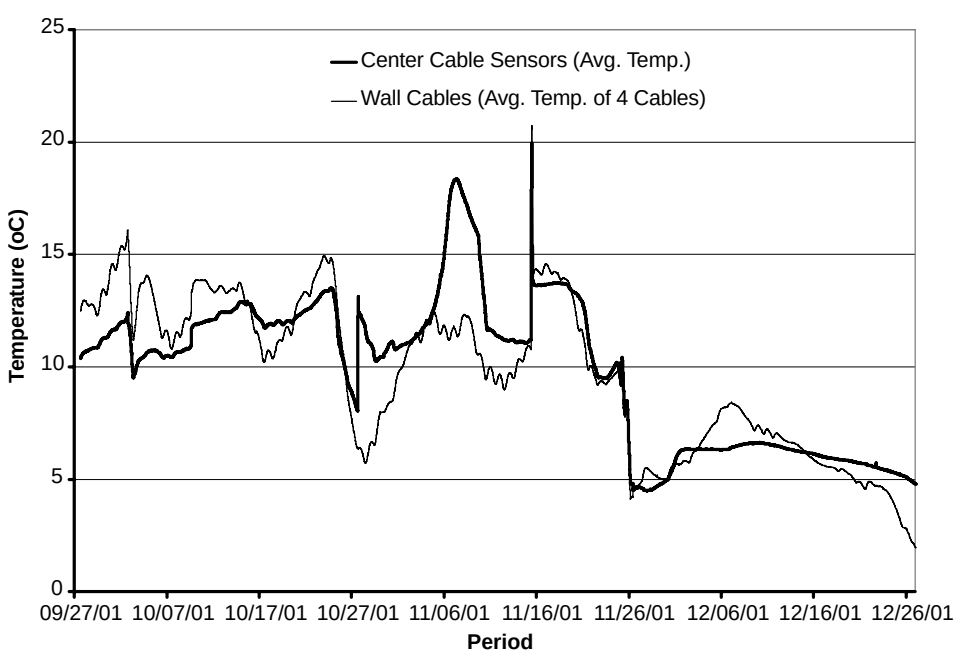

Figure 13. Temperatures in the grain mass (center and near wall) of a bin with a naturally formed active hot spot.

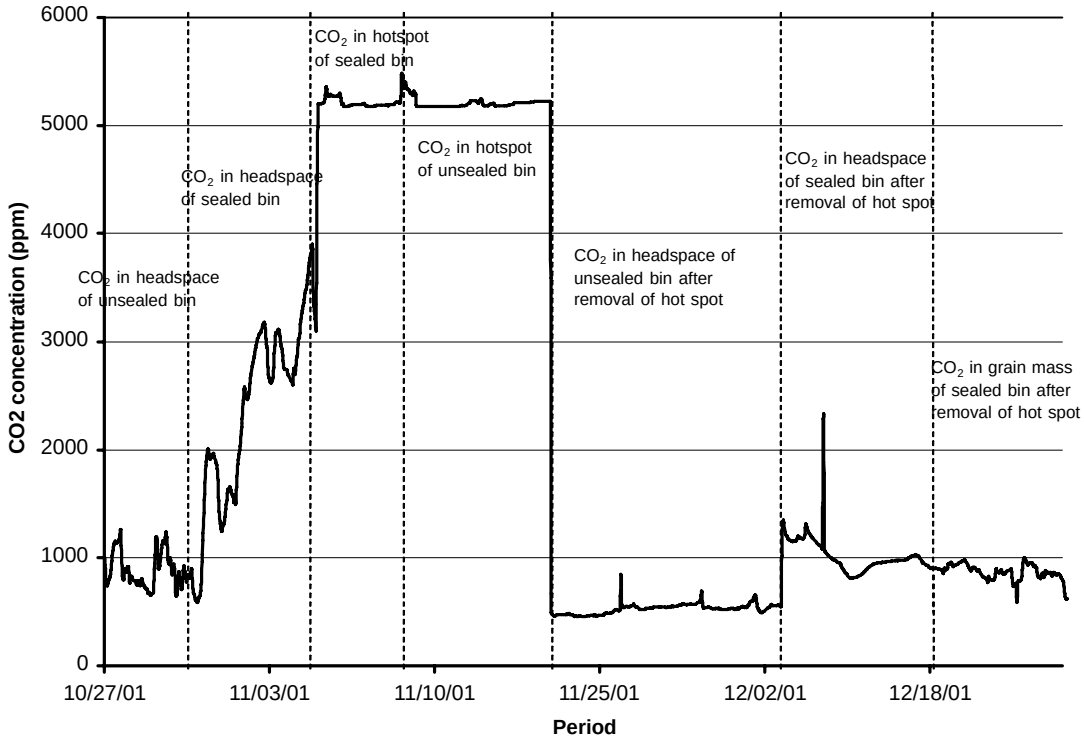

Figure 14. CO_2 concentration in the headspace and grain mass of a bin with a naturally formed active hot spot.

was relatively small compared to the total stored grain mass. However, despite the fact that this tank had 25 cables arranged in four rings, a temperature rise due to spoilage or poor storage conditions was not detected quickly enough. Using a handheld sensor to measure CO_2 in the exhaust stream of a down draft aeration system detected the onset of spoilage much earlier than the temperature cables located in the grain mass. Thus, this handheld sensor would be an effective additional tool to ensure the early detection of spoilage in stored grain.

Detection of Spoilage in a 12,500-t Steel Tank with a Fixed CO_2 Sensor

In the spring of 2004, one wall-mounted CO_2 sensor was installed (Ventostat® 8002, Telaire®, Calif.) in a fixed location in the headspace of a 12,500-t steel tank filled with about 10,000-t (400,000-bu) dried corn (average 15.5% moisture content). Hourly monitoring of the CO_2 readings indicated that throughout the winter and spring, the CO_2 concentration recorded by the sensor hovered around 400 ppm, which was essentially equivalent to the ambient CO_2 level. By mid-May, an initial peak of about 700 ppm was

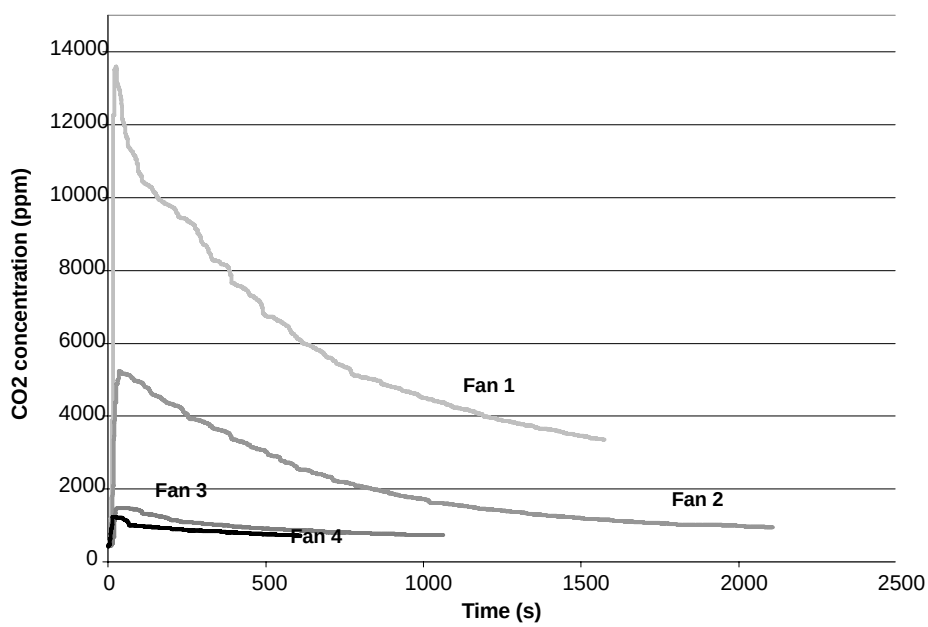

Figure 15. CO_2 concentration data collected on 9 June 2003 on a 12,500-t steel tank holding semi-wet corn. Fans 1, 2, 3, and 4 were turned on one at a time sequentially then turned off after the respective readings stabilized. The first two fans withdrew most of the CO_2 contained in the tank.

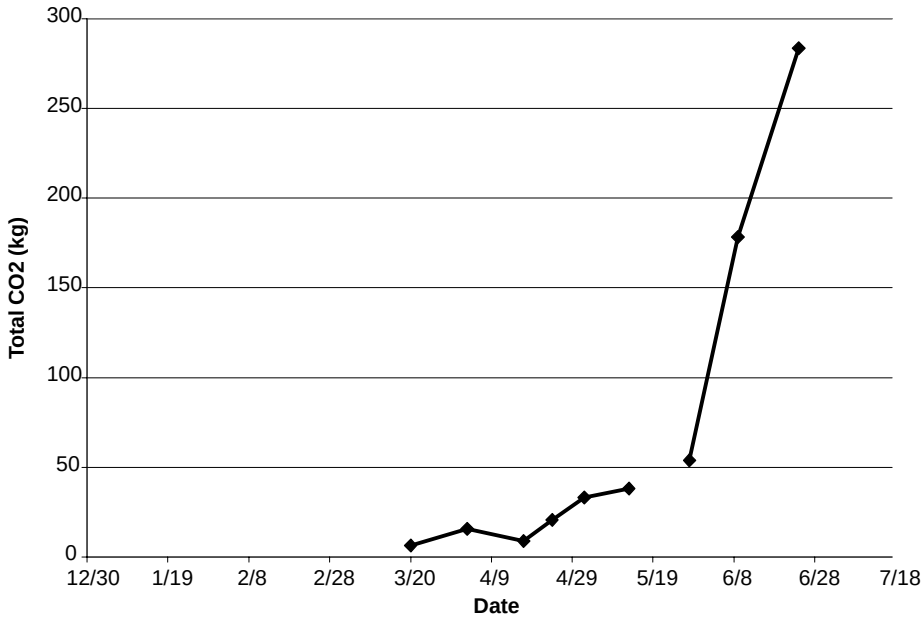

Figure 16. Total amount of CO_2 (kg) detected based on fan exhaust stream readings for a 12,500-t steel tank storing semi-wet corn from the 2002 fall harvest into the early summer of 2003.

observed that was followed by larger and increasing peaks of 800 to 1500 ppm in late May and early June (fig. 17). The bold line shows the 24-h moving average confirming the steady rise in the observed CO_2 levels recorded in the headspace, which was indicative of biological activity related to spoilage in the grain mass.

The corn was aerated during the late fall and early winter to about -1.1°C to 1.7°C. The grain was kept cool and the aeration fans were not run during the spring. Therefore, no CO_2 readings could be collected from a second sensor installed in the exhaust air stream of Fan 1 that was triggered to log data whenever it sensed the movement of air through the aeration duct. Interestingly, while the headspace CO_2 sensor detected some peaks in May, which indicated the onset of some spoilage in the grain mass, the temperature readings provided by the thermocouple cables indicated only a slow warming trend that would have been interpreted as "normal given the season" by the operations manager without the additional CO_2 readings (fig. 18). In early June, a sharp and rapid increase of the grain temperature from about 15.6°C (60°F) to over 32.2°C (90°F) was observed in the grain mass by a thermocouple located on the center cable about 3 to 4.6 m (10 to 15 ft) above the floor. In response, the operations manager turned on the aeration fans to cool the grain with the prevailing ambient air to below 15.6°C. Although the grain temperature was lowered at the location where spoilage was suspected, once the fans were turned off continued self-heating caused the grain temperature to increase above 37.8°C (100°F). The increased temperatures before and after aeration coincided with the CO_2 peaks observed in the headspace

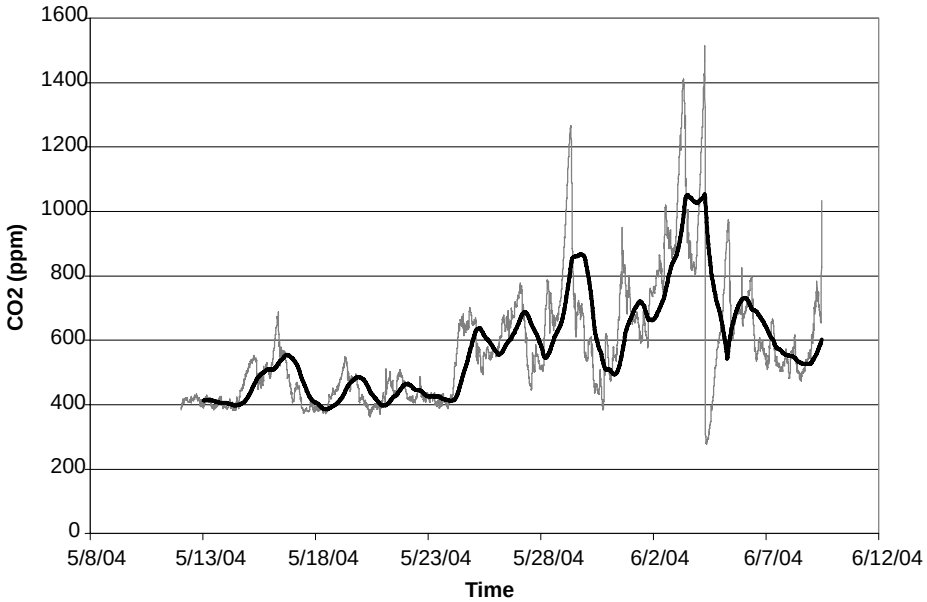

Figure 17. CO_2 readings (ppm) from a sensor installed in the headspace of a 12,500-t steel tank storing 10,000-t corn from the 2003 fall harvest into the early summer of 2004. The bold line is the 24-h moving average.

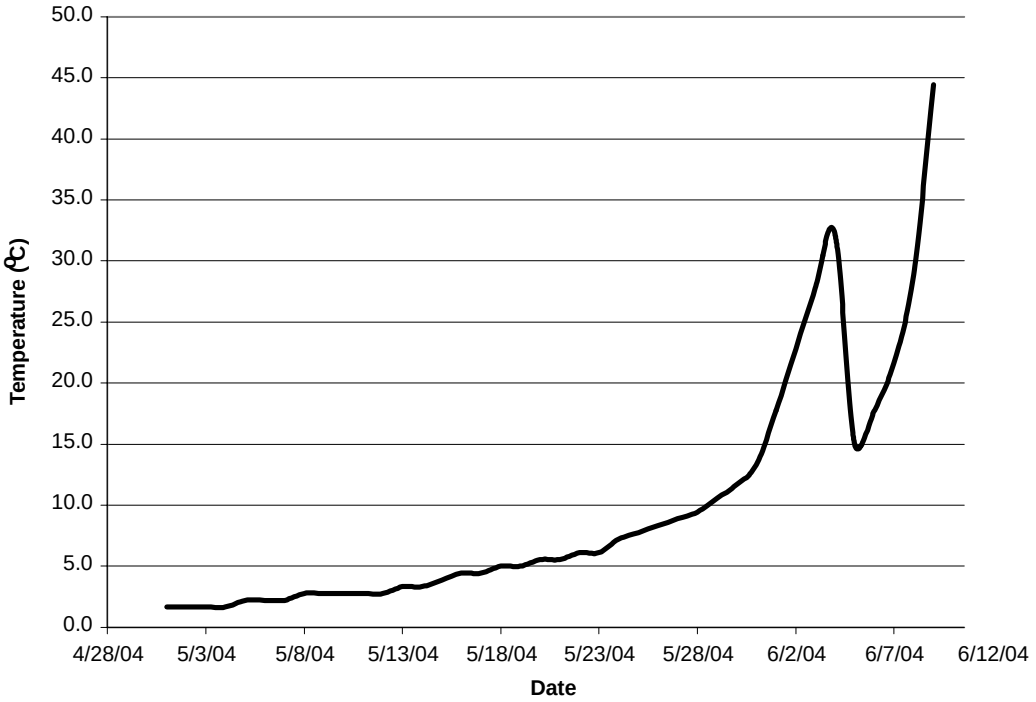

Figure 18. Temperature in the grain mass of a 12,500-t steel tank as recorded by a thermocouple located about 3 to 4.6 m above the floor and located on the center cable during May and June 2004.

during the same time period. Together they confirmed the development and location of spoilage in the grain mass and resulted in the decision to unload some of the corn. Given that spoilage was taking place in the core, the self-heating process was stopped after enough of the corn was unloaded. Therefore, the second method of installing a fixed sensor to measure CO_2 in the headspace air of a large steel tank also detected the onset of spoilage much earlier than the temperature cables located in the grain mass.

The drawback of using CO_2 sensors installed in the headspace is the extreme dusty environment, which can clog sensing parts and thus prevent gas diffusion through the vented casing. This occurred at the beginning of the data collection period when the tank was still being loaded with grain. Therefore, frequent sensor maintenance would be required with current technology. Fortunately, work is currently being undertaken to overcome this problem.

CONCLUSIONS

Based on our studies on the use of CO_2 sensors for spoilage detection in stored grain, the following conclusions were drawn:

- The water drip apparatus successfully simulated hot spot formation primarily due to fungal growth in the grain mass similar to what would normally occur in a localized mass of high moisture grain. Despite the fact that no additional measures were undertaken to seal the bin to ensure gas-tightness, it was possible to detect CO_2 produced by biological activity resulting from hot spot formation in the corn bulk.
- The CO_2 sensor located in the headspace of the bin recorded increasing CO_2 concentration levels at 400, 600, and 1800 h for Trials 1, 2, and 3, respectively. The difference in time after about 5300 to 7300 g of water had been dripped into the core of each grain mass was primarily due to the ambient and grain bulk temperature conditions of the periods when the trials were conducted. A hot spot was formed earliest in Trial 1, which was conducted early in the fall (September 2001), while the longest time for hot spot formation was in Trial 3, which was conducted during the winter period (December 2001 and March 2002).
- CO_2 concentration levels in the bin headspace increased from the initial base level of 500 to 1500 ppm, 1700 and 2300 ppm for Trials 1, 2, and 3, respectively. A similar rise in temperature was recorded by sensors in the core of the hot spot. In Trial 1, the spoilage mass rose from 20°C to 48°C, from 8°C to 54°C in Trial 2, and from 7°C to 37°C in Trial 3.
- For all three trials, there was a strong positive correlation between headspace CO_2 concentration and temperatures in the core of the hot spot. This indicated that rising CO_2 levels were supported by rising temperatures during hot spot formation. However, temperature cables were not effective and timely in detecting spoilage in the grain mass.
- Fifteen temperature sensors on five temperature cables located between 0.3 and 1 m from the hot spot module did not pick up the temperature rise recorded by the thermocouples located in the center of the hot spot module. The average temperatures of the stored corn bulk recorded by the cable sensors were 12°C, 8°C, and 7°C for Trials 1, 2, and 3, respectively, which did not indicate the occurrence of the developing hot spot in the stored corn bulk.
- CO_2 levels fluctuated inversely with diurnal temperature patterns in the headspace. Peak CO_2 levels were recorded at the minimum daytime temperatures and vice versa, which was consistent with ideal gas law behavior. As expected, there was an inverse correlation between headspace CO_2 concentration and headspace temperature, and between headspace temperature and relative humidity.

- The results from our applied studies of detecting spoilage in stored grain in various storage structures (small corrugated pilot-bin, commercial steel tank and grain pile) using fixed-mounted and handheld CO_2 sensors showed that this methodology is versatile and can serve as an additional reliable tool to compliment temperature cables for monitoring grain quality in storage.
- Our results showed that temperature cables alone might not be a reliable indicator of the stored grain condition in storage structures. In a bin with thousands of tons capacity where cables are widely spaced, the possibility of spoilage going on in the grain bulk and progressing to detrimental levels without detection is clearly a concern based on the results of these experiments.
- Although still in the application research and demonstration phase, our approach will provide the grain storage industry with a new tool for the early and more effective detection of hot spots. Interpreting CO_2 readings together with temperature cable readings will allow for more informed management decisions to counter the onset and development of stored grain spoilage.

Acknowledgements

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