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## Temperature Monitoring and Aeration Strategies for Stored Wheat in the Central Plains

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**Abstract.** *Two aeration strategies were compared to non-aeration in field tests of stored wheat in Kansas. An additional summer aeration cycle before the usual two autumn cycles produced better temperatures for insect control in the grain. Both aeration strategies yielded much better temperatures for insect control than did the naturally cooled, non-aerated bin (ca. 3,500 bu bin). In two years of tests with wheat aerated with low airflow rates in summer immediately after harvest, there were sufficient hours with air temperatures below 24°C (75°F) to cool the grain with an airflow rate of 0.11 m<sup>3</sup>/min-t (0.1 cfm/bu). However, during one year, high humidities during these nighttime periods of low temperatures resulted in final temperatures higher than 24°C due to the heating effect when the grain was slightly rewetted by the high humidity air. These results demonstrate the importance of looking at both temperature and humidity together to evaluate weather conditions for adequate cooling potential, especially during summer aeration when air temperatures are near the upper acceptable limit.*

**Keywords.** *Grain Cooling, Insect control, Grain Storage, Aeration controller, Moisture Content*

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## Introduction<sup>1</sup>

Aeration is a well-known and proven Integrated Pest Management (IPM) tool for controlling insects and other risks in stored grain. However, aeration remains an underused tool in some situations, particularly with small grains in warm climates such as in the central plains states of the U.S. The development of appropriate control strategies and simplified monitoring systems will enable aeration to be more widely used to reduce chemical pesticide use in stored grain.

The objective in aeration of stored grain is to maintain grain quality with minimal energy input. Aeration reduces biological activity by cooling the grain and preventing moisture migration by maintaining a relatively uniform temperature throughout the grain mass (Brooker et al., 1974). Holmes (1978) reported that temperature and moisture influence grain losses due to molds, bacteria, mites, and insects. Losses are inhibited when the grain temperature is kept below ca. 5°C (40°F). Several grain storage studies (Pixton and Warburton, 1971; Halderson, 1985; Qiu et al., 1987) indicated that temperature of stored grain and the equilibrium relative humidity of the void space air rather than grain moisture content are the principal factors in safe storage.

Navarro et al. (2002) stated that stored grain insects develop well at 27-34°C (81-93°F) and thrive best at about 29.5°C (85°F). Summer aeration control strategies should only use aeration when it results in cooling of the grain. Simple, thermostatic automatic aeration controllers can select the limited appropriate hours for fan operation, often at night, and run the aeration fan only when beneficial. Noyes et al. (1995) recommends these automatic controllers. Extended aeration times are generally not recommended because they can result in shrinkage (drying) losses in the stored grain. Wilson and Desmarchelier (1994) used seed wet-bulb temperature (SWBT) to control and manage aeration systems for insect population control. They stated that SWBT control of aeration systems has particular benefit in warm temperature climates that provide low temperatures at night that can be used to cool the seed down to the target SWBT.

In early autumn, as weather conditions allow, grain should be cooled to temperatures that limit insect feeding, growth, or reproduction—below 60°F—in climates where that was not achieved in the summer. A second (or third) cooling cycle in mid-winter to lower the grain mass temperature to (40-45°F) will further reduce insect and biological activity and minimize moisture migration. Harner and Hagstrum (1990) evaluated the impact of high airflow rates (>1.5 cfm/bu) for aerating wheat during warm weather months. They reported that wheat was cooled by an average of 6°C with about 9 hours of fan operation, which was sufficient reduction in grain temperature to reduce insect population growth by more than 80% in their simulations. Aeration with high airflow rates would allow Kansas producers to utilize the limited hours in July and August when ambient air temperatures are below 18°C (65°F). Typical Kansas weather in July and August affords sufficient hours below 24°C (75°F), occurring primarily at night, to achieve a cooling cycle with a low aeration rate of 0.11 m<sup>3</sup>/min·t (0.1 cfm/bu).

Sun and Woods (1997) developed a simulation model for grain cooling and applied it to cooling barley and wheat during a typical season at a location in the southeast of the U. K. They reported that fan control based on the grain and air temperature differential is effective in achieving grain cooling and preventing re-wetting during cooling. They also indicated that cooling, even during the summer months, could achieve temperatures that will greatly decelerate insect development. Chang and Steele (1995) used a grain temperature and moisture content simulation model (Chang et al. 1993; 1994) to simulate and evaluate the temperature and moisture content of wheat during storage with different aeration control strategies. They reported that based on the effectiveness and costs of controlling stored grain insects, aeration cooling in the fall and winter and after bin filling along with one fumigation in

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<sup>1</sup> This article reports the results of research only. Mention of a proprietary product does not constitute an endorsement or recommendation for its use by USDA.

the late summer appears to be the best choice among the nine aeration conditions evaluated, and that the simulation model provides a tool for evaluation of the effects of different aeration control strategies on temperature and moisture conditions of grain during storage.

Automatic control of aeration based on ambient temperatures is an inexpensive method to improve the efficiency of aeration systems. Simple automatic controllers will both reduce the time required for aeration management and improve the grain quality compared to manual control. Reed and Harner (1998a, 1998b) showed that during on-farm storage a simple aeration controller—consisting mainly of a high-limit thermostat and an hour meter—cooled summer-harvested grain more quickly and with less cost than other aeration control methods. Reed et al. (1998) found a similar benefit with these simple controllers for fall-harvested corn. This more efficient cooling regime means a simple controller pays for itself in one or two storage seasons.

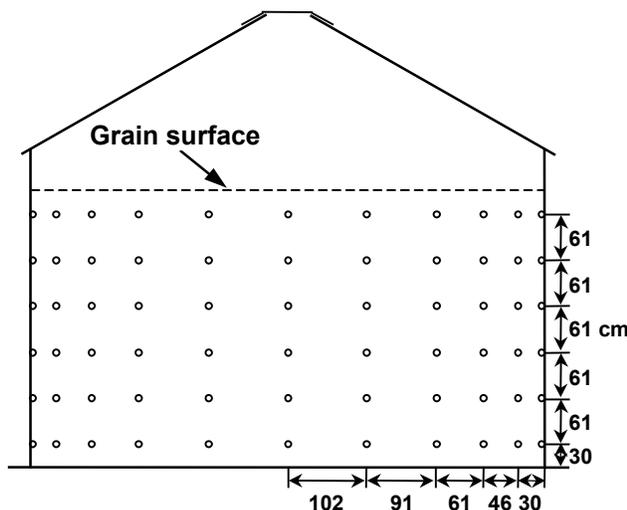
The objective of this study was to compare the effectiveness of three temperature management strategies for cooling stored wheat to safe levels: 1) no aeration, i.e., natural cooling, 2) controlled aeration at (15°C) 60°F in early autumn and 7°C (45°F) in late autumn, the standard 2-cycle cooling regimes currently used for stored wheat in the central plains, and 3) controlled aeration at 24°C (75°F) after binning in addition to the autumn cooling cycles.

## Methods

A field validation test was conducted during two storage years to evaluate the three temperature management strategies described above. The study was conducted in three bins at the GMPRC, which were filled to a height of 12 ft with hard red winter wheat for the first year (ca. 3,500 bu) and to a height of 9 ft the second year (ca. 2,700 bu). Average initial moisture content was 13.8% w.b. in 2000 and 12.2% w.b. in 2001. Aeration fans were set to cool the wheat with an airflow rate of 0.11 m<sup>3</sup>/min-t (0.1 cfm/bu) using an automatic temperature controller.

**Table 1 – Storage bin aeration treatments.**

Bin	Aeration	Description
A	2-cycle	controlled aeration at (15°C) 60°F in early autumn and 7°C (45°F) in late autumn
B	none	non-aerated (natural cooling) control bin
C	3-cycle	controlled aeration at 24°C (75°F) after binning in summer in addition to the 2-cycle autumn cooling cycles



**Figure 1. Thermocouple locations; on both the north-south axis and east-west axis.**

Grain temperatures were monitored continuously with thermocouples and a data acquisition system. A small number of HoboPro temperature and relative humidity data loggers (Onset Computers, Pocasset, MA) were also used: one in the aeration duct, one in the headspace, and four in the grain mass. Each bin was equipped with a grid of 132 thermocouple sensors as shown in figure 1. These sensors measured grain temperatures at six depths (0.30, 0.91, 1.52, 2.13, 2.74, and 3.35 m) and six radial distances from the bin center (0, 1.02, 1.93, 2.54, 3.00, and 3.30 m from the center in North, South, East, and West directions). Six

additional thermocouples were located in the headspace above the grain.

In 2000, filling of the bins was completed on July 6 and in 2001 it was completed on July 7. Immediately after filling the bins the temperature controller for the 3-cycle bin was set to run the fan when the ambient temperature was below 24°C (75°F). When the measured bin temperatures indicated the cooling front had passed through the bin the controller was reset to 15°C (60°F), ending the first cycle.

When the weather cooled sufficiently in early autumn, the controller initiated the second cooling cycle in the 3-cycle bin (first in the 2-cycle bin), again with fan runtime typically at night. When the measured bin temperatures indicated the cooling front had passed through the bins the controller was reset to 7.2°C (45°F), ending this cycle. When the weather cooled sufficiently in late autumn, the controller initiated the third cooling cycle in the 3-cycle bin (second in the 2-cycle bin). When the measured bin temperatures indicated the cooling front had passed through the bin, the fans were shut down and the fan inlets sealed. In 2000, the non-aerated bin was fumigated on September 18 since temperatures were not low enough to inhibit insects. In 2001, although temperatures were also unfavorable for safe storage, the non-aerated bin was monitored but was not fumigated until spring.

Weather conditions were monitored with a standard weather station. Temperature data at selected points in the bins were evaluated using line graphs as a function of time. The large grid of temperatures was used to draw contour plots of the bin temperatures at selected times. The equilibrium moisture content for hard wheat was calculated from the measured ambient temperature and relative humidity using the modified Chung-Pfost equation (ASAE, 2001).

## Results and Discussion

Small differences were observed between 2-cycle and 3-cycle aeration strategies each year, while large differences were observed between these aeration strategies and the non-aerated bin as expected (figure 2). The difference in the date for onset of aeration in September between the 2-cycle and 3-cycle bin in 2000 was due to a fan failure on the 3-cycle bin, causing the aeration cycle to be initiated later in that bin. Both aeration strategies yielded much more favorable temperatures for insect control in the bin center during the autumn than in the non-aerated bins. The non-aerated bin cooled naturally during the 2000 storage season, but the bin center was still too warm for safe storage late into the autumn. Without fumigation in the fall in 2001, most of that non-aerated bin heated due to insect activity.

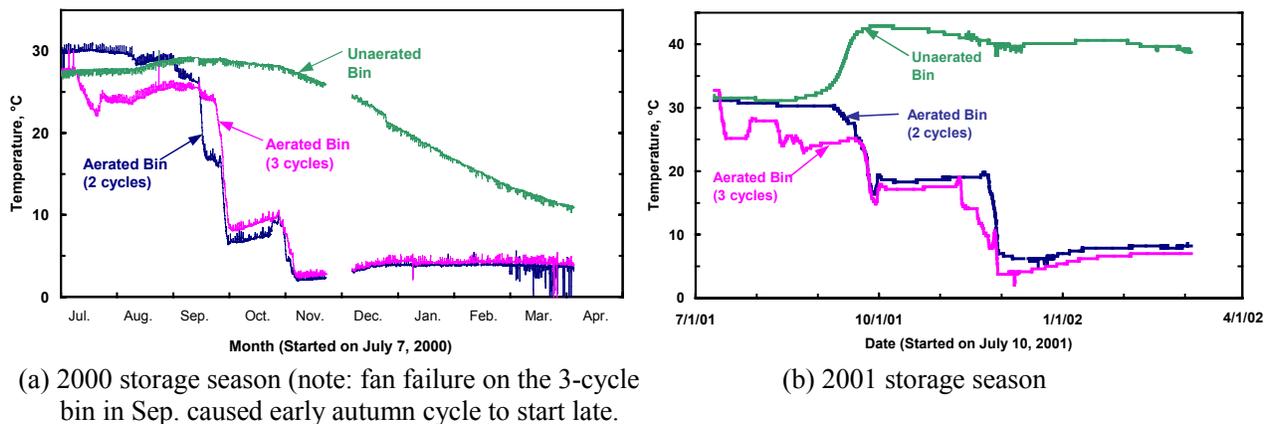
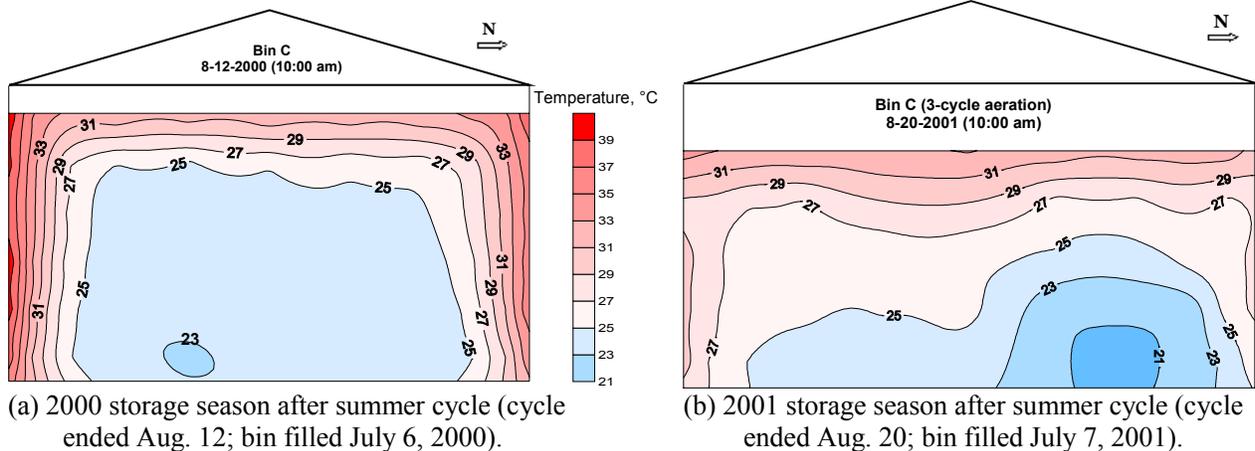


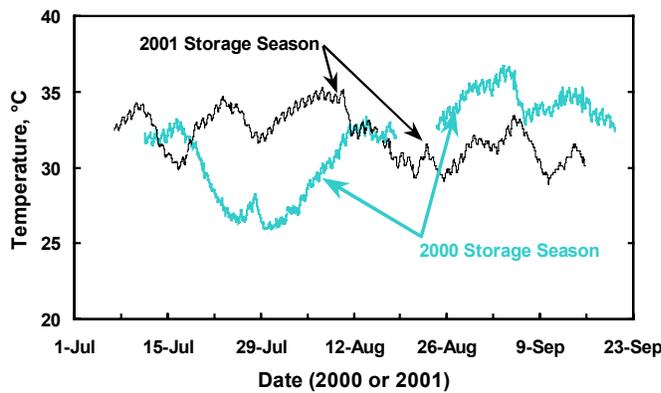
Figure 2. Temperatures at center of bins during two storage seasons.



**Figure 3. Results of summer aeration cycle in 2000 and 2001.**

### ***First (Summer) Cycle***

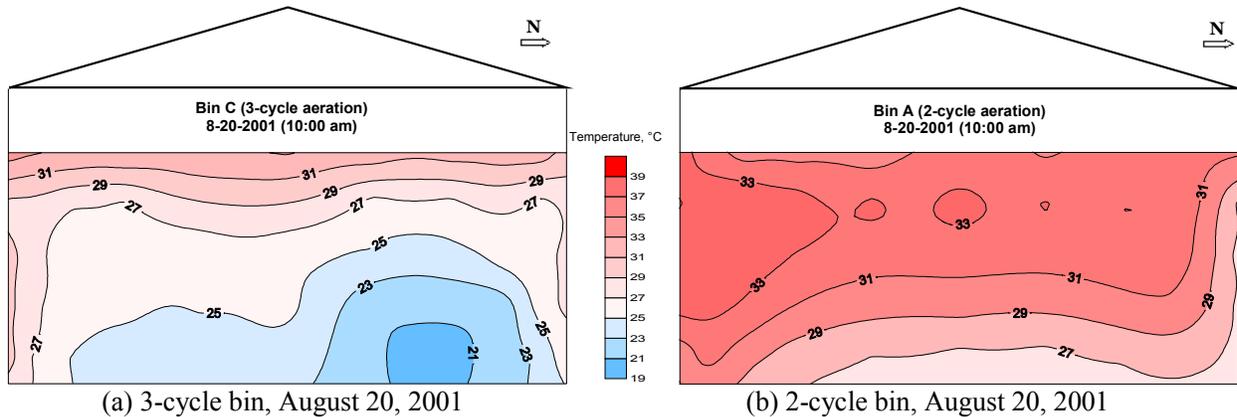
In the first year of field tests, the summer aeration cycle (the first of three cycles) was effective for reducing temperatures in much of the bin to a level that slows insect development (below 25°C) (figure 3). However, temperatures near the top and south wall of the bins subsequently tended to re-warm to levels near optimum for insect growth and reproduction. During the 2001 storage season, the bin was not cooled as well overall as it was in 2000 (figure 3) but the extended fan hours during this cycle prevented re-warming at the walls. Cooling during the summer cycle in this second year of field tests was not as efficient or effective as it was the first year. It required over 200 h of fan operation, compared to 140 h the first year, but this summer fan operation in 2001 produced less overall cooling (figure 3). The reduced cooling in 2001 appeared to result from latent heating occurring due to high nighttime humidity levels.



**Figure 4. Average temperatures 30 cm from south wall during first aeration cycle.**

Figure 4 shows a comparison of the temperatures near the south wall of the 3-cycle bin during the two storage seasons. This location approached the desired 24°C during aeration in the 2000 season but re-warmed above 35°C after aeration ended. This location, like most of the bin, did not cool well in July 2001, but was cooler during August and early September even though the weather was slightly less favorable for cooling during those two months that year. Avoiding re-warming in late summer is an advantage of extended fan hours during summer aeration.

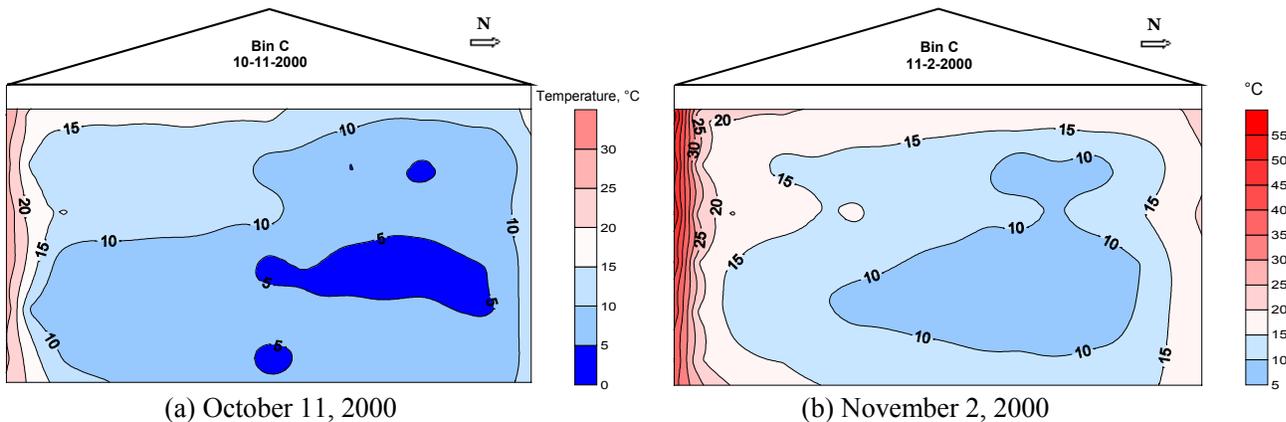
Figure 5 shows that the summer aeration produced cooler temperatures in the bin in 2001, compared to the bin that was not aerated until autumn. This difference between the two aeration treatments was even more pronounced in the 2000 season as indicated by figure 3, which shows that the 3-cycle bin was cooler after summer aeration was completed in 2000.



**Figure 5. Three-cycle aeration produced cooler temperatures in August than the 2-cycle aeration (this example from 2001 season).**

### Second (Autumn) Cycle

The second (autumn) aeration cycle lowered temperatures to a safe level for insect suppression (below 15°C) in 2000, although short maintenance cycles probably would have helped maintain the temperatures near the south wall of the bin (note figure 6). The interior of the bin had much more favorable temperatures both years than did the non-aerated bin. In 2000, a short period of atypical cold weather in early autumn yielded unusually cool temperatures during this aeration cycle. Figures 2 and 6 show that aeration during this cycle yielded temperatures in the center of the aerated bins below 10°C, although the target temperature for this cycle was 15°C. The more typical weather in 2001 produced temperatures in the center of the bins between 15 and 20°C. It appears that high humidity at night in 2001 caused a similar temperature rise in the aeration air as occurred during the summer cycle resulting in grain temperatures higher than the



**Figure 6. Aerated bin after early autumn cycle in 2000 and after walls re-warmed, three weeks later.**

temperature of the night air used for aeration. This can be seen in figure 2 where the temperatures after the early autumn cycle were still slightly above the target temperature of 15°C (although the fan only ran with ambient temperatures of 15°C and below). These temperatures above 15°C could be a problem if the bin stayed at those temperatures. With the late autumn cycle cooling the grain to around 7°C, the short time between 15 and 20°C should not cause major insect problems.

## Non-Aerated Bin

The non-aerated bin cooled naturally in the fall of 2000, after it was fumigated on September 18. Figure 7 compares the temperatures in that bin to the non-aerated bin in 2001, which was not fumigated in the fall. In 2001 insect activity through the autumn and winter prevented natural cooling of the non-aerated bin. Even with the unusually cool weather during the early autumn cooling cycle in September 2000, there was little overall difference between the average ambient temperature for the two years. Thus the majority of the temperature difference between the two years, seen in figure 7, was probably due to insect activity.

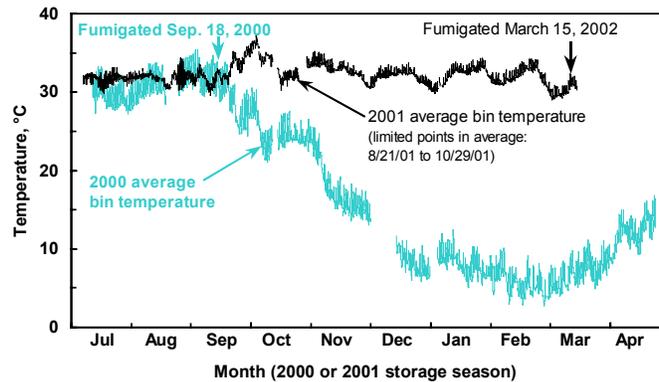


Figure 7. Average temperature in non-aerated bins.

The temperature histories for the 2001 storage season at four locations are shown in figure 8. Two of these locations clearly heated from insect activity in the fall, while two heated later in the winter, beginning in January of the next year. These four locations are typical and indicate the range spatial variation in heating from insect activity that occurred in this untreated bin. These differences correlate with proximity to the boundaries of the grain. Locations close to the boundary that were subject to cooling by ambient air did not heat much early in the winter, but eventually heated after January 1. This is consistent with the temperature contours in figure 9, which show cooler temperatures near these boundaries, as well as up the center of the bin. The cooler center is likely due to natural convection currents. It appears that natural convection currents may have distributed some cooler temperatures from the boundaries up through the bin center, leaving the two areas of warmer grain seen in figure 9.

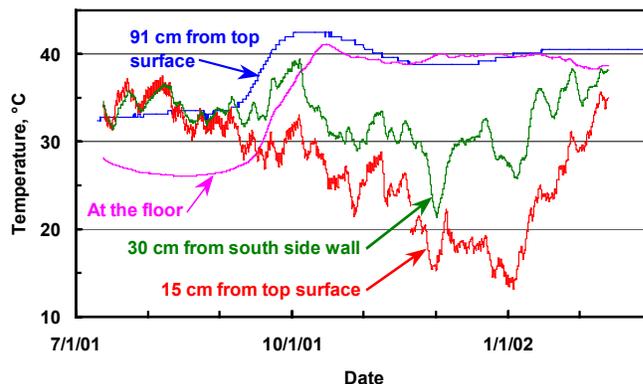
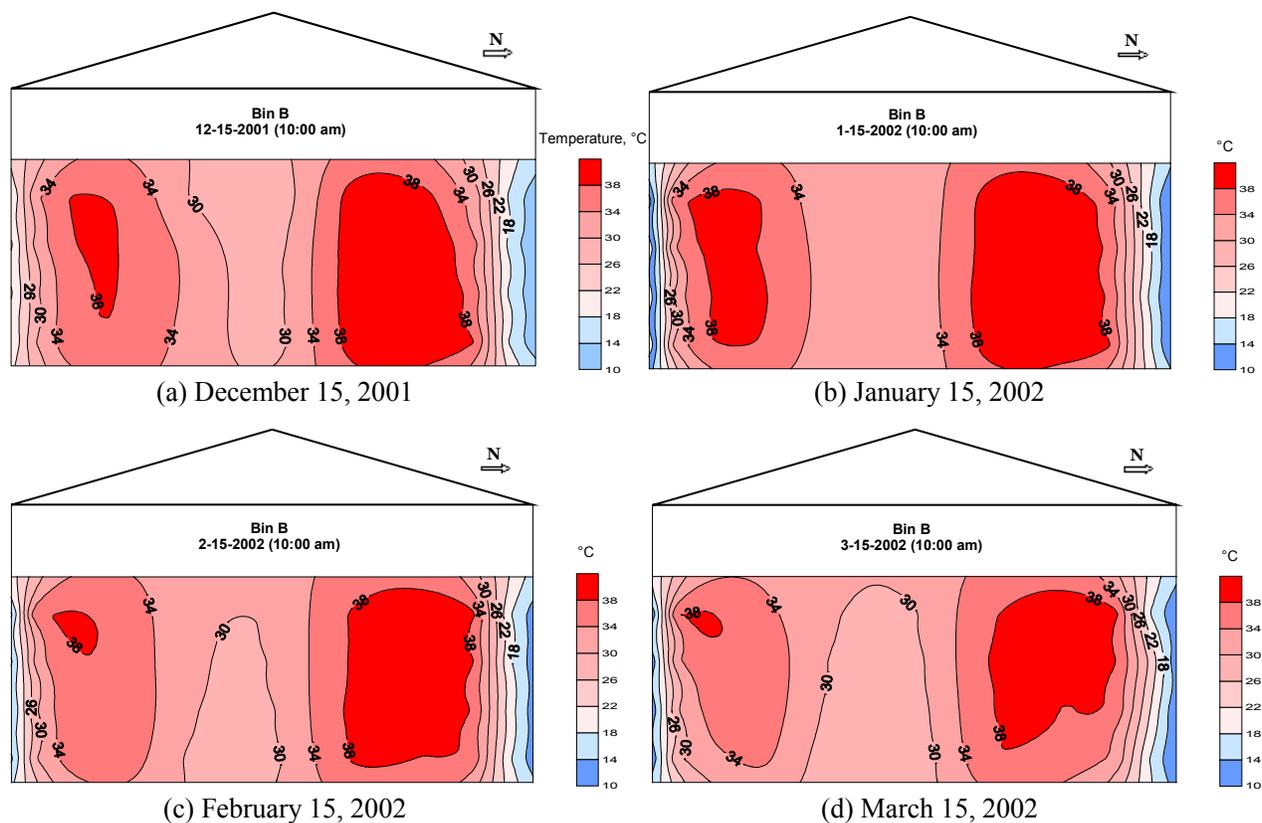


Figure 8. Various daily average temperatures in non-aerated bin, 2001.

There are only small changes in the temperature profiles shown in figure 9 during the winter period of the 2001 storage season and there appears to be an equilibrium between the heating from the insects and the natural cooling from cold ambient temperatures. The average bin temperature shown in figure 7 for 2001 remained near 32.5°C through the winter with some cycling between about 30°C and 35°C and a cycle period of about one month.



**Figure 9. Temperatures in the non-aerated bin for four months during winter; 2001 storage season.**

### ***Latent Heating Effects during Aeration***

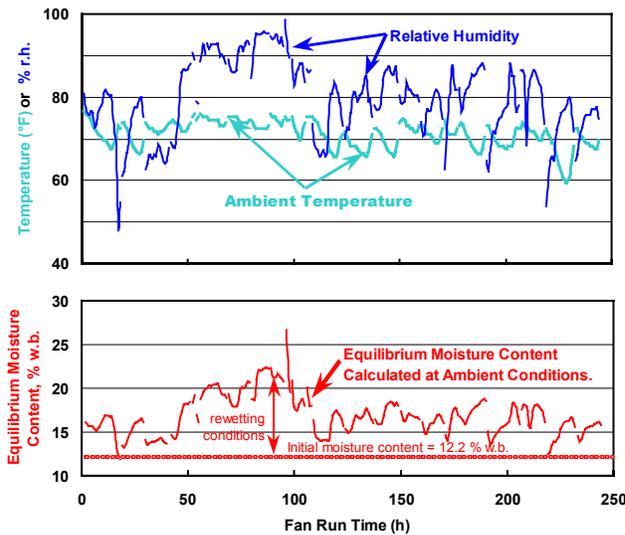
Extended aeration times are generally not recommended because they can result in shrinkage (drying) losses in the stored grain. Automatic aeration with most of the fan run-time at night tends to avoid these problems because humidities are usually high at night. In both years of this study there was no indication of shrinkage during the summer and early fall aeration cycles, but there was a problem in 2001 with rewetting the grain with the cool, moist night aeration air, which caused undesirable temperature rise in the aeration air from latent heating.

In both years of tests with aeration at low airflow rates in summer immediately after harvest, there appeared to be sufficient hours with air temperatures below 24°C to cool the grain with a low airflow rate, 0.1 cfm/bu. In the 2001 storage season there were over 240 hours for fan operation with ambient temperatures below 24°C from July 10 until August 24. However, in this second year, high humidities during these nighttime periods of low temperatures resulted in final grain temperatures higher than 24°C due to the heating effect when the high humidity air slightly rewet the grain (figures 3 and 10). An early autumn aeration cycle the same year also resulted in temperatures higher than ambient due to the heating effect from rewetting.

While there were weather differences between the two years, the temperature controller operated the fans only below 24°C in both years making the aeration differences minimal. Temperature sensors in the aeration ducts confirmed the accuracy of the temperature controller (shown on figure 10, where the “ambient” temperature is from an in-duct sensor).

Evaporative heating is a fundamental physical effect that occurs when aerating with rewetting conditions and diminishes the aeration cooling effect. Summer aeration in warm climates often faces limited hours with temperatures cool enough to be effective, and even those acceptable temperatures are borderline; if evaporative heating increases the effective aeration temperature,

the amount of acceptable hours for aeration will be reduced further. This evaporative heating caused problems for automatic control of aeration with temperature alone during 2001. During the middle of the cooling cycle, high humidities caused re-warming of grain that had been previously cooled to near the desired 24°C. These results also indicate that it is important to look at both temperature and humidity together to determine if typical weather conditions are acceptable for adequate cooling during summer aeration.



**Figure 10. Summer aeration, 2001. Rewetting conditions (all fan hours at night; ambient conditions measured after air passed through the fan).**

The undesirable latent heating experienced in 2001 may be preventable using aeration controllers that control aeration fans based on both temperature and relative humidity. Aeration control based on relative humidity in the U. S. has not been widely accepted for various reasons. Two common problems are that the humidistats have been difficult to maintain and sufficient fan run-time was not always achieved to affect adequate cooling of the grain when using humidistats (Noyes et al., 1995). The lack of adequate fan run-time could result if the upper limit of acceptable humidity were set too low, stopping the fan during times of moderate humidity that would have allowed some grain cooling. If humidity control could be properly applied, a benefit would be to reduce or eliminate undesirable latent heating during high humidity conditions. The data from 2001 (figures 2b and 10) indicate that an upper humidity limit between 85 and

90% relative humidity would probably have reduced the latent heating problems without preventing other fan operation needed for cooling. The appropriate upper limit will vary with temperature and grain moisture content so that a general recommendation of a fixed upper humidity limit is probably not possible. The SWBT method (Wilson and Desmarchelier, 1994) may provide one method of accounting for all of these factors.

## Conclusions

1. Summer aeration reduced temperatures in stored wheat to a level that reduces insect activity as compared to temperatures with aeration only in autumn and it improved temperatures dramatically compared to naturally cooled bins.
2. Summer aeration with low airflow was useful for cooling stored wheat, but was dependent on night humidity levels as well as temperatures for its total effectiveness; thus, evaluations of summer aeration should consider humidity levels along with temperature levels to determine potential effectiveness.
3. One autumn fumigation treatment was effective to prevent heating from insect activity in non-aerated stored wheat sold in the spring; without autumn fumigation, insect activity prevented the non-aerated bin from benefiting from natural cooling during the winter.

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