PROGRESS REPORT – PHM1505 Palmer new insights NA grain drying

June 1, 2016 - May 31, 2017

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<tr><td>2.</td><td colspan="4">Title of Research Project:
New insights into natural air grain drying</td></tr>
<tr><td>3.</td><td colspan="2">Start Date:
June 1, 2015</td><td colspan="2">Completion Date:
November 15, 2018</td></tr>
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4. Executive Summary

The overall objective of this research is focussed on developing better management practices for storing grain to achieve the following:

1. Safety: to store the grain as safely as possible, with the least spoilage or deterioration,
2. Drying: to dry the grain quickly for sale to an acceptable moisture content, but not to over-dry,
3. Efficiency: to condition the grain efficiently, at the lowest cost and the least inconvenience,
4. Evenly: to maintain consistent moisture content from the top to the bottom of the bin.

Currently, the management practice for storing grain in steel bins is to run an aeration fan continuously until the grain is dry using air flow rates of 0.75 to 1 cfm/bu. If the grain is dry, the fan is sometimes used to cool the grain using lower airflow rates of 0.1 to 0.2 cfm/bu. Previous work in this project showed that turning the fan on and off at certain times can increase the efficiency of grain drying. The objective this year was to determine if lowering the airflow rate from 1 cfm/bu to 0.4 or 0.1 cfm/bu would result in sufficient grain drying.

A total of six steel hopper bins were used in the 2016 study; two bins each with a capacity of 2,250 bushels (bins 9 & 10), and four larger 3,500 bushel bins (bins 16, 17, 18, 19). All bins were equipped with horizontal perforated aeration tubes and attached fans. The bins were instrumented with sensors, measuring the temperature and relative humidity of the in-coming air, and the temperature and relative humidity of the out-going air at the top of the bin. Data from the sensors were logged every 68 minutes. All six bins were outfitted with fan controllers. The air flow was reduced by building an air vent between the fan and the aeration tube to let some of the air out, and by attaching plastic covers over the fan inlet to decrease the diameter of the inlet. The air flow was set to approximately 0.1 or 0.4 cfm/bu at the bin outlet (lid) as directed by protocol.

Results from this year's work shows that low air flow rates of 0.4 cfm/bu are effective at drying grain. Unfortunately, controller error resulted in poor quality data in regards to evaluating continuous air versus temperature differential controls (bins 16 and 18, wheat). Further analysis to verify the 80% relative humidity threshold value showed there is no one number that fits all situations. The relative humidity threshold is dependent on many variables, such as grain type, moisture content, and temperatures of grain and air, which change readily. From this conclusion, it is safe to suggest building

an absolute humidity controller would be the best to achieve grain drying that meets the project's objectives.

There have been many significant observations since the beginning of this project. The research is improving our understanding of the dynamics of in-bin grain drying and the development of grain storage management practices. Future trials aim to answer questions on the effect of additional heat to dry grain quickly.

5. Methods

In 2015, the Prairie Agricultural Machinery Institute (PAMI) was consulted to evaluate the effect of air flow rates on drying and cooling of tough wheat. They conducted bench scale trials on 6 bins of 15 bushel capacity using air flow rates of 1.0, 0.5 and 0.1 cfm/bu for 48 days. Wheat at 18.4% MC was put into all six bins and at the end, the MC was 16.3%, 16.5%, and 17.1% for the respective flows of 1.0, 0.5 and 0.1 cfm/bu. As expected, the higher flow rate resulted in more drying; but, there was not much difference between the 1.0 and 0.5 flows. The commonly accepted rule of thumb is that airflows of 1 cfm/bu are required for drying and 0.1 cfm/bu for cooling. These PAMI trials demonstrate that low air flows will dry, albeit not as much, and that drying and cooling are not separate; cooling is drying. The final temperature of the grain for all PAMI runs was close to 4^{o}C for all bins. This would be close to the mean outside temperature, as expected.

The PAMI trials only used the conventional, continuously-run fan strategy as it is the same management strategy that most producers are using today. It is very simple, as it requires no sensors or fan control, and does result in grain drying. However, it is not energy efficient and it does not provide the safest storage, as it heats and wets the grain during the day; though it will serve as a benchmark to compare other control strategies against. Based on PAMI's 2015 results, in 2016 IHARF tested the effect of a low (0.1 cfm/bu) and high (0.4 cfm/bu) air flow rate in combination with a continuous or +2 degree offset. Results from this trial should confirm past conclusions of more efficient and effective grain drying when using a temperature offset with a higher rate of air flow. IHARF tested PAMI's 2015 results in 2016 as the trials being conducted by both organizations are taking place at the same time each year.

Experimental Design and Set-Up:

Six steel hopper bins were used in the 2016 study; two bins each with a capacity of 2,250 bushels (bins 9 & 10), and four larger 3,500 bushel bins (bins 16, 17, 18, 19). All bins were equipped with horizontal perforated aeration tubes and attached fans. The bins were instrumented with temperature and relative humidity sensors, measuring the temperature and relative humidity of the in-coming air, and the temperature and relative humidity of the out-going air at the top of the bin. Additionally, each of the six bins was fitted with nine vertical sensor strings that were hung from the reinforced bin roof and evenly spaced throughout the bin (Figure 1). The vertically hung cables contain temperature and relative humidity sensors every four feet, for a total of 76 sensors in each of bins 9 and 10 and 104 sensors in each of bins 16, 17, 18 and 19. Data from the sensors were logged every 68 minutes. The moisture content of the grain in the bin was determined using Henderson equilibrium moisture content (EMC) equations. The bins were equipped with a specially designed sampling tube in order to allow grain sampling at four different points throughout the height of the bin, accessible from the ground, to facilitate the determination of grain moisture content at four bin levels. All six bins were outfitted with fan controllers. The air flow was reduced by building an air vent between the fan and the aeration tube to let some of the air out, and by attaching plastic covers over the fan inlet to decrease the diameter of the inlet as shown in Figure 3. The air flow was set to approximately 0.1 or 0.4 cfm/bu at the bin outlet (lid) as directed by protocol. 0.4cfm/bu was the maximum flow rate achievable with a 5hp fan on a 3,500bu bin.

A run, or trial, started immediately after two bins were filled with freshly harvested grain and the fans were run under a specified control strategy (Table 1). The weight of the grain was measured with a truck scale at the time of loading and unloading the bin. Two bins were filled simultaneously in order to ensure the grain in the bins were as uniform as possible in regards to moisture content (Figure 2). This was accomplished by emptying one truck load of tough grain into the first bin, the next truck load into the second bin, and back to the first. In the event of rain, the fans were stopped and the bin lids were closed so that water did not enter the bin. After the rain, the fans were activated and the bin lid was opened. Figure 1

Table 1: 2016 trial run specifics.

	Bin 9	**Bin 10**	**Bin 17**	**Bin 19**	**Bin 16**	**Bin 18**
Control Strategy	Continuous	Continuous	+2^{0}C	+2^{0}C	+2^{0}C	+2^{0}C
Grain	Barley	Barley	Barley	Barley	Wheat	Wheat
Fan Start Date and Time	Aug 22 10:00 am	Aug 22 10:00 am	Aug 22 10:00 am	Aug 22 10:00 pm	Aug 30 1:00 pm	Aug 30 1:00 pm
Fan Shut Down Date and Time	Sept 20 12:00 pm	Sept 20 12:00 pm	Sept 20 12:00 pm	Sept 20 12:00 pm	Sept 14 11:50 am	Sept 14 11:50 am
Air Speed at Bin Lid (km/hr)	2.0	6.5	1.7	6.7	1.6	6.3
cfm/bushel	0.15	0.4	0.1	0.38	0.1	0.37

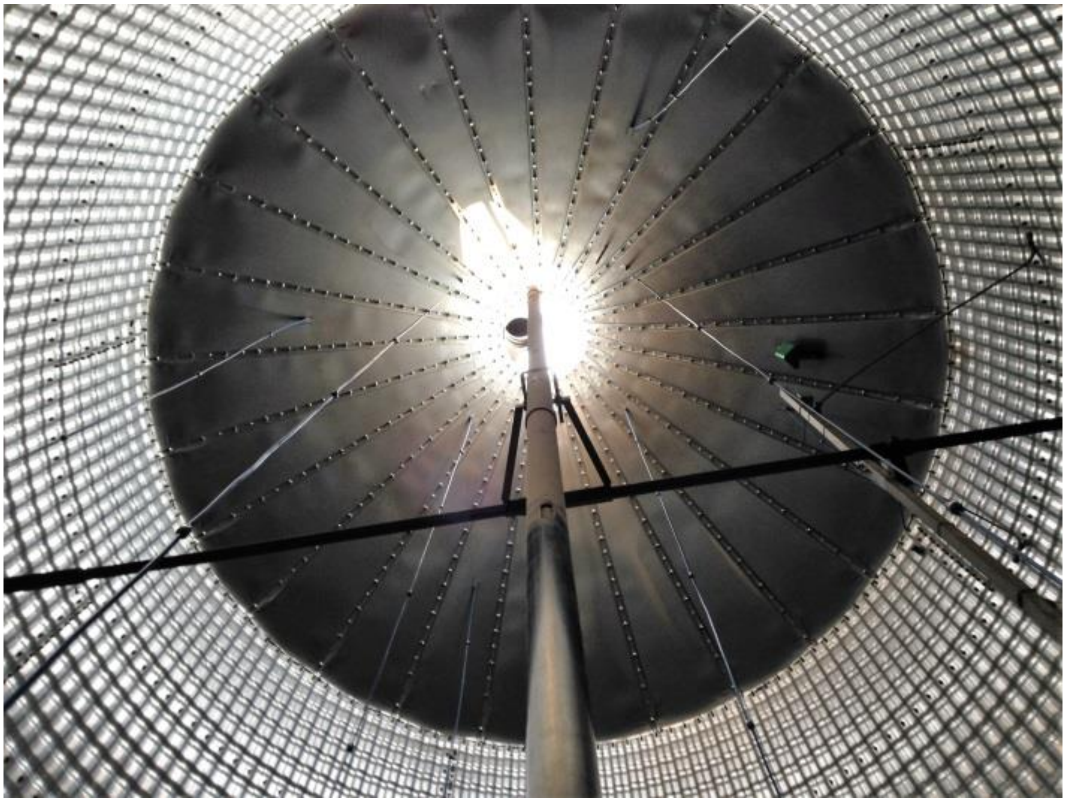
Figure 1: Sampling tube and sensor strings inside of test bin.


Figure 2: Simultaneous filling of test bins, 2015.


Figure 3: Inlet reduction cover and air vent to reduce cfm/bu.

The two *fan control strategies* used in the 2016 trials are described below:

- ***Continuously*:** in which fans were run continuously (24 hours/day) from the start to the end of the trial period (with the exception of rain periods). This strategy was used on bins 9 and 10. It is a very simple strategy as it does not require any sophisticated sensors and calculations. It results in a higher duty cycle, but it does not accurately determine drying conditions and there are many hours that wetting occurs.
- ***+2 Temperature Differential*:** $T_{air} < T_{grain}+2$, in which fans were activated only if the air temperature was less than the grain temperature $+2^0$C. This strategy was tested in bins 16, 17, 18 and 19. As before, seven temperature sensors at the mid height of the bin were used as the input for the control.

Theory and Calculations:

A systems approach was used where each bin was considered a black box, to which only the inputs and outputs were considered. There was an equal amount of air leaving the bin as there was air entering the bin through the fan. Air contains water and as the air moves through the bin it can either pick up more water or deposit water. The degree of drying is determined by calculating the net amount of water being removed from the bin. If the amount of water in the air leaving the bin is greater than the amount of water in the air entering the bin, drying occurs. If the amount of water in the air leaving the bin is less than amount of water in the air entering the bin, wetting occurs. The amount of water in the air is calculated with the following psychrometric formula:

$$W = W_S \times RH/100$$

$$W_S = 0.000289\,T^3 + 0.010873\,T^2 + 0.311043T + 4.617135$$

Where W (grams/m^3) is the mass of water in one cubic meter of air, W_S (grams/m^3) is the maximum mass of water that saturated air can hold at a specific temperature (T), expressed in ^{0}C, and relative humidity (RH) expressed as a %.

How safe the grain is depends on the temperature and moisture content of the grain when it enters the bin. The objective for safe storage is to maximize the number of safe days by lowering the temperature and the moisture content (MC). Safe days are the number of days in which grain can be stored safely to a specific spoilage level. According to Fraser & Muir (1981), safe days are the number of days until the germination capacity is reduced to 95%. For wheat and cereals, safe days can be calculated as:

Safe Days = 10^(6.234 -0.2118 MC – 0.0527 T)

The amount of deterioration can be calculated in terms of the spoilage index. The spoilage index is an accumulation of the reciprocal of Safe Days. Accumulation is calculated on a daily basis.

Spoilage Index = Σ (1/ safe days) x 100

The data obtained through the IntraGrain cable system downloads data every 68 minutes, resulting in the spoilage index to be calculated as:

Spoilage Index = [Σ (1/ safe days)/21.176] x 100

Moisture content represents the amount of water in the grain, and is given on a wet basis (wb) as:

MC (%) = Weight of Water/ (Weight of Dry Matter + Weight of Water)

Fan efficiency can be determined by its duty cycle. It is a percentage of fan-on time with respect to the total trial time.

Duty Cycle (%) = (fan ON time/total time period) x100

6. Progress during the reporting period:

Large amounts of data were collected in 2016 from a total of 284 temperature sensors and 284 relative humidity sensors, with readings taken every 68 minutes. Grain was dried and cooled using temperature differential and continuous strategies, but due to controller error, no definitive conclusions can be made on the effect of continuous drying versus temperature differential on drying. While the temperature differential controller was faulty, bins 17 and 19 did run correctly for similar amounts of time; therefore, it was acceptable to compare air flow rates between the bins as a non-continuous treatment. A summary of the results of each run are shown in Table 3. The average decrease in temperature and moisture content across from bins 9, 10, 17, and 19 were 15^{0}C and 2.8% respectively. When grain was loaded into the bins, their safe days ranged from 4 to 13 days. At the end of the run, their safe days ranged from 89 to 517 days. The 0.4 cfm/bu air flow rate provided safer grain storage than the 0.1 cfm/bu strategy under continuous and non-continuous strategies. The number of safe days for the 0.4 cfm/bu air flow strategy was higher only because it was able to dry the grain faster and then keep cooler for storage.

Table 2: 2016 trial run results matrix.

Bin # / Facts	Bin 9	Bin 10	Bin 17	Bin 19	Bin 16*	Bin 18*
Control Strategy	Continuous	Continuous	+2^{0}C	+2^{0}C	+2^{0}C	+2^{0}C
Grain	Barley	Barley	Barley	Barley	Wheat	Wheat
CFM/bu	0.15	0.4	0.1	0.38	0.1	0.37
Bin Average Initial MC (%)	18.8	18.2	19.0	18.5	14.8	15.4
Bin Average Final MC (%)	15.1	13.2	17.8	16.6	14.1	14.2
MC Difference (%)	3.7	5.0	1.2	1.9	0.7	1.2
Initial Temp (^{0}C)	30.3	28.2	30.9	30.3	24.7	25.8
Final Temp (^{0}C)	14.3	14.2	9.8	11.7	10.7	9.2
Temp Change (^{0}C)	16.0	14.0	21.1	18.6	14.0	16.6
Temp Drop / 1% MC removal	4.3	2.8	17.6	9.8	20.0	13.8
Initial Tonnes of Grain	50.530	50.510	80.420	80.660	95.560	94.735
Final Tonnes of Grain	48.720	48.161	78.873	78.778	94.755	93.518
Water Removed (kg)	1,810	2,349	1,547	1,882	805	1,217
Duty Cycle (%)	74	72	39	43	47	47
Safe Days Initial	6	13	4	9	63	42
Safe Days Final	214	517	89	134	480	529
Spoilage Index	50	30	91	53	11	11

* Not included in the analysis due to controller error.

The duty cycle of the 2016 trials varied from 39 to 74%. Theoretically, the duty cycle of continuous runs should be 100%, as they were programmed to run 24 hours a day. But there were times when the fans were stopped due to rain. While no definitive conclusions can be made about the temperature differential strategy as mentioned above, it is clear from the results matrix that turning the fan on and off results in greater energy efficiency while drying the grain.

The amount of water removed or added was calculated on 68 minute basis for the entire running period of all the bins. Figure 4 represents the amount of water added or removed (kg/hr) in bin 9 and bin 10 (Figure 5). The first day was critical as a large amount of water was removed from both bins, although bin 10, with an air flow rate of 0.4 cfm/bu, was able to remove more water faster. It is recommended that the fans be turned on immediately, even as the bin is being filled, and left to run continuously for 24 hours. Most of the hours in Figure 4 and Figure 5 show a positive amount of water being removed where drying is occurring. However, one can observe a few hours with negative water removal in which wetting was occurring. The bins controlled by the temperature differential strategy saw the same trend in that the higher air flow rate resulted in more drying. The difference between the temperature differential controllers and continuous is that water is not typically added back into the bin because the controller will turn off the fan when conditions are not favorable for drying. Of course, we cannot verify that this occurred with the controller errors this year.

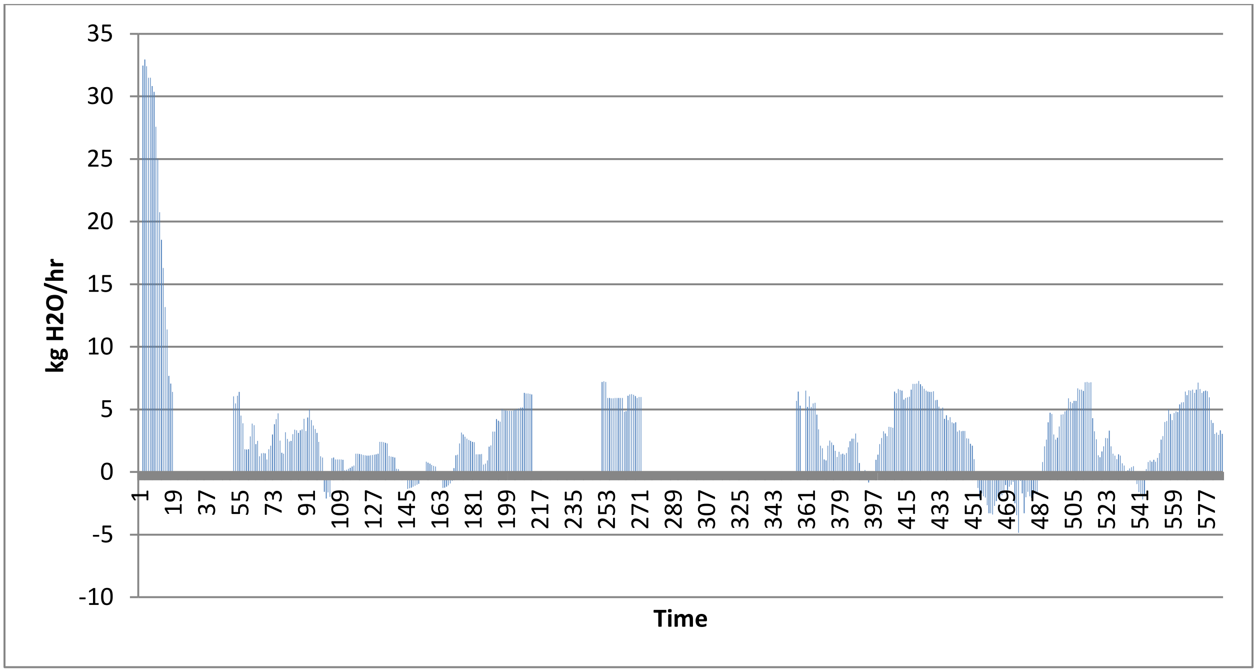

Figure 4: Bin 9 (0.15 cfm/bu) water removal in respect to time (hours), 2016 barley.

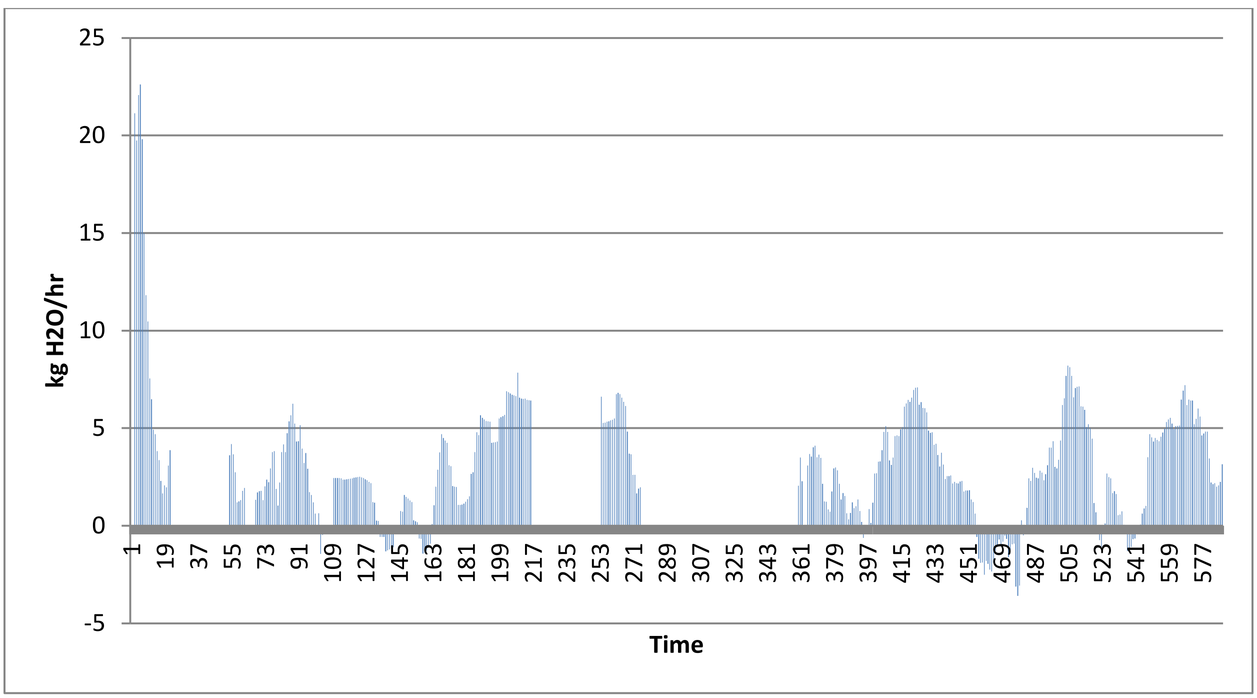

Figure 5: Bin 10 (0.4 cfm/bu) water removal in respect to time (hours), 2016 barley.

Industry recommends an air flow rate of 1 cfm/bu for effective grain drying and 0.1 cfm/bu for grain aeration. Results from PAMI comparing rates of 1.0, 0.5, and 0.1 cfm/bu on grain drying proved the 1 cfm/bu recommendation could be reduced in half and still have effective drying. This has further been seen in our trials at IHARF, where the maximum air flow rate produced by the fans was 0.4 cfm/bu. Drying results from the different air flow strategies in bins 9, 10, 17, and 19 are shown in Figure 6 and Figure 7. The 0.4 cfm/bu strategy resulted in the most drying, but had greater swings in variation from top to bottom under the continuous setting. It was not surprising to find less variation occurring in the temperature differential strategy since the fan should not be running when conditions are not favorable for drying. Additionally, the higher air flow rate appears to be better at grain drying. The least drying occurred with the low air flow strategy, but eventually did dry the grain to acceptable levels like that of the high air flow rate. It is interesting to observe that both air flow rates converge at approximately 445 hours to approximately 15% MC in all four bins. However, the best strategy, in terms of drying the grain quickly, would be the high flow rate at 0.4 cfm/bu.

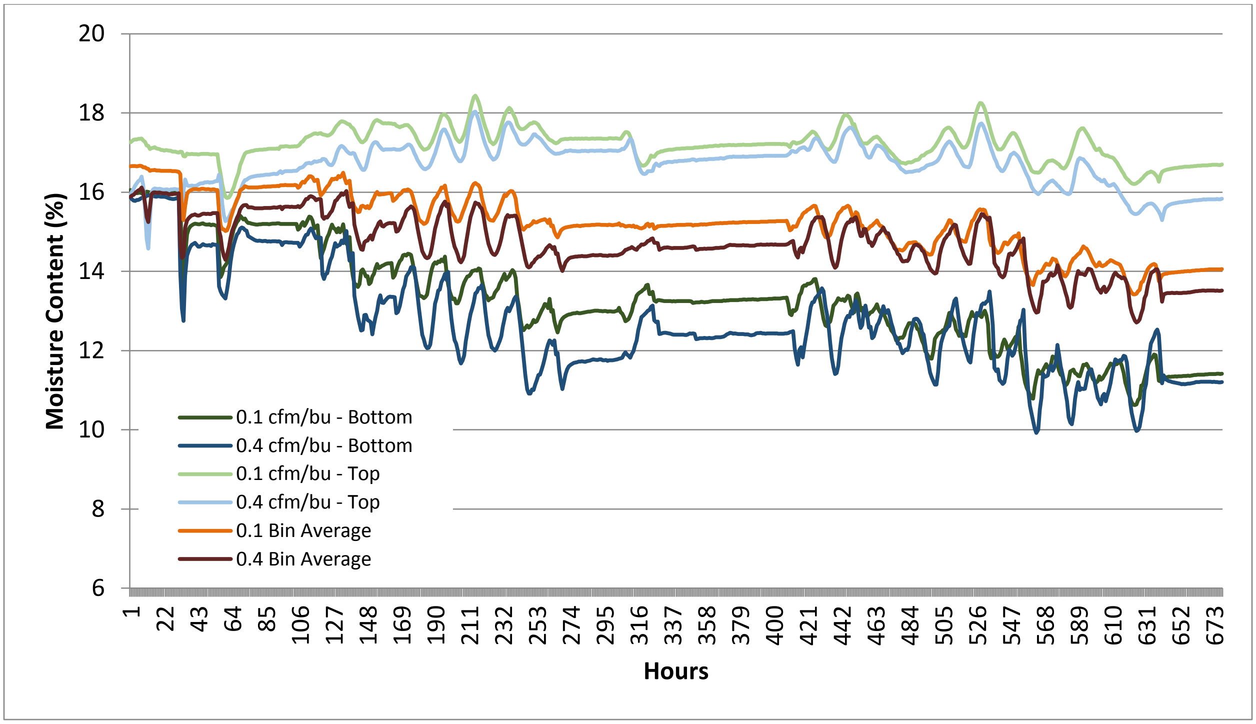

Figure 6: Bin 9 & 10 MC change at the top, bottom and overall bin average, 2016 barley.

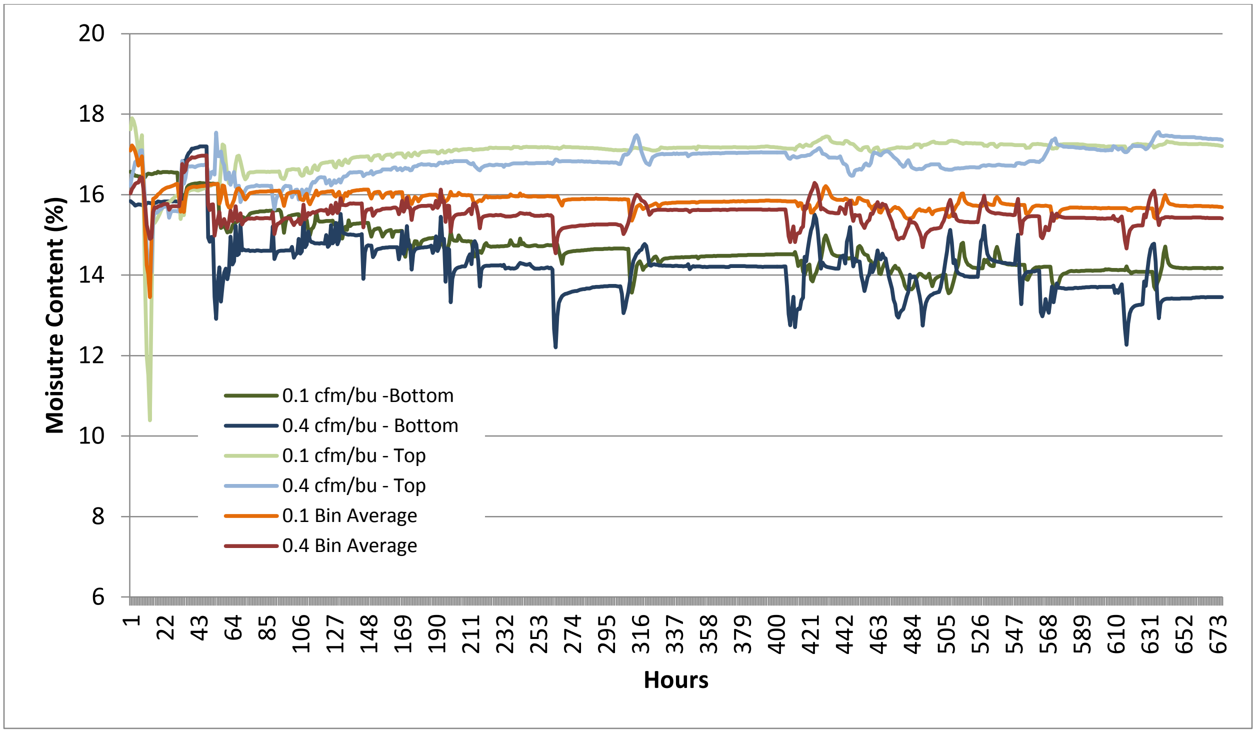

Figure 7: Bin 17 & 19 MC change at the top, bottom and overall bin average, 2016 barley.

Evaluating the differences in MC from the top to bottom of each bin with different air flows and timing routines also showed differences (Figure 8 and Figure 9). It was observed that the 0.4 cfm/bu air flow rate was more variable in both continuous and temperature differential strategies, while the 0.1 cfm/bu was more constant. Additionally, greater discrepancies between the top and bottom moisture content of the high air flow rates occurred earlier on in the process, while the lower air flow rate saw greater differences at the end of the trial. Once again, this is likely due to the moisture moving more quickly up the bin when using higher air flow rates. Interestingly enough, the continuous air flow treatment shows higher differences in top to bottom moisture content at the lower air flow rate and the opposite for the non-continuous air flow treatment. The differences between the two (0.7 and 0.9 %MC, respectively) are not likely to be significantly different, but it is interesting to note for further research.

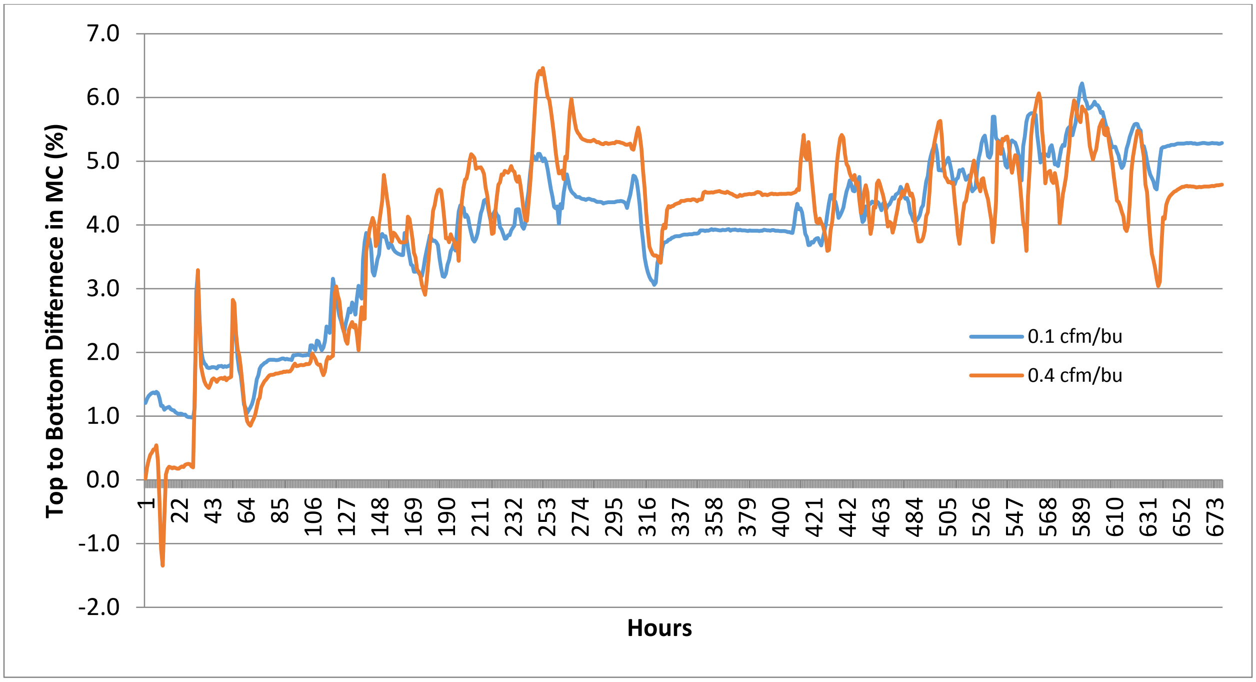

Figure 8: Bin 9 & 10 MC difference from top of the bin to the bottom, 2016 barley.

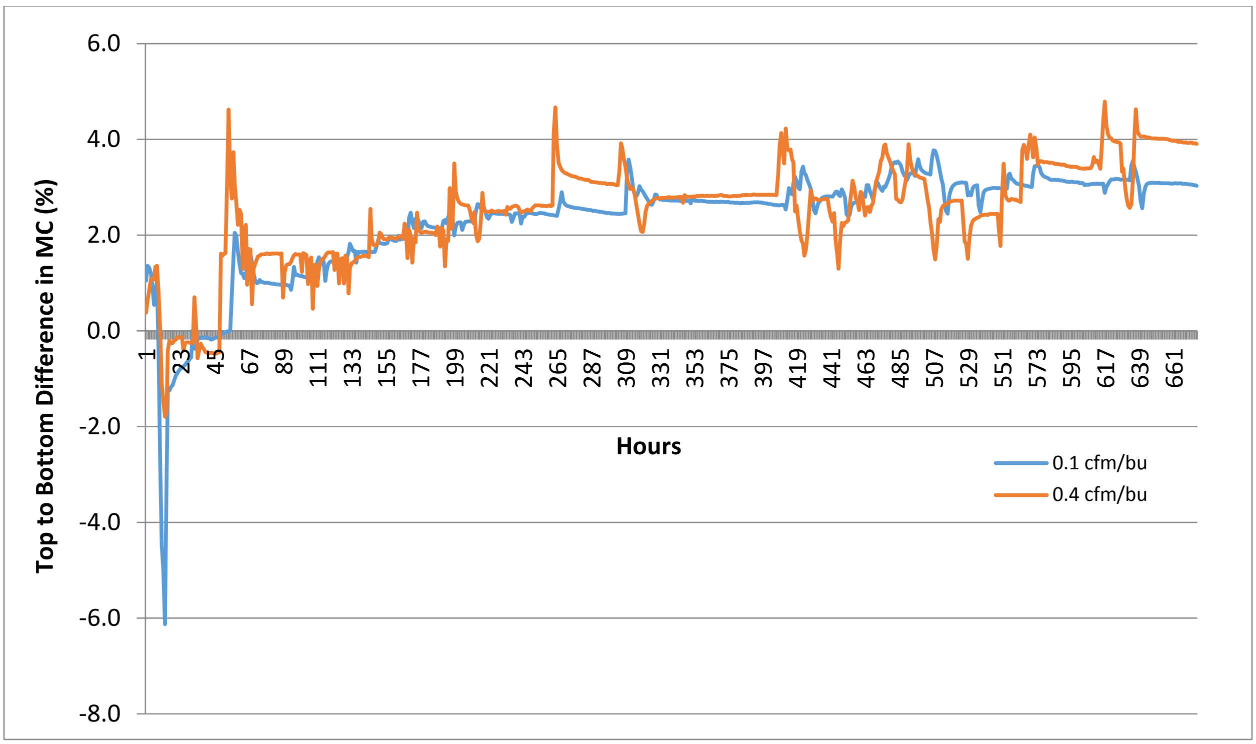

Figure 9: Bin 17 & 19 MC difference from the top of the bin to the bottom, 2016 barley.

The average MC of the grain before and after fan operation, from lowest to highest points within the bin, is represented in Table 3. After the fan operation, the highest MC appears to be in upper central core, while lowest MC appears to be in lower central core. There was gradual rise in MC from bottom to top of the grain inside the bin. In general, there was a decrease in MC in all the levels after the runs were completed. The biggest changes in MC at each sensor occurred in the bins with air flow rates of 0.4 cfm/bu.

Table 3: Initial and final MC of test bins, from lowest to highest points.

BIN 9 Barley Continuous 0.15 cfm/bu		**BIN 10** Barley Continuous 0.4 cfm/bu		**BIN 17** Barley +2 0.1 cfm/bu		**BIN 19** Barley +2 0.38 cfm/bu		**BIN 16** Wheat +2 0.1 cfm/bu		**BIN 18** Wheat +2 0.37 cfm/bu		Sensor Height
Initial MC (%)	Final MC (%)	Initial MC (%)	Final MC (%)	Initial MC (%)	Final MC (%)	Initial MC (%)	Final MC (%)	Initial MC (%)	Final MC (%)	Initial MC (%)	Final MC (%)	
-	-	-	-	18.5	18.3	18.3	18.7	13.4	14.2	14.7	14.5	Top
18.8	18.3	18.5	16.2	18.9	18.8	18.6	18.0	14.9	14.3	15.3	15.1	↑
20.0	17.5	19.0	12.3	19.4	19.3	18.5	17.3	15.7	14.9	15.8	14.5	
18.3	11.1	18.1	11.2	19.5	18.7	19.3	15.5	15.0	14.5	15.0	14.4	
17.4	11.7	16.5	13.1	19.8	15.8	18.8	15.8	15.1	13.0	16.8	14.1	
17.7	14.1	16.7	12.7	17.7	15.1	16.3	12.4	14.3	13.9	14.1	13.0	Bottom

Aside from the bin experiments, further evaluations of grain aeration concepts were done to verify the 80% relative humidity rule. A spreadsheet was built using the Grain Drying with Natural Air calculator (planetcalc.com/4959) to see how the threshold relative humidity changes between different types of grain, moisture content, and as the temperature difference between air and grain widens. Graphing the values as shown in Figure 10 and Figure 11, shows there is no simple, reliable 'rule of thumb' for relative humidity. A single point change in moisture content (top vs. bottom graph) causes the relative humidity to jump almost 20% in many cases. The difference in temperature between the grain and air also greatly affects the threshold relative humidity. For example, the threshold humidity could be anywhere from 25-100% when the air temperature is -10 to +10 degrees different from the grain temperature. From these conclusions, it is clear there is no simple number or formula to determine the threshold humidity. Findings from these calculations further suggest building a controller that calculates absolute humidity to regulate fan status is still the best option for optimal grain drying. The absolute humidity controller would work best as it considers the effect of temperature on relative humidity. Work conducted by PAMI under IHARFs direction in 2016 showed that the absolute humidity controller was better for grain drying over a degree offset of 1 or 2. This is because the air and grain temperatures were relatively equal throughout the project and the outside RH was high. If the temperature between the air and grain were significantly different, the +2 degree offset controller would likely have dried the grain more efficiently.

PAMI's 2016 work looking at an absolute humidity controller will direct our work for the 2017 season. This year, we will test the absolute humidity controller on IHARF's farm sized bins (2 x 3,500 bu), compared against the standard practice of running the fans continuously (2 x 3,500 bu). To further clarify, we will be looking at two bins of barley; one absolute humidity controlled, one continuous fan, and two bins of spring wheat; one absolute humidity controlled, one continuous fan. We will be looking at the absolute humidity controllers ability to cool the grain, dry the grain, and the resulting effects on the spoilage index and days of safe storage of the grain, and comparing it to the industry standard of running the fans continuously as the check.

On IHARF's 2,250 bu bins, supplemental heat will be explored. During the harvest of 2016, IHARF was inundated with phone calls asking for information regarding supplemental heat to dry down crops. These conversations lead us to testing the effects of adding supplemental heat to the bins during the heat of the day, while only using aeration to cool and dry the grain back down during the subsequent night. One bin will be used with the supplemental heat, while using the standard practice of running the fan continuously as the check.

An off farm collaborator has been identified to participate in this years trials. Two 20,000 bu bins with the IntraGrain system in the Indian Head area will be filled with wheat, and dried through implementing an alternative fan control strategy, compared against their regular fan operation. This will verify that the alternative fan strategies also work on larger bins.

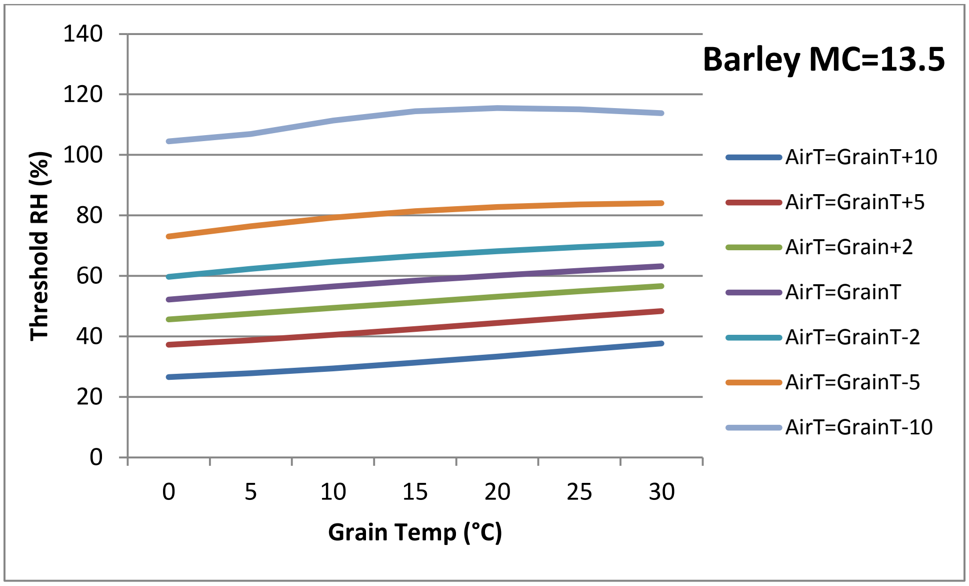

Figure 10: Change in threshold RH at different grain temperatures, 13.5% MC barley.

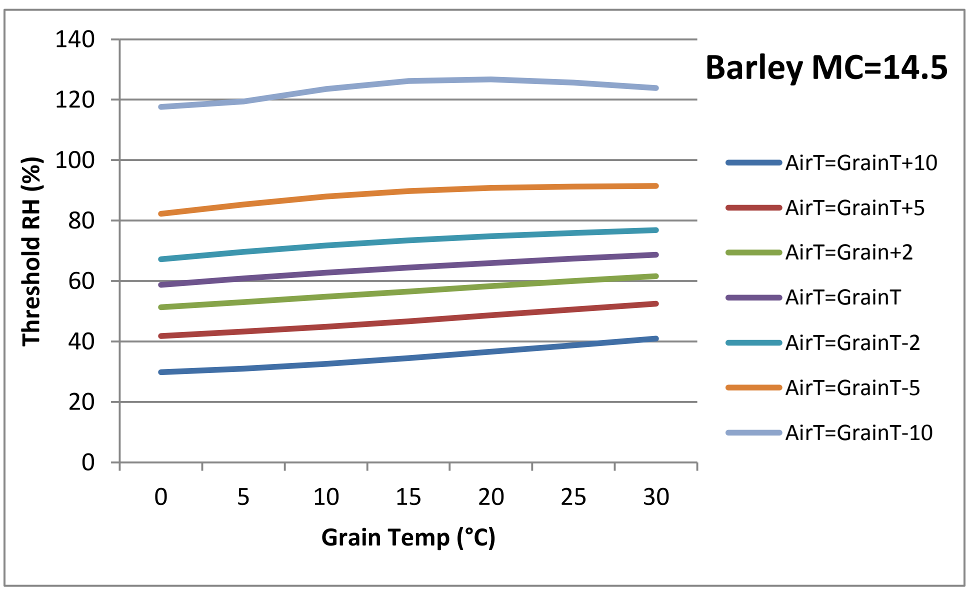

Figure 11: Change in threshold RH at different grain temperatures, 14.5% MC barley.

Canola Run Trial Results: Winter Storage

A study was conducted to monitor the winter storage of canola. Two of our smaller instrumented bins, 9 and 10, were used. Both are 2,250 bushels and were instrumented with 9 sensor cables. We did not run the fans as the canola was already dry, and cold from moving it in February. The lids on both bins were closed after filling them, and remained closed. The intake on bin 9 was sealed, while the intake to the fan on bin 10 was left open to allow for some convection current.

The canola was put in the bins on February 28, 2017, with temperatures of -9.8°C and -10.2°C for bins 9 and 10 respectively. Monitoring is still underway, but for the purpose of this report, the data analyzed stopped on May 27, 2017, and the temperature of the canola had gone up to 4.4°C and 4.6°C, a 14.2°C and14.8°C increase. This works out to about a 1.14°C rise per week.

At the start of the run, the mean outside temperature was approximately -12°C, and at the end of the run close to 10°C. As is shown in Figure 12 and Figure 13; the temperature of the canola follows the mean temperature but lags by approximately five degrees. It is clear that the bottom warms up the most, followed by the top. The middle of the bin is the slowest to respond to a temperature increase.

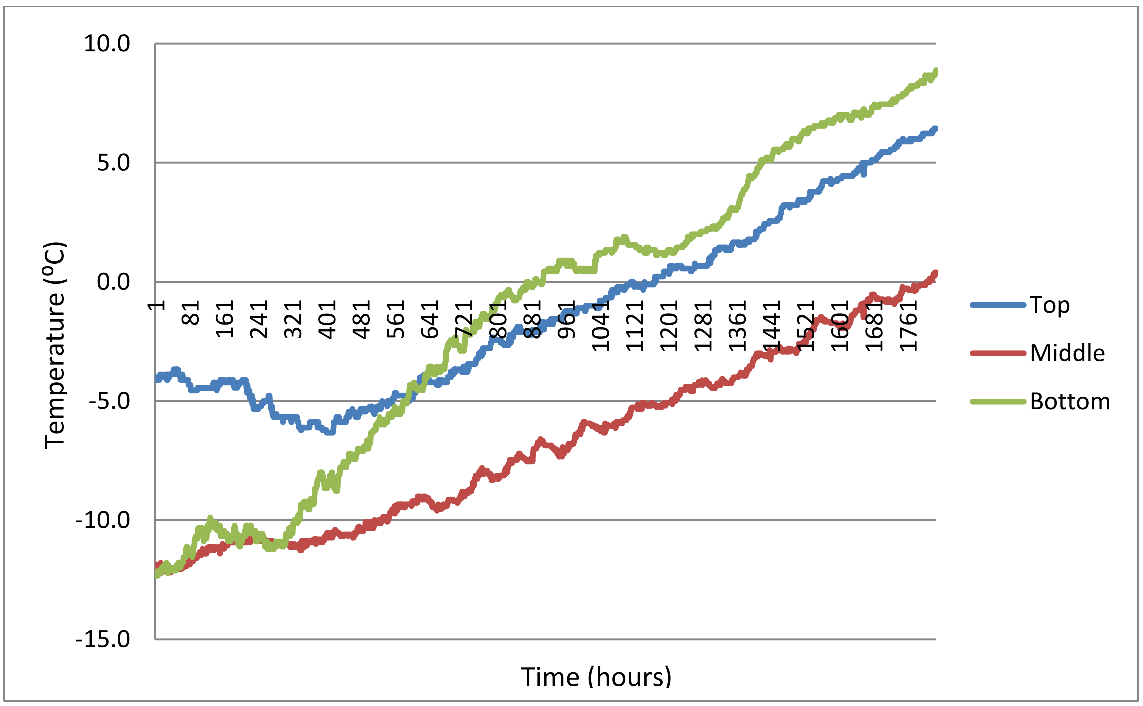

Figure 12: Temperature of bin 9 (sealed fan), canola, February 28-May 27, 2017.

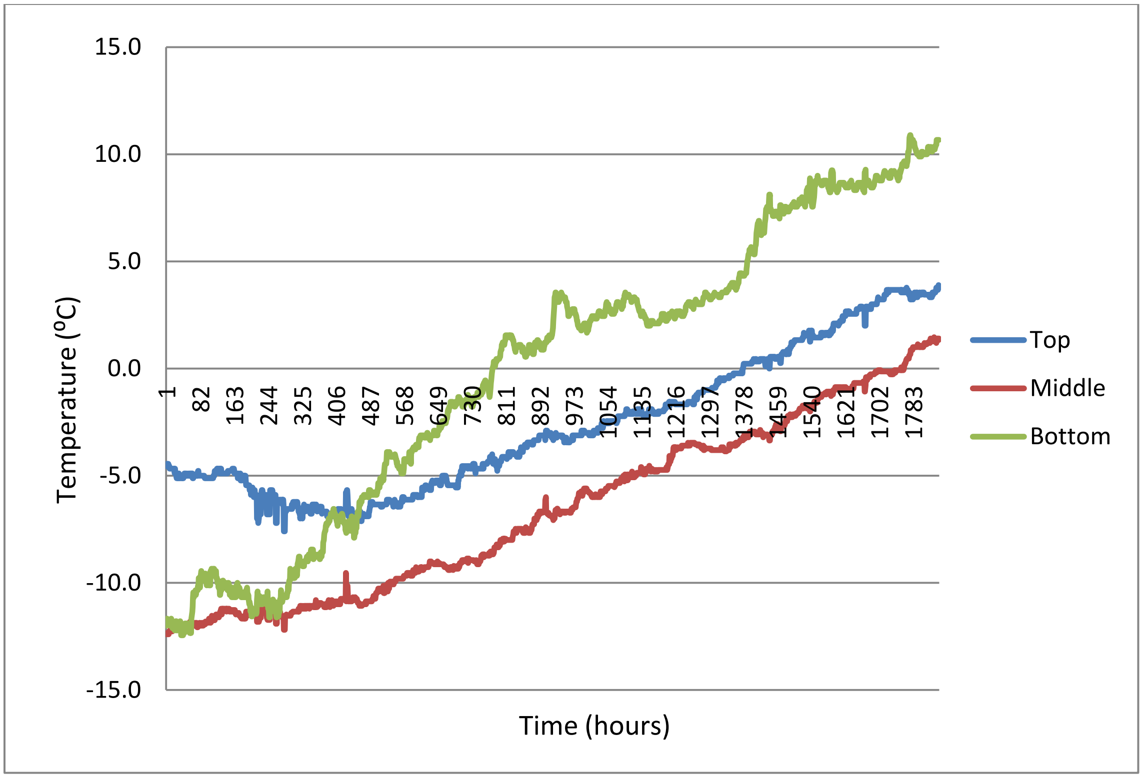

Figure 13: Temperature of bin 10 (open fan), canola, February 28-May 27, 2017.

It appeared that the moisture content went up slightly, 8.2 to 8.6%, and 8.8 to 9.1%. This really isn't significant, and technically the moisture content should have remained the same since the bins were more or less sealed. However the fan intake was not sealed on bin 10 and it can be noticed that the lower layer of grain decreased in moisture; whereas in the sealed bin the lower layer shows no decrease in moisture.

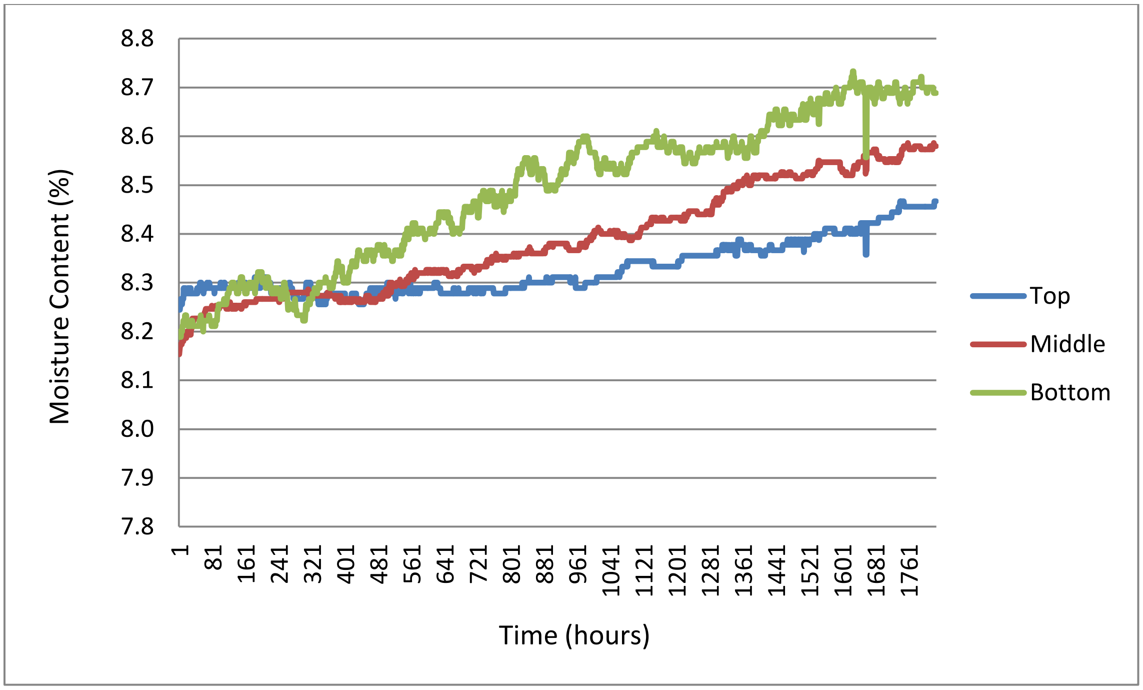

Figure 14: Moisture content of bin 9 (sealed fan), canola, February 28-May 27, 2017.

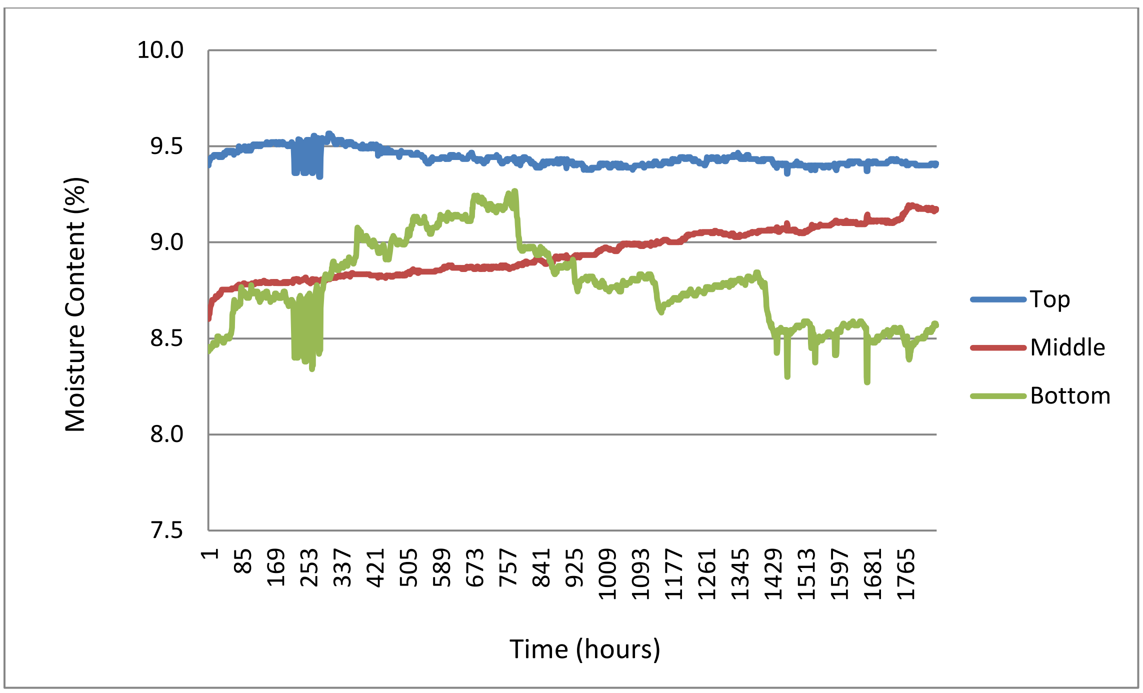

Figure 15: Moisture content of bin 10 (open fan), canola, February 28-May 27, 2017.

The conclusion that can be drawn from this is that grain, in a sealed bin, will warm up; lagging the outside mean temperature by approximately 5^{o}C. The winter to spring warming was 1.14^{o}C/week.

7. Progress of project to date

Accomplishments: 2015

- Clear objectives were established for grain storage management:
  - Safety: to store the grain as safely as possible, with the least spoilage or deterioration,
  - Drying: to dry the grain quickly for sale to an acceptable moisture content, but not to over-dry,
  - Efficiency: to condition the grain efficiently, at the lowest cost and the least inconvenience,
  - Evenly: to maintain a consistent moisture content from the top to the bottom of the bin.
- Tools or techniques were developed to measure relevant parameters throughout the bin on an hourly basis. These parameters included temperature, relative humidity, moisture content, spoilage index and absolute humidity.
- A technique was developed to measure the amount of drying taking place in a bin on an hour by hour basis. By using psychrometric equations, it was possible to calculate the net amount of water leaving the bin. This technique was extremely useful in observing the dynamic drying process. The bin is considered a black box in which air enters the bin through the bottom and leaves through the top. Drying will occur if the air leaving the bin contains more water than air entering the bin. A diurnal grain drying cycle was found. Drying primarily takes place at night.
- The relationship between drying and cooling was established. The data clearly demonstrates that grain dries as it cools.
- An understanding of why and how condensation forms on the inside of a bin. When the air inside the bin comes into contact with a cold wall or roof that is below its dew point temperature, condensation occurs. Under such conditions, the fans should not be run. Condensation can occur even with dry grain.
- A determination of what constitutes a drying condition. If the absolute humidity of the air inside the bin is greater than the absolute humidity of the outside air, drying will occur and fans should be turned on. A calculator has been developed to determine when conditions are suitable for drying. The inputs are grain moisture content (%), grain temperature (^{0}C), and the outside air temperature (^{0}C). The output is the threshold relative humidity for several different types of grain. If the outside airs relative humidity is less than this threshold, drying will occur. A larger difference is indicative of better drying conditions. The calculator can be found at http://planetcalc.com/4959/
- Controller strategies were proposed and developed to address the various management objectives:
  - ***Night-Only:*** In this strategy, the fan runs only at night. It is a simple, low cost strategy as it does not require any complex calculations or expensive sensors. Since the fan only runs half the time, it is much more efficient compared to running the fan continuously; however, it does not take into consideration the actual condition of the grain and outside air. For example, this strategy could result in the fan running when the outside conditions are not favorable for drying. It does keep the grain colder than continuous fan operation and therefore safer.
  - ***Temperature Differential:*** With this strategy, fans are activated if the grain temperature is higher than outside air temperature ($T_{air} < T_{grain}$ +off-set). It requires only two simple temperature sensors, one in the grain and the other in the outside air. This method keeps the grain cold and is therefore a very safe method. However, it is not perfect in terms of drying the grain as it does not take into account the moisture content of the grain and relative humidity of the outside air. There may be times when the relative humidity of the outside air is very high, resulting in some wetting depending on the grain moisture content.

- Large amounts of water are removed and large temperature drops occur on the first day of fan operation. Therefore, it is recommended that the fans be turned on as soon as freshly harvested grain is loaded into the bin.
- The data shows a gradual change in moisture content from the top to the bottom of the bin. There was no distinct line or front.
- Substantial drying can take place with low flows. The PAMI trials demonstrated that a 50% reduction in flow, reduced the drying rate very little. A flow of 0.5 cfm/bu was adequate for drying. This was verified with our 2015 trials that used a flow of 0.35 cfm/bu.

Accomplishments: 2016

2015 accomplishments were confirmed including:

- An airflow of 0.4 cfm/bu is sufficient for grain drying,
- Diurnal drying cycle,
- Temperature differential controllers work,
- The top of the bin drys last,
- No wetting front, rather a gradual change in both temperature and moisture,
- Large amounts of water are removed the first day of running the fan,
- Determination of what constitutes a drying condition, using absolute humidity,
- Better understanding of why and how condensation forms on the inside of a bin,
- Relationship between cooling and drying measured and confirmed: 1% MC per 15^{o}C.

The amount of water in the air is known as the absolute humidity and it can be calculated with psychrometric equations from the relative humidity and temperature. This concept of absolute humidity combined with EMC equations led to the formation of the Absolute Humidity Controller. This controller only has the fan running when drying conditions exist between the grain and outside air. This was shown theoretically and demonstrated with PAMIs 2016 trials, and will be further verified with IHARFs testing in 2017.

A grain drying calculator was developed. The theory of the absolute humidity controller was used as the basis to develop the grain drying calculator, which can be accessed from a smart phone, www.planetcalc.com/4959/. This calculator could be used to show if a specific condition is favorable for drying and for conditions of condensation.

Moisture content measurements from the moisture cables that rely on relative humidity and temperature to determine moisture content can only give accurate readings if there is no airflow for a substantial amount of time. A period of time must be given to allow the grain and air to equalize.

The bins were densely populated with temperature and relative humidity sensors in 2016. We wanted to answer the question as to whether or not pockets of inconsistent temperature or moisture content existed. No such pockets were detected.

There was a substantial pressure drop across the perforated tube. The pressure on the inside and outside the perforated screen was measured with a manometer (inches of water). Better ways to inject the air into the grain without this pressure drop should be investigated, such as open bottom ducts.

A basic rule of thumb was better established for the drying/cooling relationship by analyzing more data. We've identified the moisture content of the grain is reduced by one percentage point for every 15^{o}C that the grain is cooled.

A blog was started as a means to publish FAQ about grain drying. Email replies to individual farmers were used to specifically advise producers on their specific grain drying questions. Specific calculations of the conditions were worked out. This blog was the inspiration for the absolute Humidity Controller as well as the Grain Drying Calculator. This also led to a better understanding of when there would be conditions for condensation within the bin. The blog can be found at: www.grain-aeration.com.

There is a blog, “Seed Energy: How much moisture can the energy in the grain remove?”, that goes through the calculations to show that almost all the specific energy in the grain can be used to dry the grain. Or the specific heat of the grain can be used very efficiently to dry the grain (latent heat of evaporation). The 15^{o}C per 1% rule of thumb demonstrates a high degree of drying efficiency with almost all the specific energy of the grain going into evaporation of the moisture in grain.

The blog also has many interesting calculations and arguments on grain drying such as:

- 0.4 cfm/bu is sufficient to dry grain,
- Using too big a fan can be detrimental as well as being inefficient,
- Condensation at the top of the bin,
- An Absolute Humidity Controller is optimum,
- Calculators can be used for optimum control as well as determining condensation,
- How to install Grain Drying Calculator on a cell phone
- Supplemental heat calculations,
- Supplemental heat can lead to condensation,
- Cycling supplemental heat is much better than continuous heat,
- Supplemental heat sources: natural gas is the best, electricity is the most expensive,
- There is no one size fits all; it depends on the situation and the objective, the amount one is willing to invest in equipment, and how convenient and automatic the system is,
- Safety and security of grain is paramount,
- Best to leave your bin open and vented until the coldest part of year, and then seal the bin to keep it cold, and don’t let warm air hit the grain and create condensation. When the grain temp warms to the mean temp of day (maybe September) open the bin so that the grain temp is cooled more rapidly with convection currents through the bin or could cool with fan,
- Cooling the grain to below a certain temp could kill fusarium -20^{o}C?
- There is a significant pressure drop across the perforated aeration tube,
- The air flow stays more or less the same throughout our trial runs; does not change as the grain is dried,
- Increased temperature at the bottom of the bin was evident, caused by friction of the air entering the bin,
- Night drying works, but we soon run out of energy in the grain.
- The importance of the relationship between temperature, relative humidity and absolute humidity lead to the creation of a web site calculator that provides that relationship. www.planetcalc.com/2167/.