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Attachment to final report

SAGIT Project USA119

Strategies to enhance the value of on-farm grain storage in southern Australia

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Contents

1. Acknowledgements

This report summarises the findings of four years of study of grain storage in silos at Balaklava, South Australia. This work was supported by:-

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- SAGIT project – USA119 Strategies to enhance the value of on-farm grain storage in South Australia for 2019 to 2021.

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The silo monitoring and control equipment was provided by OPIsystems, Canada.

The upgrade of the two 3 kW fans to 5 kW fans were provided by Kotzur Silos and Cyclone Silos.

2. Key findings

3. Recommendations

4. Incoming grain condition

4.1. Harvest timing

Grain in southern Australia is generally harvested from late autumn to early summer. Harvest occurs after the grain has dried to below storage moisture limits. The weather at this time of year is characterised by many hot days (>30℃) and low humidities. Prolonged periods between drying and harvest can result in:-

- Shedding of the grain onto the ground during high wind events and thus loss of grain quantity at harvest.
- Rainfall occurring that can rewet the grain and result in quality losses.
- Over drying of the grain which results in a loss of grain mass.

4.2. Incoming grain temperature

Testing over multiple seasons showed that the grain entering the silo was up to 11°C hotter than the ambient temperature when harvested (Figure 1). For example, on a 30°C day the grain coming into the silo was around 41°C. This can be explained by the grain being heated above ambient by being in the direct solar radiation from the sun.

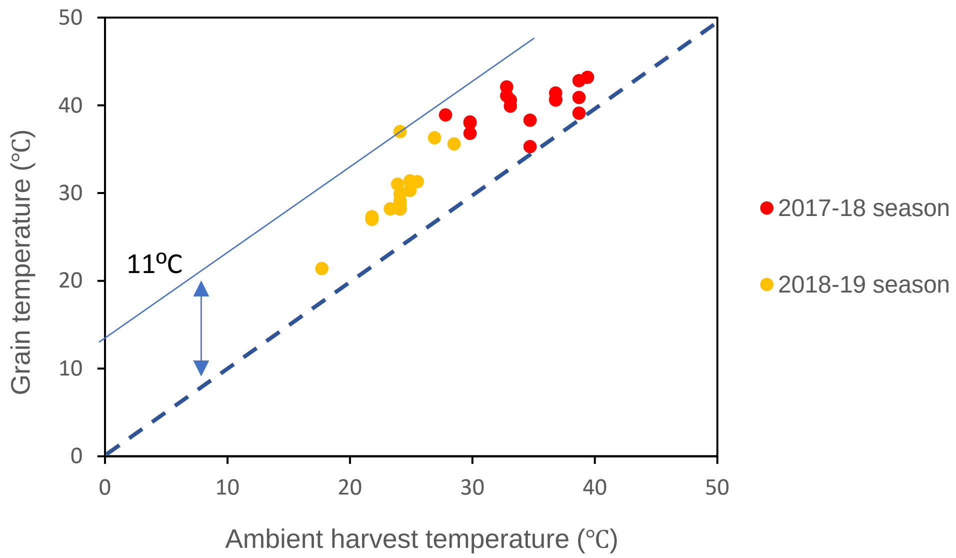


Figure 1. Harvested grain temperature is higher than ambient

Finding 1. Grain coming into the silo was up to 11℃ hotter than the ambient temperature at the time of harvest.

Recommendation 1. In order for stored grain to be below 20°C for insect control the grain in the silo will often need to be cooled.

4.3. Incoming grain moisture content

As harvest does not occur unless the grain is below the recommended storage moisture limits, and due to harvest capacity limitations, there is often a delay of several days/weeks between the start and completion of the harvest. Hence, some of the grain can be over dried. During our testing, up to 5% loss of mass below the maximum receival limit of 13.5% wb was observed.

For example, 1,000 tonnes of wheat valued at $300 per tonne with a 5% increase in weight will give an extra $15,000 of income.

Relevance: As farmers are paid for their grain on a weight basis, they can maximise their income by having the grain moisture content as close as possible to the storage/receival limits. It is possible to condition the grain using aeration to bring it closer to the receival limit (see later results in this report).

Finding 2. Grain coming into the silo was up to 5% lower in moisture content than the receival limits.

Recommendation 2. Conditioning the grain via aeration to increase its moisture content can be financially beneficial.

5. Silo structures

5.1. Galvanised vs white paint

Testing at Balaklava, South Australia compared the wall temperatures of a galvanised and a white painted silo. The silos are shown in Figure 2.

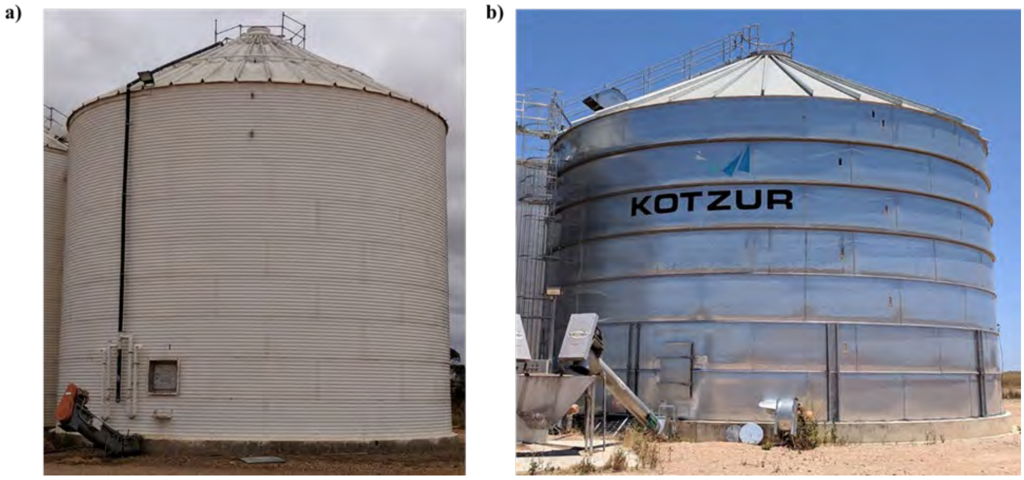


Figure 2. On-farm grain silos used for comparative testing of wall temperatures at Balaklava, South Australia: a) 1,000 t white painted silo; b) 1,200 t galvanized silo

The white painted silo was measured to keep the inside face of a silo wall facing the sun to no more than 5°C above ambient whilst a galvanised silo had wall temperatures up to 16°C above ambient (see Figure 3). This means that on a day of 40℃ the white silo wall temperatures would reach 45℃ and the galvanised silo would reach 56℃.

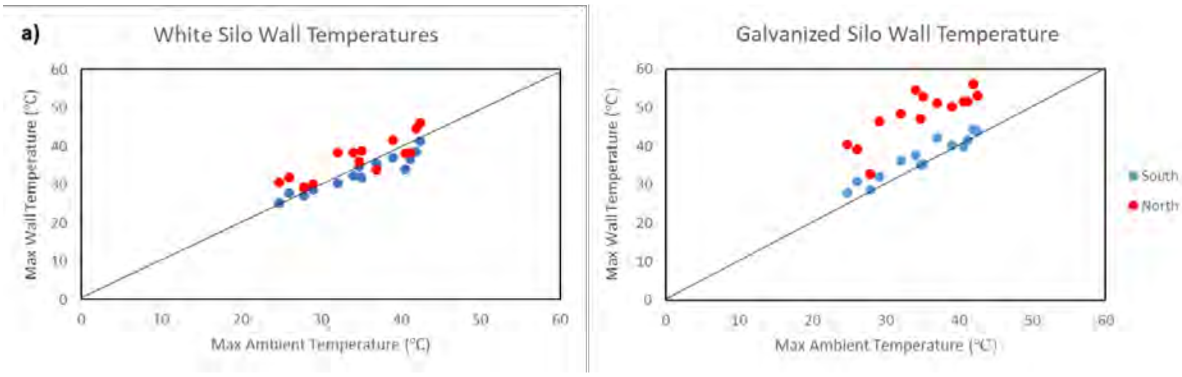


Figure 3. Comparison of white painted and galvanized silo wall temperatures

Finding 3. A white painted silo keeps the silo walls cooler but they can still reach in excess of 50°C on a hot day.

On the side away from the direct sun's rays, the wall temperatures of the galvanised and white painted silos were equal to the ambient air temperature.

Whilst the white paint kept the silo wall much cooler, the temperatures of the white painted wall and hence, that of the grain touching the wall, were still much higher than the desired maximum grain temperature of 20℃ to help control insect growth.

Relevance: White paint on the steel silo wall does keep the grain at the wall 11℃ cooler than the galvanised steel wall, but for a 40℃ day means that the grain near the wall only reaches 45℃ vs 56℃. Both these temperatures are higher than the 20℃ recommended to control insects in silos.

5.2. Depth of wall heat into the grain

Sensors were placed into the grain at distances of 50, 150, 250, 450, 650 and 1,200 mm from the wall. The results showed that the heat from the wall in the direct sun reached in 150 mm for the white painted silo and the higher wall temperatures of the galvanised silo reach in 250 mm. The grain temperature near the wall was observed to fluctuate diurnally between the wall maximum and the ambient minimum temperatures. Thus, on hot a day of 40℃ with a nightly minimum of 25℃, the grain near the wall cycled between 45 and 25℃ for the white painted silo and 56 and 25℃ for the galvanised silo.

The temperature of the grain near the silo wall was influenced by the ambient air temperature, solar radiation and wall treatment and not by the temperature of the grain at the core of the silo, as shown in Figure 4. The relative humidity of the grain near the wall did not change with grain temperature variations.

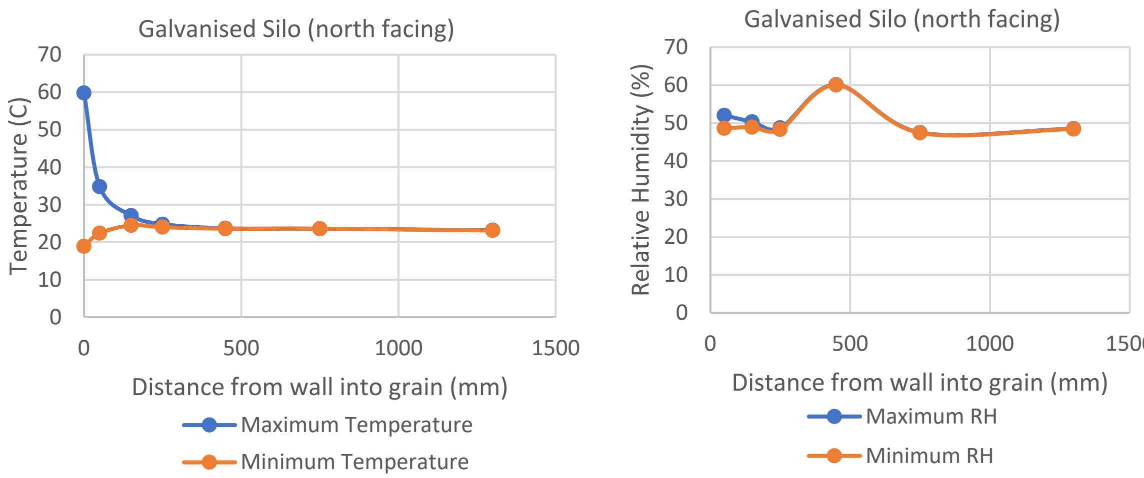


Figure 4. Example of daily variation in grain temperature and relative humidity for Galvanised silo 24/2/2019 at Balaklava, SA.
Daily maximum was 40°C and daily minimum was 16°C.

As the grain temperature by the silo wall increased, the relative humidity of the air did not vary much, showing that the moisture from the grain moved to the surrounding air keeping it at a similar humidity to the grain in the core of the silo. Thus, the warm temperature and moderate relative humidity near the wall is ideal for insect population growth.

5.3. Proportion of grain heated by the wall

As the depth of penetration of heat from the wall is independent of the silo diameter, a larger diameter silo will have a lower proportion of its grain heated by the wall.

For a 100 t capacity silo of 4.5m diameter, the volume of grain within 150 mm of the wall is 12.9% and within 250 mm of the wall is 21%. These values reduce for a 1,200 t silo with 12.8 m diameter to 4.6% of total volume for 150 mm in from the wall and 7.7% for 250 mm in from the wall.

Relevance: Regardless of aeration cooling of the grain in the silo, the temperature of the grain near the walls cycled to be at or above ambient during the day and cooled down to ambient during the night.

Finding 4. The grain near the silo wall has its temperature influenced by the wall temperature and not the grain's core.

Recommendation 3. Larger diameter silos are preferred if grain temperature is to be kept below 20°C for insect control.

5.4. Roof and headspace temperatures

Temperature and humidity sensors were placed just in from the roof of a 1,000 t white painted silo and 1,200 t galvanised silo. Sensors were also placed in the headspace above the grain. With the central and outer roof vents open, the air temperatures just below the roof were measured to be even hotter than that of the silo walls. The temperature below the galvanised roof was typically 26℃ above ambient at the roof peak and 21℃ near the roof eave, whilst the white painted roof had temperatures typically 16℃ higher than ambient at the roof peak and 11℃ near the roof eave (see Figure 5). At night the roof temperatures cooled to the minimum ambient temperature.

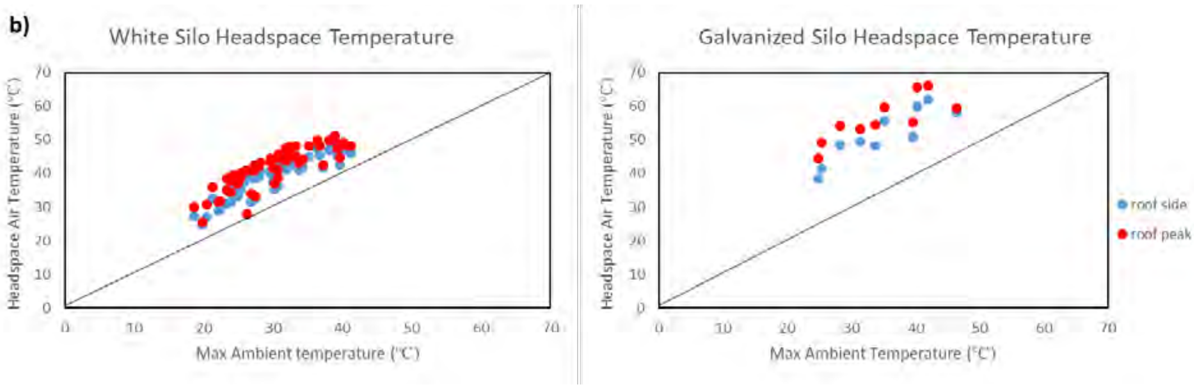


Figure 5. White and galvanized silo headspace temperatures just below roof at the roof peak and roof near the eave(roof side).

For example, on a hot 40℃ day, the air just below the galvanised silo roof reached 66℃ and the white painted silo reached 56℃.

Opening the silo vents for aeration or having them closed during fumigation did not show any significant difference in headspace temperatures in the 1,000 t white painted silo, as shown in Figure 6. The headspace temperature was a function of ambient temperature and roof treatment (galvanised vs white painted). Measurements without aeration showed that at night, when the minimum temperature was reached, the headspace temperature was similar to the outside ambient temperature and then as the day warmed the headspace temperature increased from the grain surface with distance up to the roof temperature.

With aeration operating during a cool night, the headspace air was near the grain temperature and was not influenced by the ambient night temperature (see Figure 6).

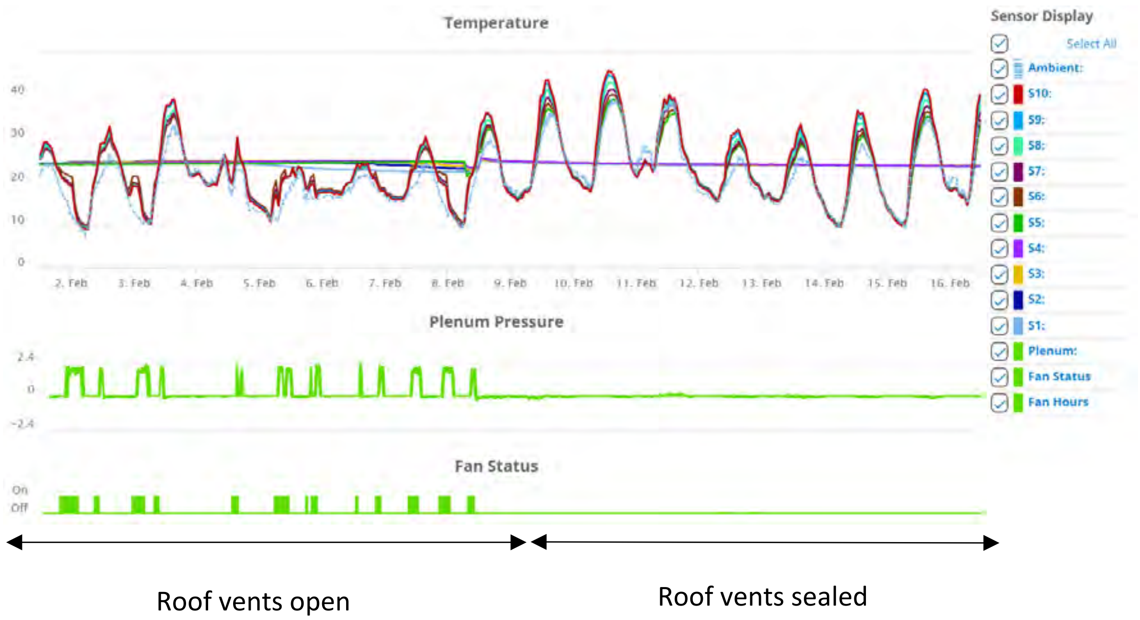


Figure 6. Ambient, grain (S1 to S6) and headspace temperatures (S7 to S10) for 1000 t white painted silo with silo vents open during aeration and with silo roof vents sealed during fumigation. February 2021.

As shown in Figure 7, the relative humidity of the air in the headspace with the vents open, was related to the ambient humidity, but with the silo sealed the relative humidity in the headspace was close to the relative humidity in the grain.

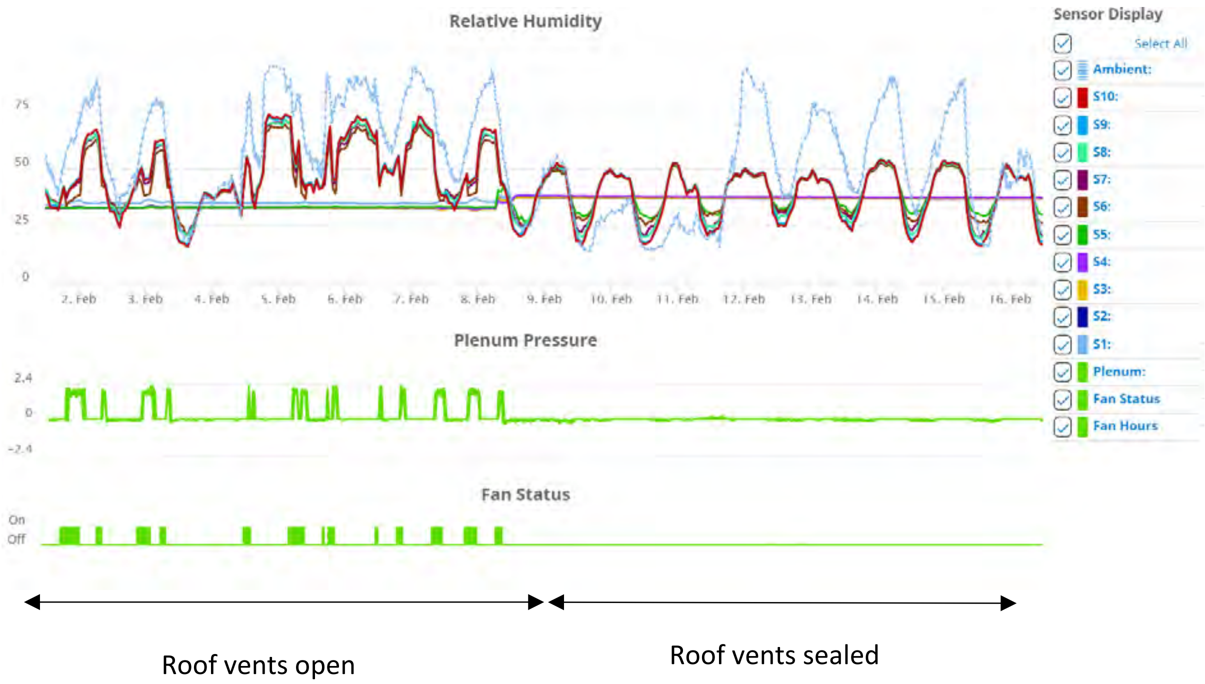


Figure 7. Ambient, grain (S1 to S6) and headspace relative humidity (S7 to S10) for white painted silo with silo vents open during aeration and with silo roof vents sealed during fumigation. February 2021.

Three months of data for the white painted silo from December 2020 to March 2021 for temperature and relative humidity is shown in Figure 8 and 9, respectively. The rapid variation in grain conditions of temperature and humidity is when the silo was partially emptied and then refilled with more grain. These graphs show how over many months, the headspace maximum temperature is greater than ambient and the relative humidity in the headspace remains lower than the nightly increase in the ambient relative humidity.

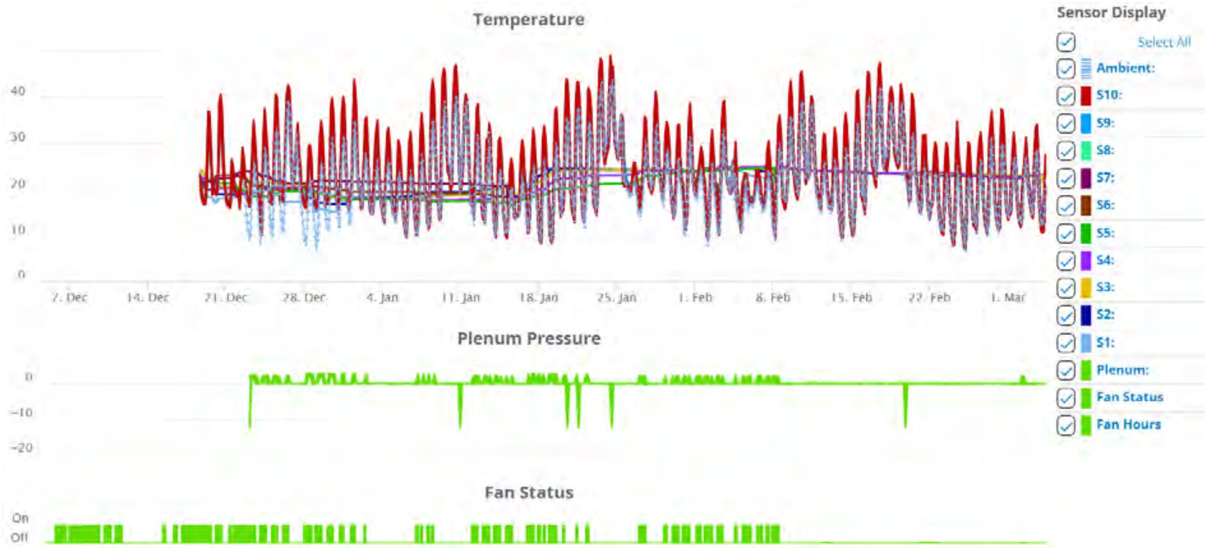


Figure 8. Long term temperature trends in white painted silo:
In grain = S1 to S6; headspace = S7 to S10.

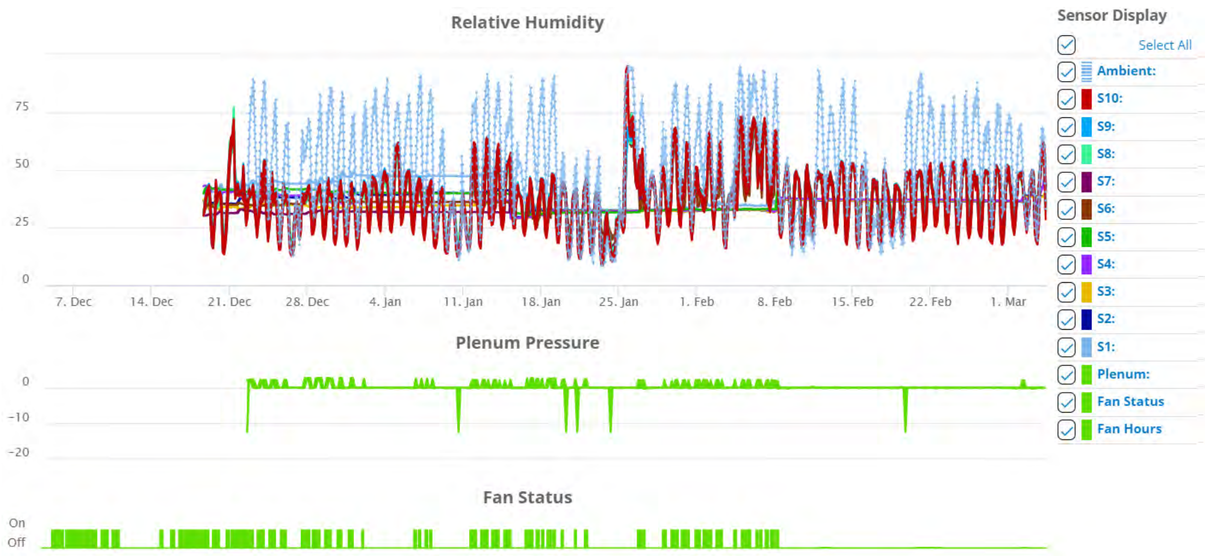


Figure 9. Long term humidity trends in white painted silo:
In grain = S1 to S6; headspace = S7 to S10.

Finding 5. The silo roof gets even hotter than the silo walls. The silo headspace during the day was hotter than the ambient temperature by up to 26°C for a galvanised silo and 16°C for a white painted silo.

Finding 6. There was no measurable difference in headspace temperature with the silo roof vents open or sealed.

Finding 7. With the roof vents closed the relative humidity in the headspace was close to that of the relative humidity in the grain.

5.5. Keeping all the grain cool

With the stated objective to keep all of the grain to below 20℃ the only method to achieve this would be to insulate the silo. Insultation of steel structures is undertaken in many industries where the contents are to be kept cool. Examples can be seen in the wine, housing and fuel storage industries.

Insulating a grain silo could be achieved in two ways:-

- Spray on coating with a hard outer layer.
- Covering the silo with insulating fibres and coating that with a metal skin.

An example of wine tanks covered with insulation and a white aluminium cladding is shown in Figure 10.

Figure 10. Example of insulated wine tank to control temperature of the contents.
http://www.thermowrap.com.au/Gallery.aspx

Example: For a 1,200 t silo the cost of purchase is around $250,000 and the cost of insulation using either method was quoted by suppliers as being around $35,000. Thus, the cost of insulating a 1,200 t silo is approximately $1.50 per tonne when amortised over 20 years.

Finding 8. A white painted silo is cooler than galvanised but to maximise the benefits in insect control and quality retention steel silos should be insulated. The cost of this is around $1.5 per tonne when amortised over 20 years.

Recommendation 3. Insulating the silo (spray on coating or cladding) is the only way to keep all of the grain and headspace cool.

6. Aeration cooling of grain in 100 t silo

6.1. Fan performance

Aeration cooling of grain in a 100 t silo at Balaklava was monitored for two seasons. The silo had a 0.37 kW fan. The silo is shown in Figure 11 and its fan performance in Table 3.

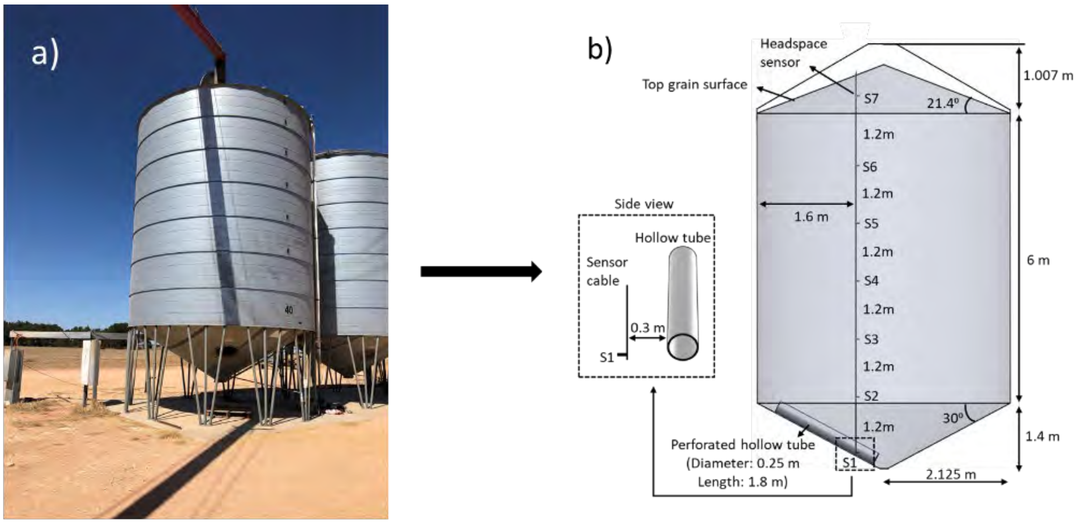


Figure 11. 100 t silo at Balaklava: a) Site; b) Sensor schematic

Table 3. Fan performance for 100 t galvanised silo.

Date	Grain	Fan	Air flowrate	l/s/t	Pressure
Dec 2019	Barley 90 t	350 W	0.22 m^3/s lid fully open	2.4	423 Pa
			0.19 m^3/s lid resting open	2.1	

Typically, the 100 t silo is left with the lid unlocked but resting on the seal and the air pressure from the fan opens the lid when the fan is running. It was measured that the airflow from the fan is lowered by the fan having to lift the lid. By fully opening the lid when the fan is running an extra 16% of airflow can be achieved.

6.2. Aeration cooling performance

The results of running the fan continuously for 97 hours during a cool spell was enough to cool the grain in the silo (peas) from around 30°C to close to 20°C, as shown in Table 4 and Figure 12.

It was observed that during intense summer rainfall events that with the lid down but not locked, water was able to enter the silo via the lid and wet up the top grain. This was able to be dried with subsequent aeration

Table 4. Aeration cooling of field peas in 100t silo with 97 fan hours.

	6/12/2020		
	Temp (°C)	RH (%)	MC (%)
Top	30.9	28	9.8
Middle	30.4	32.3	10.3
Bottom	27	47.5	11.9

11/12/2020		
Temp (°C)	RH (%)	MC (%)
22.9	26	9.7
20.6	34.2	10.6
20.1	44.4	11.7

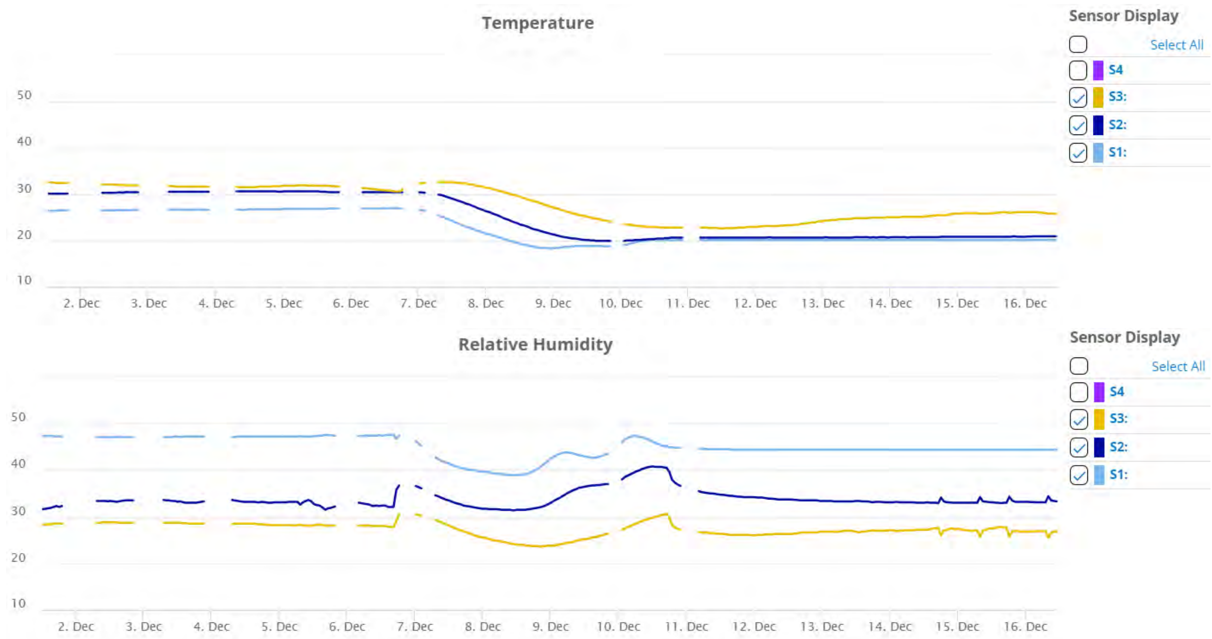


Figure 12. Aeration cooling of field peas in 100 t galvanised silo

The cooling of grain in the 100 t silo could be further optimised by using an automatic controller that turns on the fan only when the ambient air is below the grain temperature to stop the reheating of the grain when ambient is above the air temperature.

7. Aeration cooling of grain in 1,000 t silo

7.1. Fan performance

The white painted silo had a V-shaped underfloor duct connected to the aeration fan. Initially, the silo was fitted with a 3 kW fan. This was upgraded in 2020 to a 5 kW fan. The 3 and 5 kW fans are shown in Figure 13.

Figure 13. Original 3 kW fan (left) and new 5 kW fan (right)

The measured fan airflow rates are shown in Table 5. As shown in Table 5 the airflow rate into the silo was doubled by upgrading the fan from 3 to 5 kW.

Table 5. Fan performance with 1,000 t silo filled with grain (peak at 12.3 m height).

Date	Grain	Fan	Airflow rate	l/s/t	Inlet pressure (Pa)
Dec 2017	845 t Oats	3 kW	1.01 m^3/s	1.2	546
Dec 2018	970 t Barley	3 kW	0.954 m^3/s	0.98	668
Dec 2020	963 t Barley	5 kW	2.12 m^3/s	2.2	1,541

The 1,200 t galvanised silo had dual 3 kW fans with their performance shown in Table 6.

Table 6. Fan performance for 1,200 t galvanised silo filled with grain (peak at 10.4 m height).

Date	Grain	Fan	Air flow rate	l/s/t
Dec 2017	1,160 t wheat	2 x 3 kW	2.09 m^3/s	1.8

7.2. Airflow testing at peak in grain

It is known that air will take the easiest path. Measurements using the 1,000 t silo confirmed that more air came out the top surface near the walls than near the grain peak. Thus, there is a dead-zone of minimal air movement at the grain's peak.

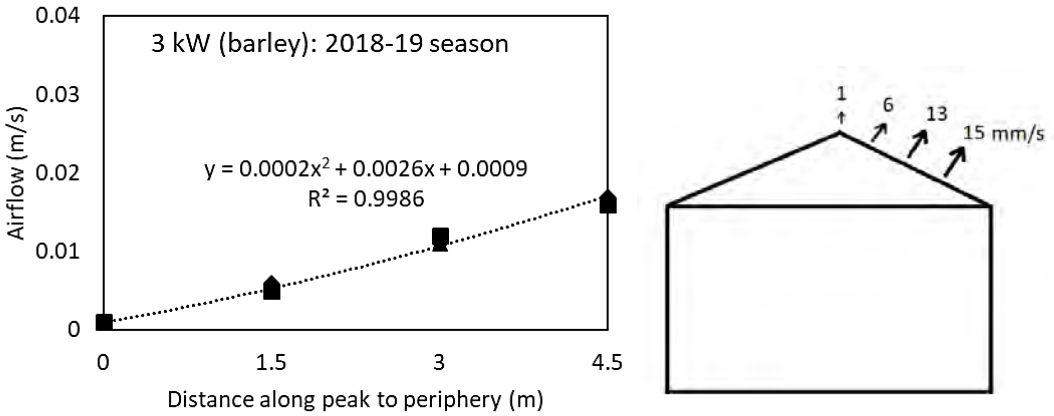


Figure 14. Measurement of airflow out of grain peak

Finding 9: Airflow through the grain at its peak was much less than near the walls

7.3. Aeration cooling

Four sensor strings were placed in the 1,000 t white painted silo to measure the status of the grain at 1.2 m height intervals, as shown in Figure 15.

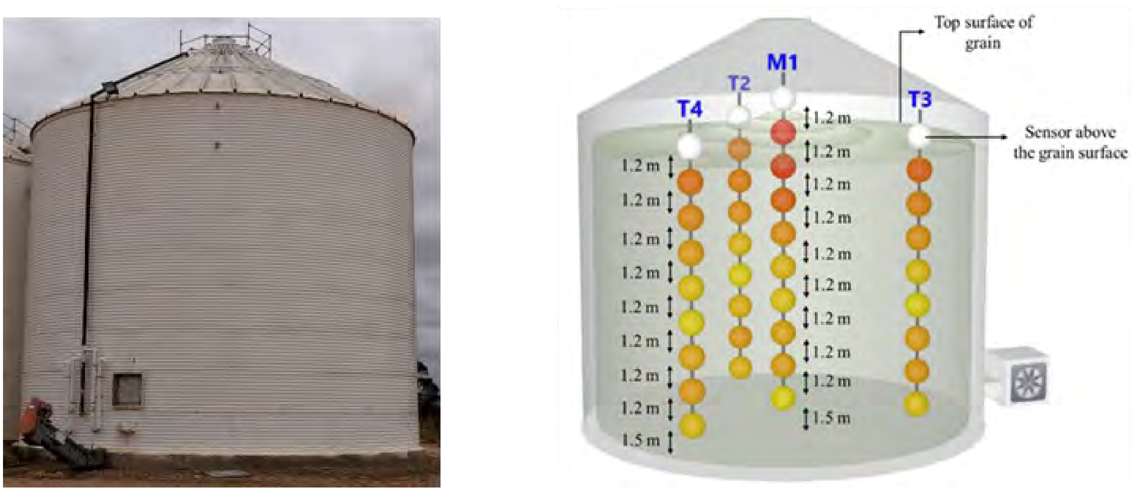


Figure 15. White painted silo with sensor cables fitted at Balaklava (1,000 t capacity)

Three seasons of aeration data are shown in Figure 16.

The results showed that ambient air can be used to cool the grain in the silo to below 20°C. The data of 2017/18 showed 1096 fan hours being used. This large number of fan hours was due to due to the fan running continuously at the start, irrespective of ambient air conditions to follow some promoted methodologies of running the fan once the silo was filled. This just resulted in the grain continually being cooled and reheated.

	M1	T2	T3	T4	M1
S10	18.6				12.0
S9	41.2	18.1	17.9	18.0	7.7
S8	37.3	33.1	33.9	32.9	7.7
S7	33.9	32.1	31.8	31.3	7.5
S6	30.9	30.8	30.4	29.9	7.8
S5	28.1	28.1	27.4	27.4	8.5
S4	27.1	26.4	26.3	26.3	8.3
S3	29.3	28.4	29.4	29.2	8.1
S2	29.8	30.1	30.0	30.0	8.5
S1	26.3	28.5	27.1	27.9	9.7

After cooling →

	M1	T2	T3	T4	M1
S10	19.8				11.4
S9	20.2	19.4	19.6	19.5	11.2
S8	23.6	23.6	22.9	22.9	8.4
S7	23.1	23.6	22.3	22.3	8.4
S6	22.3	23.6	22.1	21.8	8.5
S5	22.4	23.2	23.1	21.7	8.9
S4	22.6	22.8	21.9	22.2	9.5
S3	20.9	22.1	20.8	21.8	10.2
S2	18.7	21.2	18.6	19.6	11.0
S1	14.8	19.9	14.8	19.1	12.1

Figure 16a. Aeration cooling of 1,000 t white pained silo with 3 kW fan
Oats = 1096 fan hours from 27/11/17 to 20/03/18;

	M1	T2	T3	T4	M1
S10	21.9				12.6
S9	35.9	21.4	20.9	21.6	8.3
S8	29.3	29.5	30.0	33.7	9.8
S7	26.3	26.3	26.3	27.2	9.5
S6	30.9	25.1	25.1	24.9	11.0
S5	30.9	30.9	30.9	31.1	10.1
S4	25.9	29.7	28.4	28.4	11.4
S3	26.6	26.9	25.4	23.5	10.3
S2	26.3	27.6	28.5	27.1	11.2
S1	23.5	25.1	22.3	21.1	11.5

After cooling →

	M1	T2	T3	T4	M1
S10	20.9				13.3
S9	21.1	20.6	20.5	20.6	10.6
S8	19.4	18.8	18.3	18.0	11.1
S7	18.3	17.6	17.4	17.2	11.1
S6	17.7	17.9	17.8	17.5	11.1
S5	18.2	18.2	18.2	17.9	11.2
S4	18.4	19.0	18.5	18.1	11.4
S3	18.4	19.6	18.9	18.4	12.0
S2	18.6	18.9	17.8	18.6	12.3
S1	15.1	15.3	13.4	15.5	12.7

Figure 16b. Aeration cooling of 1,000 t white pained silo with 3 kW fan
Barley = 452 hours from 25/11/18 to 5/03/19

Before

	M1	T2	T3	T4	M1
S10	19.4				15.0
S9	19.6	18.5	18.9	18.8	15.1
S8	19.5	19.3	19.2	19.3	14.7
S7	19.7	19.3	19.4	19.4	14.7
S6	33.4	19.5	19.6	19.7	10.0
S5	32.6	19.8	21.0	22.8	10.0
S4	36.5	34.6	34.0	30.7	10.9
S3	29.4	34.9	36.4	34.4	10.9
S2	37.3	28.2	29.3	29.8	9.0
S1	30.0	32.9	35.8	37.3	10.1

→

After

	M1	T2	T3	T4	M1
S10	18.0				9.2
S9	18.1	17.4	17.8	17.6	9.2
S8	19.0	17.7	18.0	17.9	9.0
S7	23.9	17.9	18.1	18.1	8.7
S6	22.2	21.4	21.0	20.9	8.8
S5	19.4	20.2	20.0	19.7	9.8
S4	18.4	18.9	18.8	18.4	10.3
S3	20.1	18.4	18.4	18.1	9.5
S2	20.3	19.5	19.6	20.2	9.2
S1	19.7	20.2	18.8	19.9	9.9

Figure 16c : Aeration cooling of 1,000 t white pained silo with 5 kW fan
Barley = 140 fan hours from 5/12/20 to 12/12/20

As shown in Figure 16b, using 452 fan hours and selectively operating the fan when the ambient temperature was less than the grain temperature the grain could be cooled to well below 20°C.

The increase in fan power from 3 to 5 kW resulted in an even faster cooling of the grain in the 1,000 t silo with only 140 fan hours used to cool the grain to 20°C in December 2020, as shown in Figure 16c.

Measured data showed that for the large silos that had their roof vents left fully open during periods of hot weather, that after a hot windy period when the fan was turned on with the next cool spell that the temperature in the grain quickly rose about 5°C, as shown for multiple times in Figure 17.

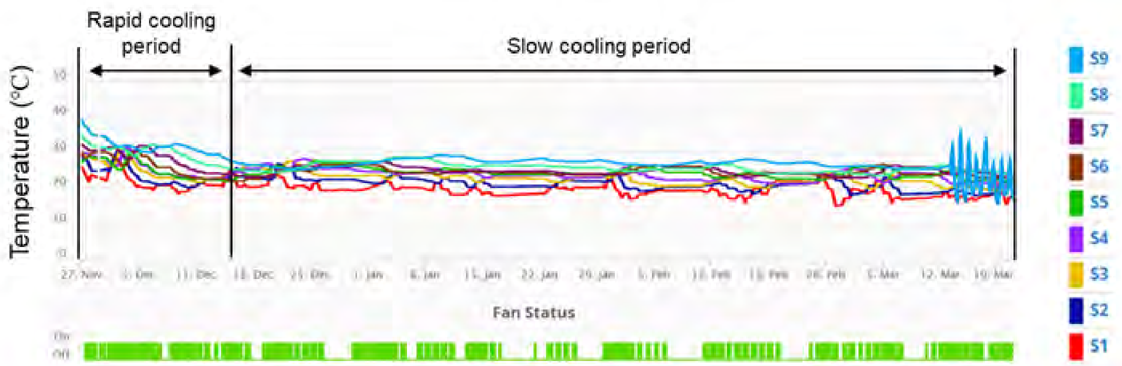


Figure 17. Example of multiple reheatings of grain (sensor S1 at bottom) during storage.

It was the combination of heat and wind resulting in a vacuum being created in the headspace that pulled hot air in through the fan and into the silo (Figure 18). At times the fan impellor could be seen to spin on its own as the air was being drawn into the silo. This incoming air heated the lower grain in the silo. Once the fan was started on the next cool spell this heat was then blown up through the silo reheating the grain. Hence, a lot of energy and time was wasted cooling, reheating and then cooling the grain many times over. In hindsight, it would have been better to cool and then seal the silo to stop hot air from entering.

Finding 10. Aeration cooling during summer can cool the grain to below 20°C.

Finding 11. Aeration cooling can be undone by hot windy days when hot air enters and reheats the grain.

Recommendation 4. Sealing the silo on windy hot days can stop aeration cooling from being undone.

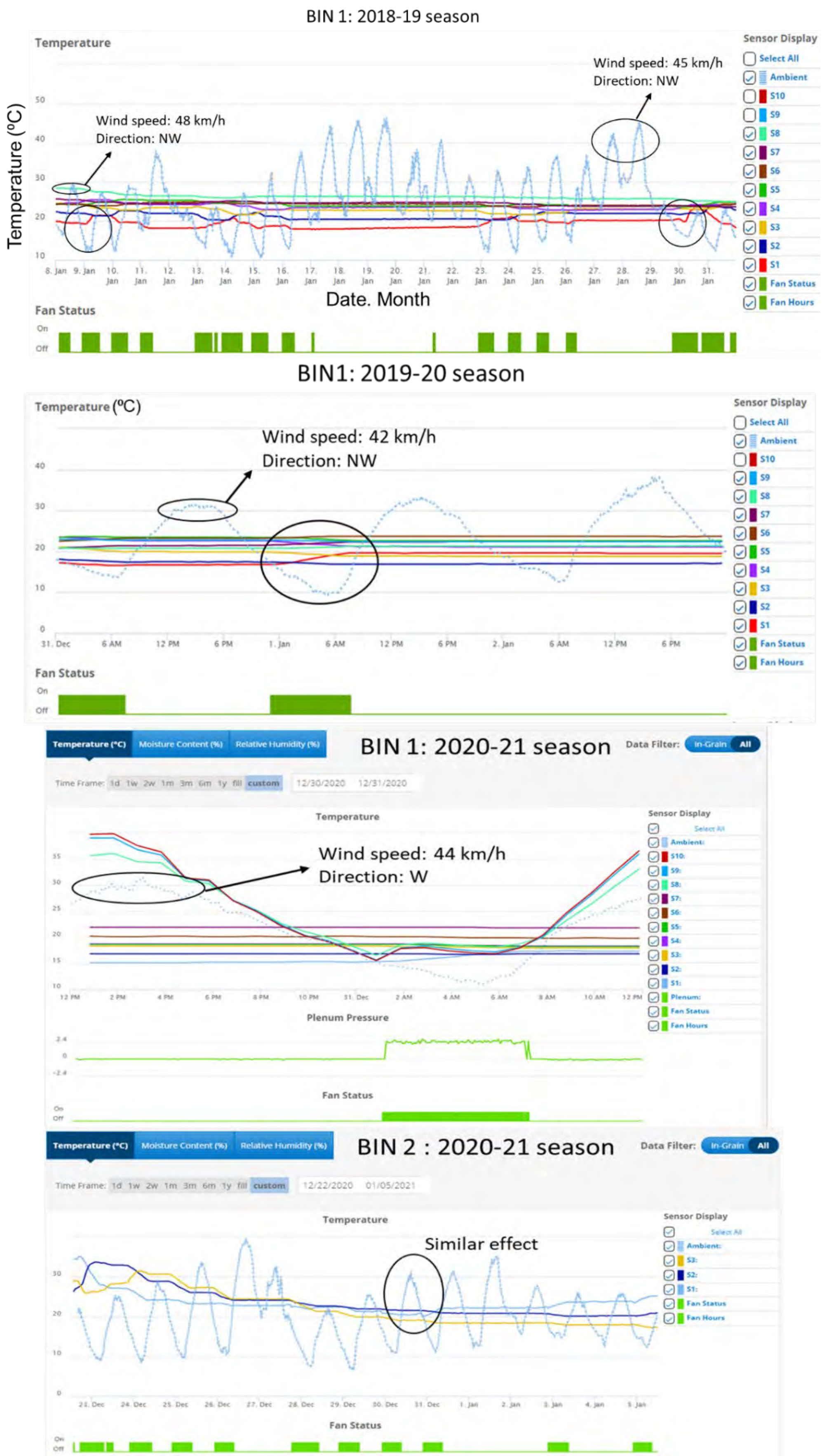


Fig 18. Grain reheating following periods of heat and wind.

7.4. Sealing the silo automatically

One solution to stop the reheating of the grain is to automate a shutter on the fan inlet as shown in Fig 19. A controller was used to close the door whenever the ambient air temperature was above 25°C. This was used during early 2021 on a silo and solved the problem of grain reheating.

Figure 19. Electric actuated door to seal the fan inlet during periods of higher temperature. Door open (left) and door closed (right)

Recommendation 5. To keep the contents of a silo cool over summer, an automated silo fan shutter can be added that operates on the basis of ambient air temperature.

8. Results from modelling of silo aeration

8.1. Modelling of silo aeration

Computer modelling of grain in a 100 and 1,000 t silo was undertaken to replicate the silos at Balaklava, as shown in Figure 20. The temperature and moisture content of the grain was calculated over time based on the actual grain starting conditions, ambient air conditions, and fan operation to validate the model.

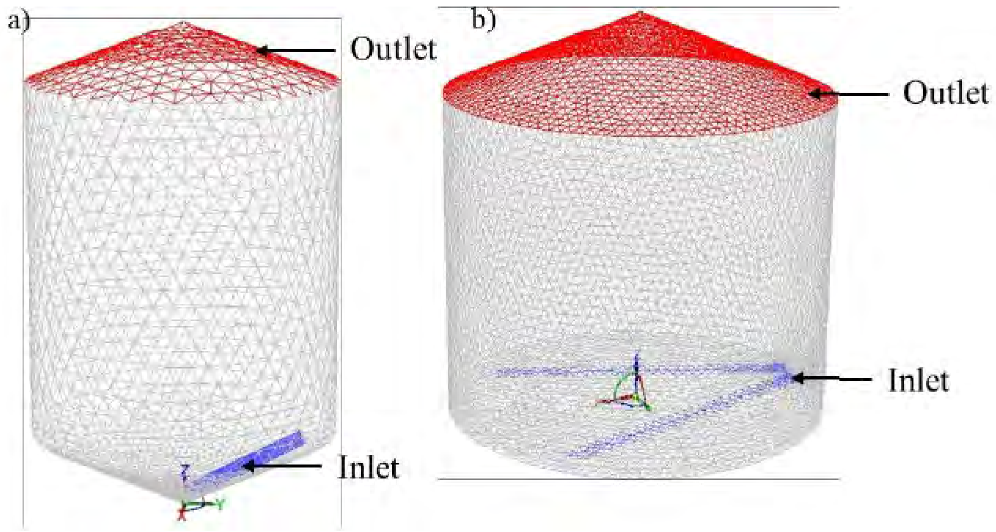


Figure 20. Example of the computer model of 100 and 1,000 t silos to calculate aeration performance.

The model was able to predict temperatures within 1.5°C and 0.4% moisture content over one month of on/off aeration.

An example of modelling of actual fan operation with a 3 kW fan in a constant running mode with oats in a 1,000 t silo is shown below. The ambient conditions are shown in Figure 21. Early in the run time the ambient temperature reached 36°C and then reduced to 13°C. The relative humidity of the air equated to grain equilibrium moisture contents ranging from 10 to 35%.

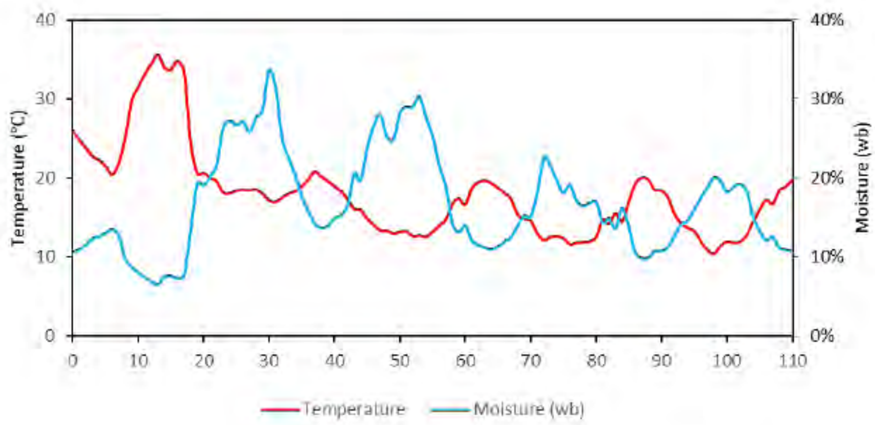


Figure 21. Ambient temperature and humidity conditions during continuous aeration

Predicted results after 48 hours of the fan continuously operating are shown in Figures 22 and 23 for temperature and moisture content, respectively. Figure 22 shows that after 48 hours the heat at ¾ way up the silo had moved to the top and the short period of high ambient temperature resulted in the lower grain having an increased temp zone that will need to be blown up through the silo.

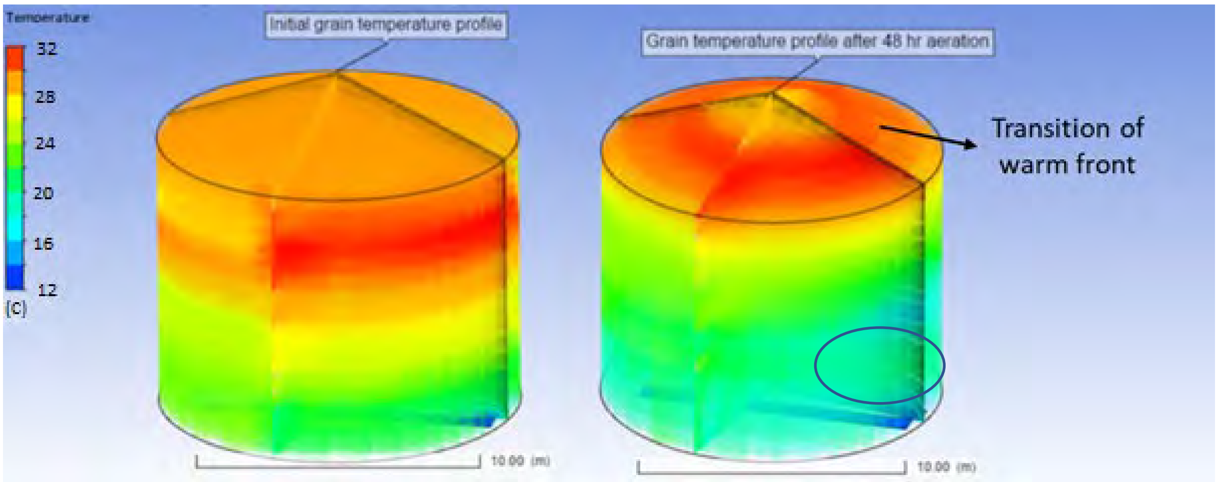


Figure 22. Example of heat (red zone) moving up through oats in 1,000 t silo after 48 hours of fan operation.

As shown in Figure 23, the 48 hours of aeration acted to equalise the moisture between the different layers of grain. The short time of aeration did not achieve an overall large effect on moisture content and much more time would be needed.

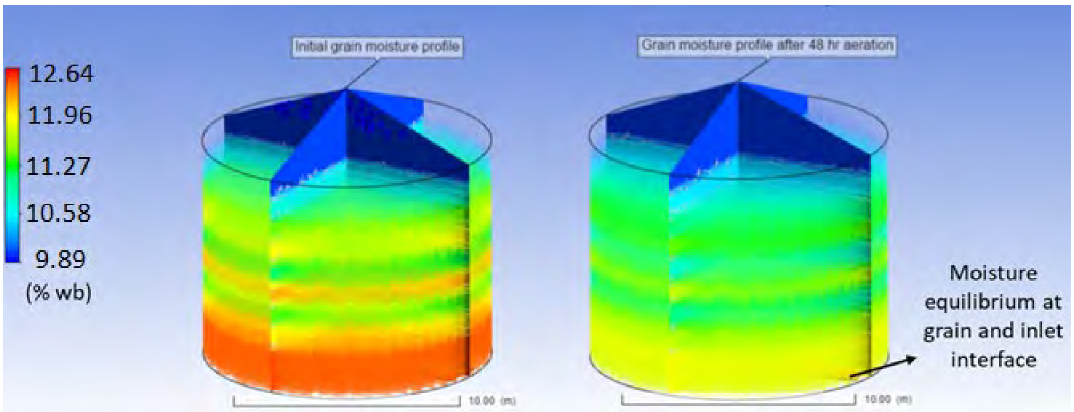


Figure 23. Calculated grain moisture content of oats in a 1,000 t silo after 48 hours of fan operation.

Both measured and modelled data were similar at all the sensor locations for the same duration.

8.2. Defining a dead-zone of low air movement in the grain

Effective silo aeration is to have air movement throughout the silo. An industry accepted rule of thumb is to have at least 2 litres/second/tonne (l/s/t) entering a silo. For the 1,000 t silo with 12.8 m diameter this equates to an air velocity of 0.016 m/s up through an empty silo. For a typical grain porosity of 0.5, using a limit of 2 l/s/t will result in air flowing through the grain at a velocity of 0.032 m/s. For this work a dead-zone was defined as an area with air passing through the grain at less than half the required velocity if the airflow was flowing uniformly throughout the grain.

8.3. Modelling of air velocity in 100 t silo

The predicted airflow velocities within the grain in the 100 t silo is shown in Figure 24. The presence of dead-zones with airflow low less than 0.013 m/s was close to negligible for the 100 t silo. This is shown by the vary low volume of grain shown as dark blue in Figure 24.

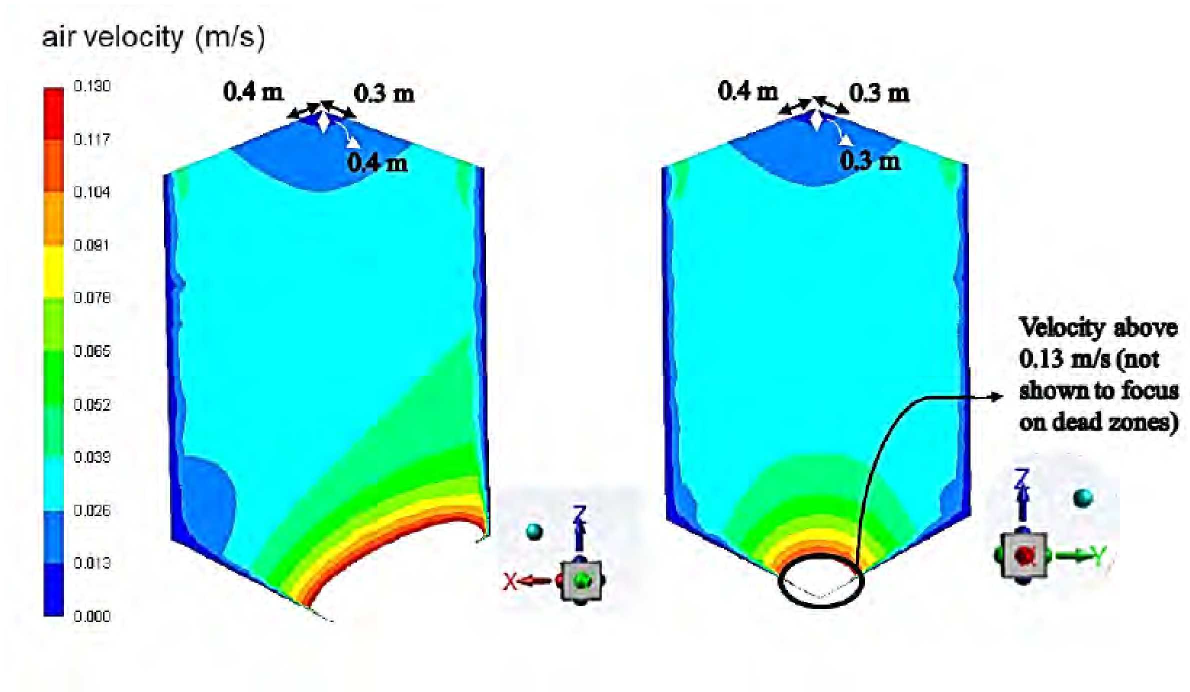


Figure 24. Calculated air velocity profile in 100 t silo filled with 90 t barley

Finding 12. The 100 t silo had negligible dead-zones of stagnant air within its contents.

8.4. Modelling of air velocity in 1,000 t silo and fan sizing

For the 1,000 t silo with an under floor V- shaped trench and 3 kW fan, the dead-zones of air flow velocity of less than 0.016 m/s are considerable,as shown by the dark blue regions in Figure 25.

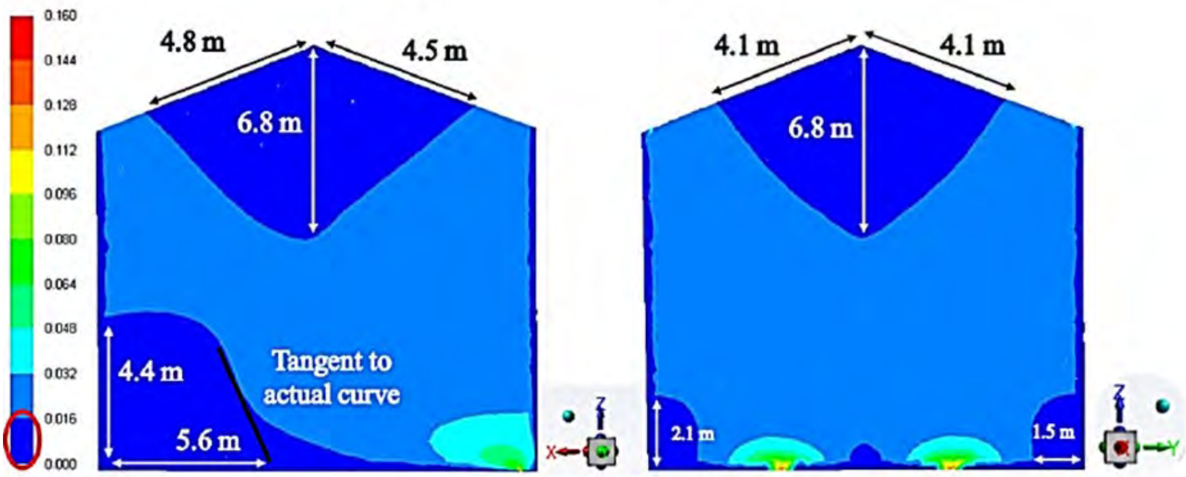


Figure 25. Calculated air velocity profiles in a 1,000t silo with 3 kW fan and filled with barley

By doubling the volume flowrate of air entering the silo (going from the 3 to 5 kW fan) the dead-zones in the silo at the top and bottom are reduced, as shown in Figure 26.

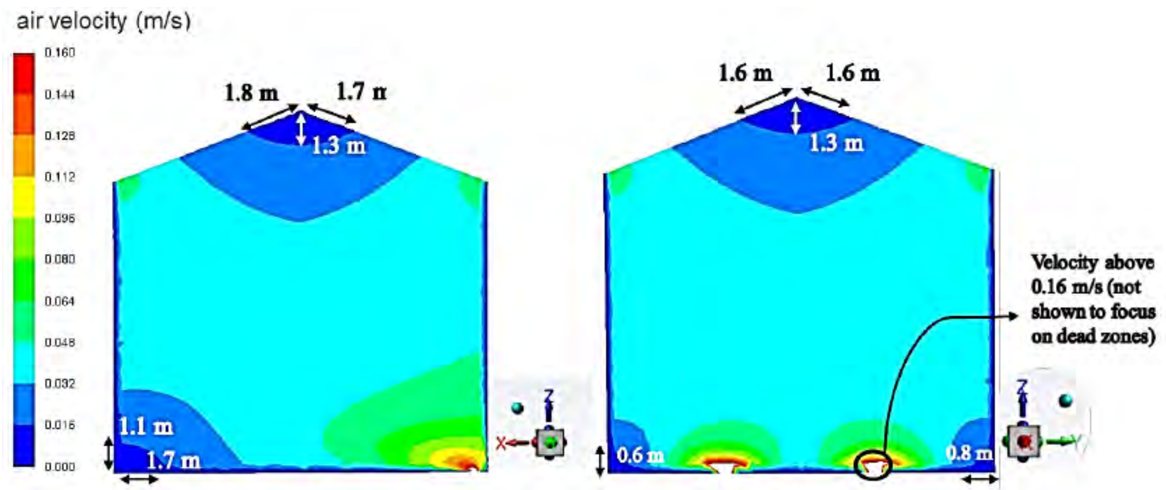


Figure 26. The same situation as Figure 29, except with double the flow rate of air into the silo (e.g. upgrading to 5 kW fan).

Finding 13. Increasing the fan on the 1,000 t silo from 3 to 5 kW reduced the volume of dead-zones in the silo.

8.5. Modelling of coring

Centre filling of silos results in a peaked grain configuration. This peak entices the air to take the easiest exit path out of the grain and thus air flows out of the grain at the sides and avoids flowing out the peak (see Section 7.2). Levelling the grain top surface has been shown in overseas studies to evenly distribute the airflow out of corn and cereal grains. As it is a labour intensive procedure to level the grain, another option is to take out some grain after filling the silo (core the silo) to reduce the size of the peak and reduce the variation in airflow at the top grain surface. A 1,000 t silo filled with barley was considered for validating this hypothesis.

The computer modelling examined various coring amounts, as shown in Figure 27.

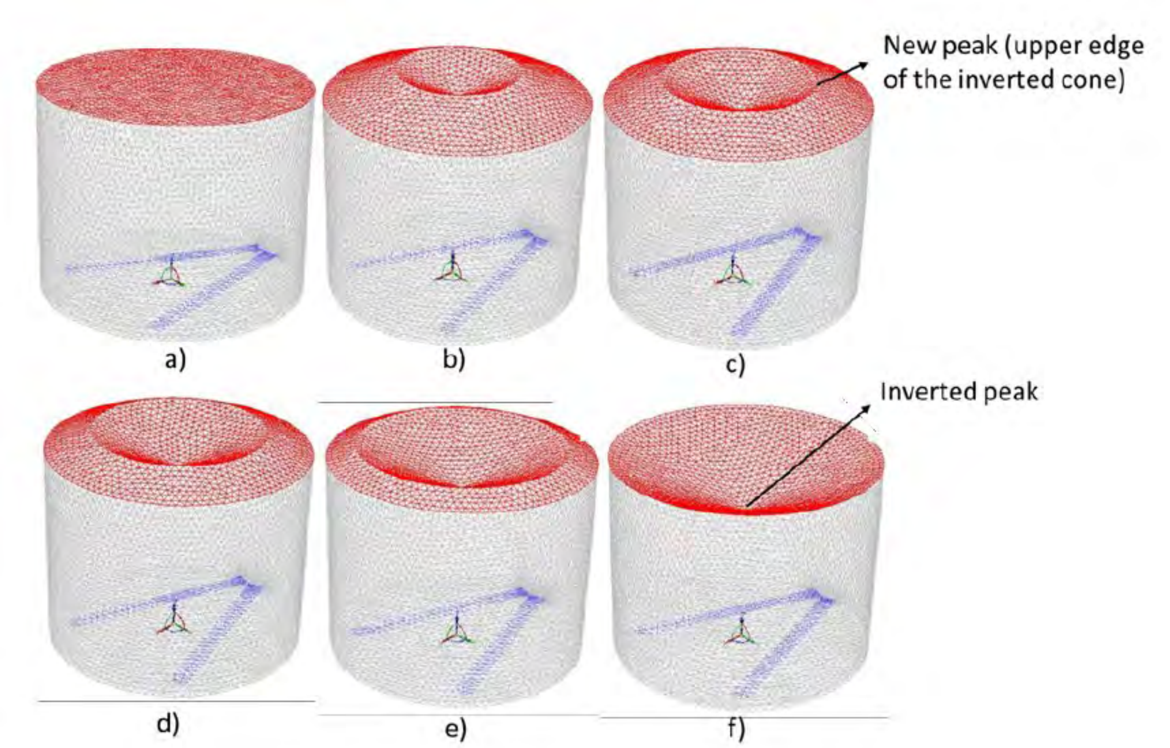


Figure 27. Cored grain options: a) levelled; and tonnes removed ; b) 16 t; c) 32 t ; d) 48 t; e) 80 t; f) 158 t.

Modelling calculations showed that when using the 3 kW fan that removal (coring) of 80 t of grain (Figure 27e) gave the most uniform expulsion of air from the top of the grain.

With an increase in the airflow into the silo by increasing to a 5 kW fan only 16 t of grain (Figure 27b) needed to be removed to give an air velocity leaving the grain that is greater than 0.016 m/s.

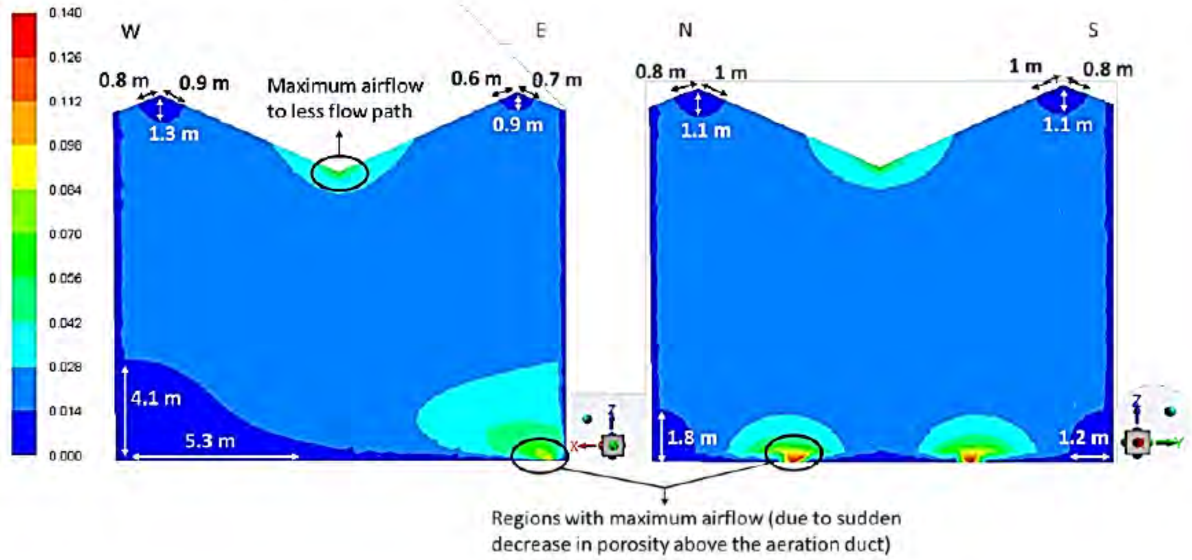


Figure 28. Airflow through grain with 80 t removed and 3 kW fan.

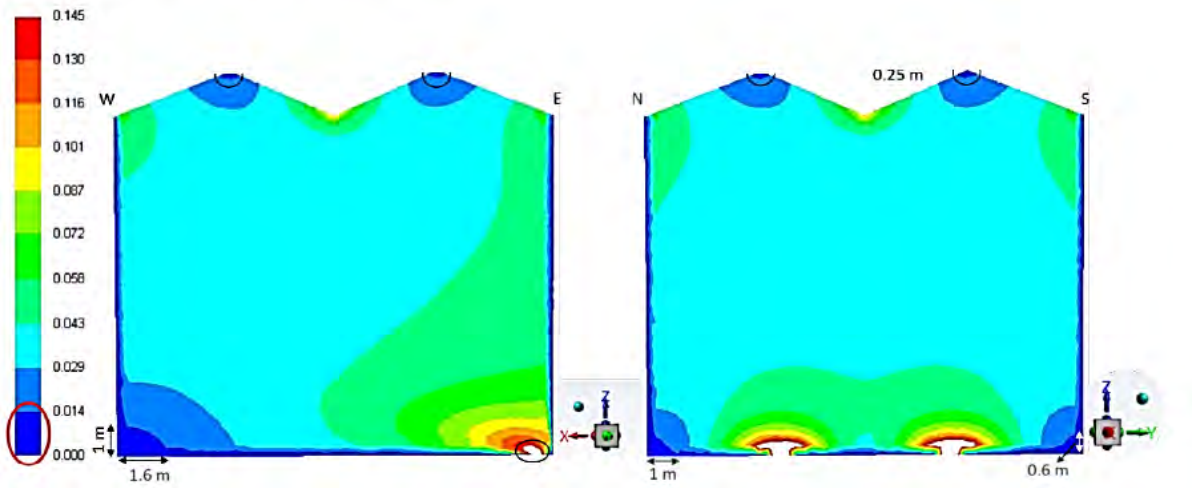


Figure 29. Airflow through grain with 16 t removed and 5 kW fan.

Recommendation 6. To remove dead-zones in the grain peak, emptying of some of the grain from the silo (coring) should be undertaken. The amount of coring required is a function of fan and silo size.

8.6. Modelling of 1,000 t silo floor ducting

A range of various floor designs were examined as shown in Figure 30.

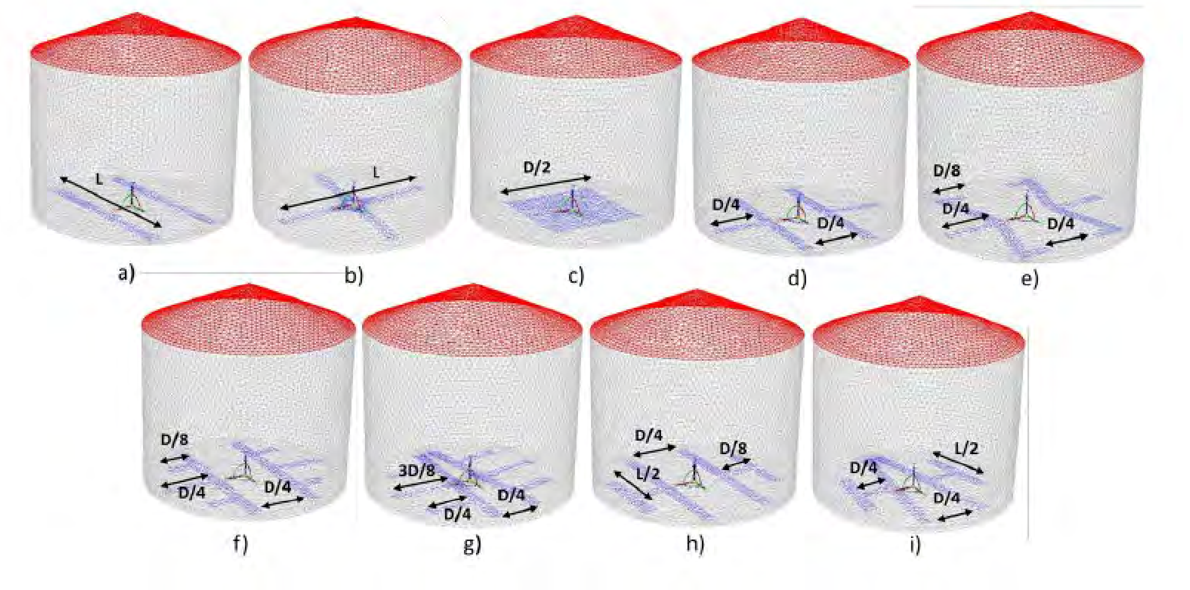


Figure 30. Range of silo floor designs evaluated

Modelling showed that the best floor design to minimise dead-zones at the intersection of the floor and wall was option "g" in Figure 30 and Figure 31.

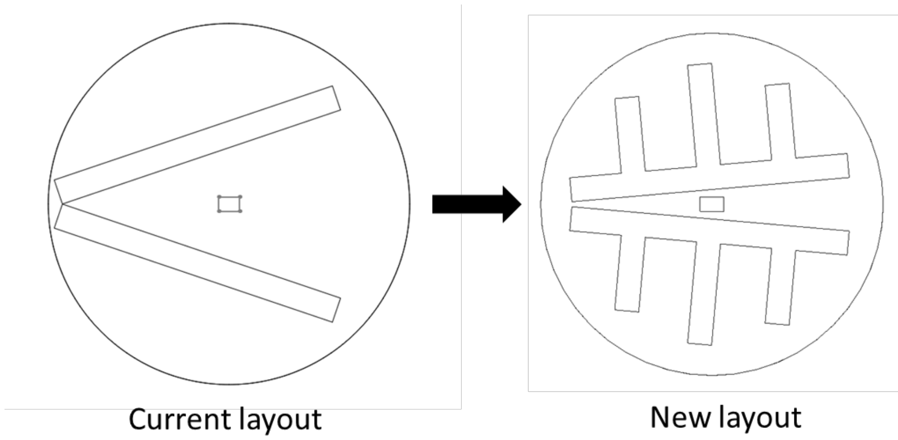


Figure 31. Recommended floor design for reduced dead-zones at the floor and wall intersection.

This new design increases the open area of the floor from 15 to 26% with the reduction in dead-zones at the floor region shown in Figure 32. This new design still provides centre emptying and an outside path for the sweep auger wheel. It features a more uniform distance from the trench to the wall all the way around the periphery.

The improved floor ducting which gave more uniform air flow at the base of the silo also went on to reduce the volume of dead-zone at the top of the grain.

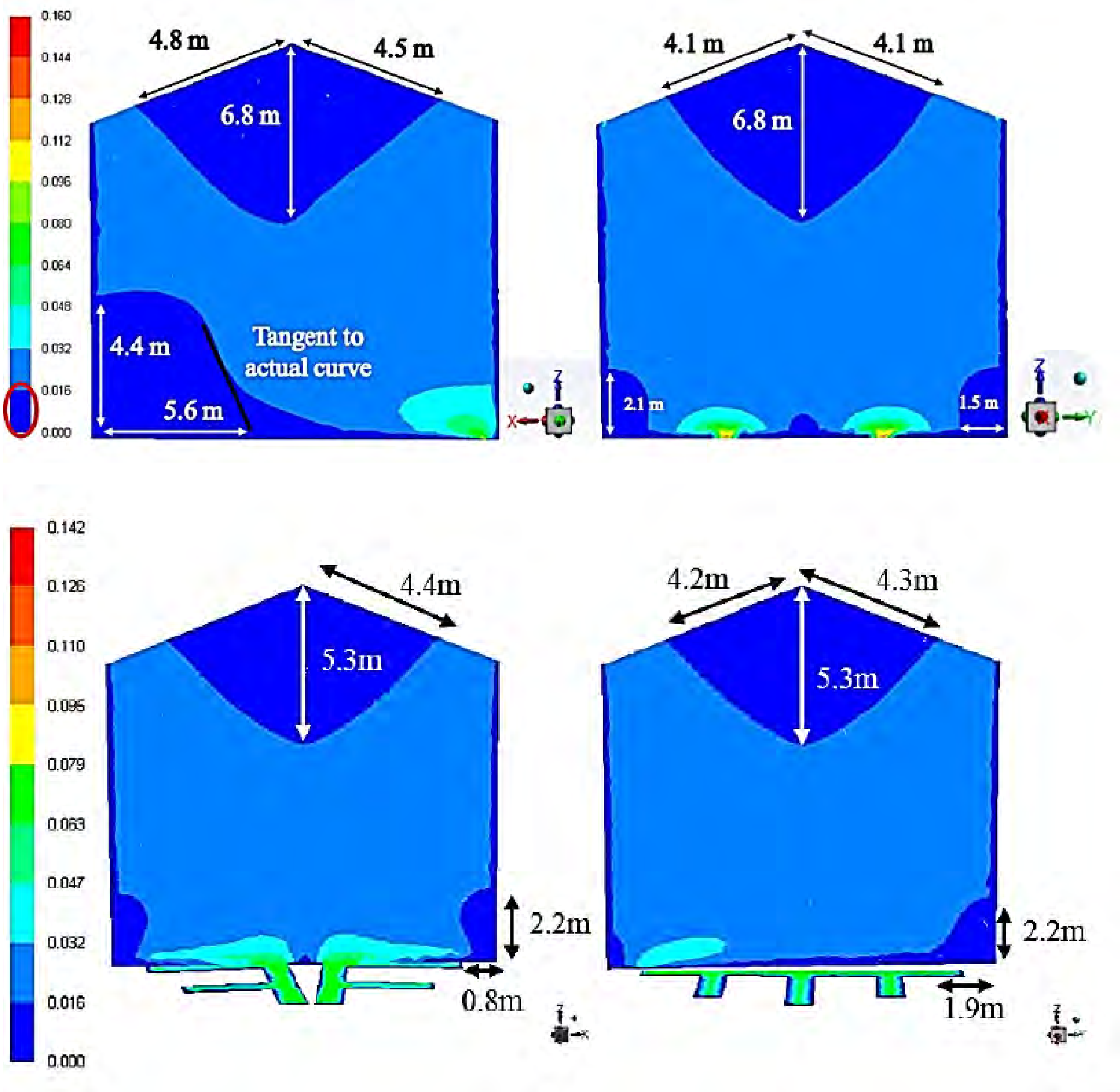


Figure 32. Comparison of air flow velocity for current V floor (top) and an improved floor design (bottom) for barley in 1,000 t silo with 3kW fan

Recommendation 7. The floor ducting can be improved to reduce dead-zones at the junction of the floor and wall.

8.7. Analysis of ambient air conditions in southern Australia

Analysis was made of the past 9 years of Bureau of Meteorology weather data for four major grain growing locations in southern Australia (Roseworthy, Minnipa, Minlaton and Horsham) during and soon after harvest when the grain in the silo needs to be cooled as soon as possible to reduce insect activity.

To present available fan hours, they are shown as the number of hours in a 4 week period within various temperature ranges. If the grain is 40°C, even starting aeration with 30°C air will cool the grain. However, in the longer-term air below 20°C will be needed if the grain is to be cooled to below 20°C.

Figure 33 shows that there are over 300 hours for every 4 week period that can be used to cool grain after harvest. This would be more than enough time to cool the grain to below 20°C.

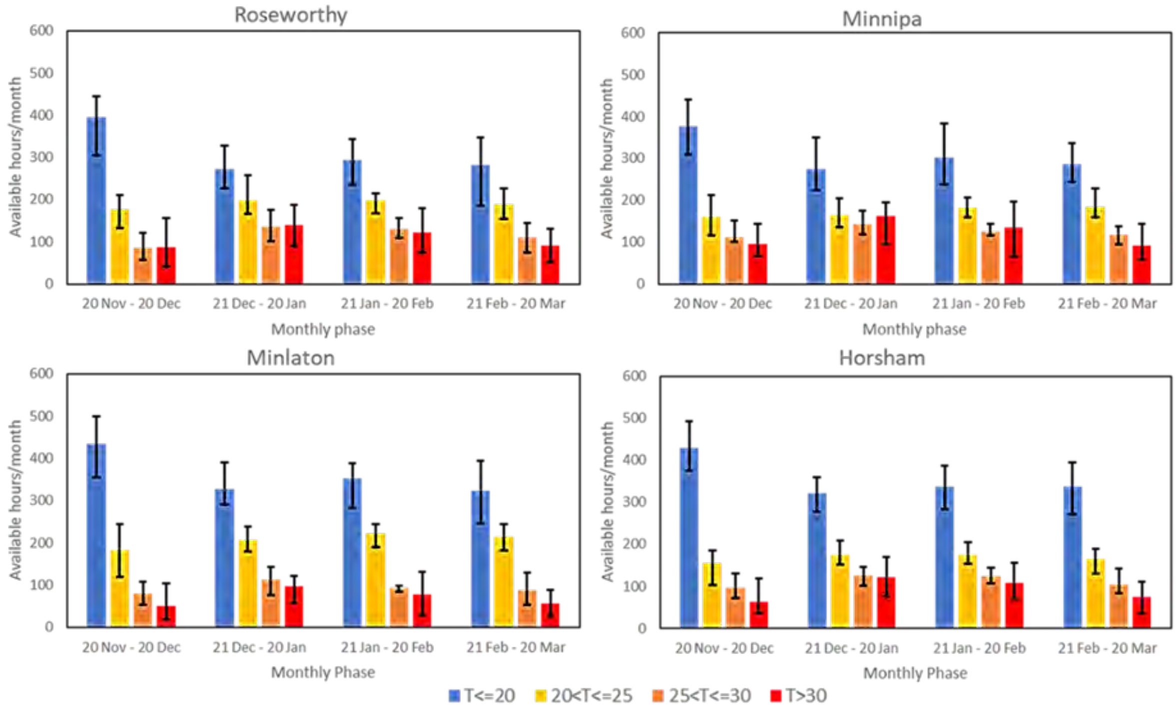


Figure 33. Ambient temperature variations (9-year average and extremes) in 4 major grain growing locations in southern Australia

Finding 14: There are many hours each week in which the ambient temperature is below 20°C and suitable for aeration cooling of grain in a silo.

Recommendation 8. As the period of time when the ambient air temperature is below 20°C is varying, a local temperature reference should be used to control fan operation.

For barley at 20°C and at the storage limit of 13.5% mc this equilibrates to an equilibrium relative humidity of 44%. Hence, ambient air less than 44% relative humidity will act to dry to grain to be below 13.5% mc and air with relative humidity greater than 44% will act to wet the grain to above 13.5% mc.

The weather data was further analysed to divide up the time periods when the temperature was less than 20°C into the following humidity ranges:-

- RH < 40%. This will dry the grain.
- 40 < RH < 55%. This will be good for aeration.
- 55< RH < 65%. This will be good for aeration.
- 65 < RH< 80%. This will be good to start to increase grain moisture content but it will make the grain too wet over the long term.
- RH >80%. This will make grain too wet over the long term.

Hence, to condition barley air conditions of <20°C and RH of 40 to 65% would be ideal. The data is presented in Figure 34 and shows that for every 4 weeks there are over 100 suitable fan hours available.

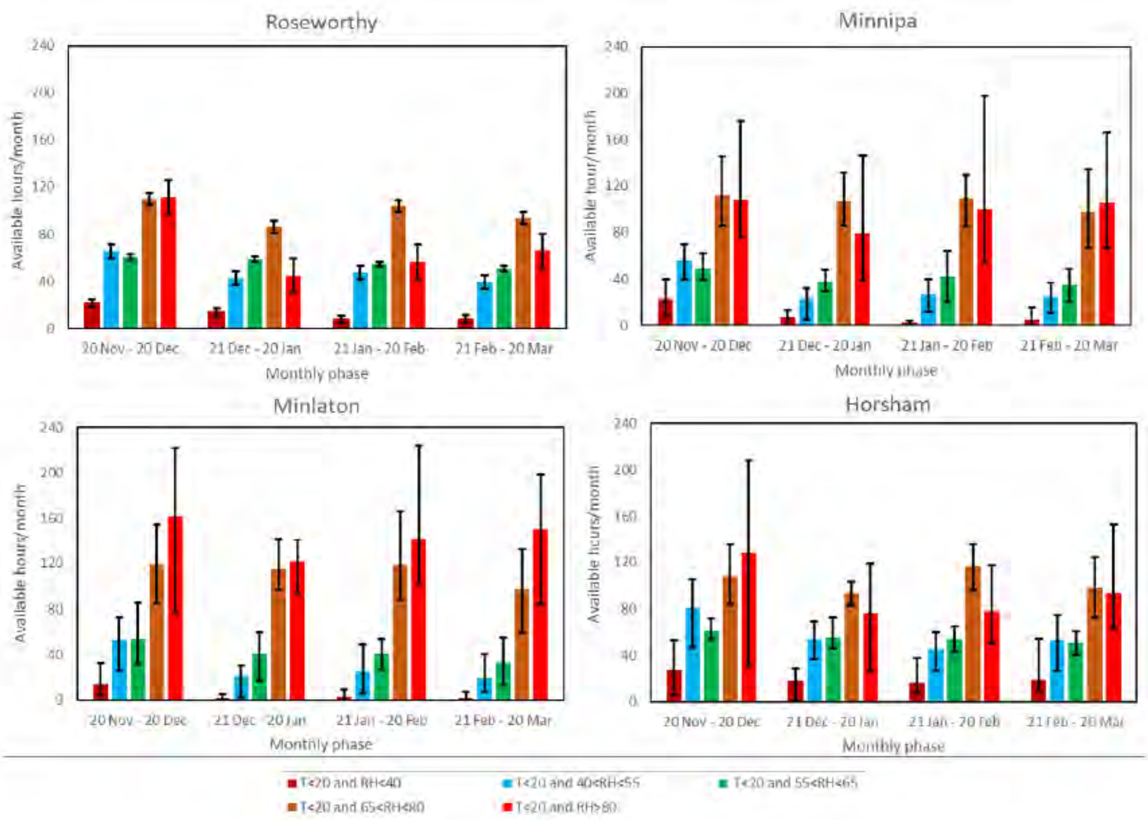


Figure 34. Breakdown of times of temperature < 20°C for various relative humidity categories in 4 major grain growing locations in southern Australia.

Finding 15. There are many hours in each 4 week period in which the ambient temperature is below 20°C and there is a suitable relative humidity for grain conditioning to increase its moisture content.

Recommendation 9. As the period of time when the ambient air temperature is below 20°C has the full range of relative humidities, a silo aeration controller should take into account both the grain and ambient relative humidities.

8.8. Predicted fan hours for cooling

The actual ambient temperature and relative humidity at Balaklava from Nov 2018 to March 2019 is shown in Figure 35.

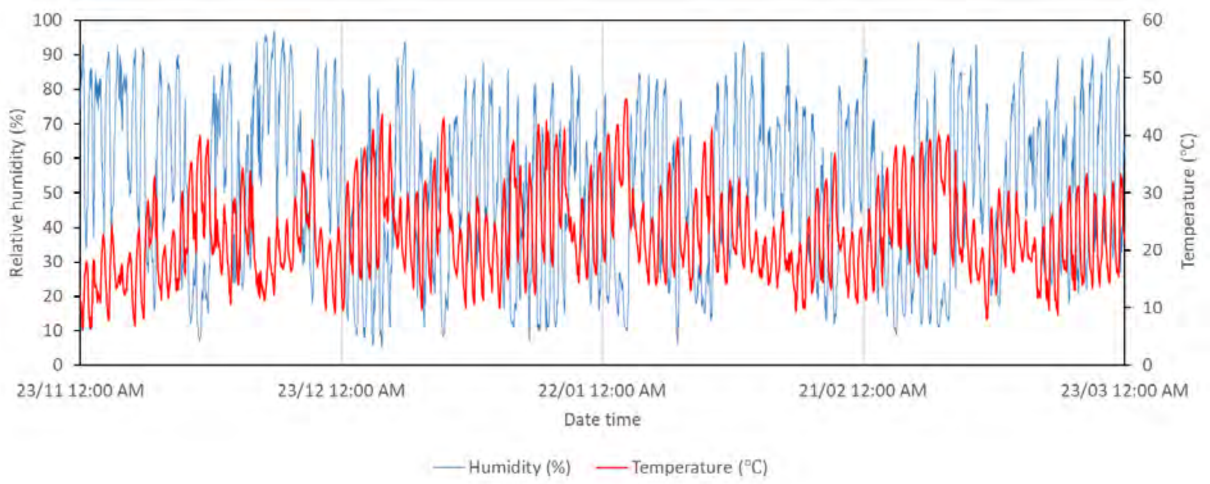


Figure 35. Actual ambient temperature and humidities at Balaklava, SA from Nov 2018 to March 2019. The actual fan run hours are shown above each 4 week period.

The resulting grain temperature and moisture content measured by the sensors in the grain during aeration are shown in Figure 36 for the weather conditions shown in Figure 35.

The ambient conditions of Figure 35 were used in computer simulations of various aeration fan control scenarios. The scenario that gave the fastest grain cooling was to run the fan whenever the ambient air was less than the grain temperature at the base of the silo.

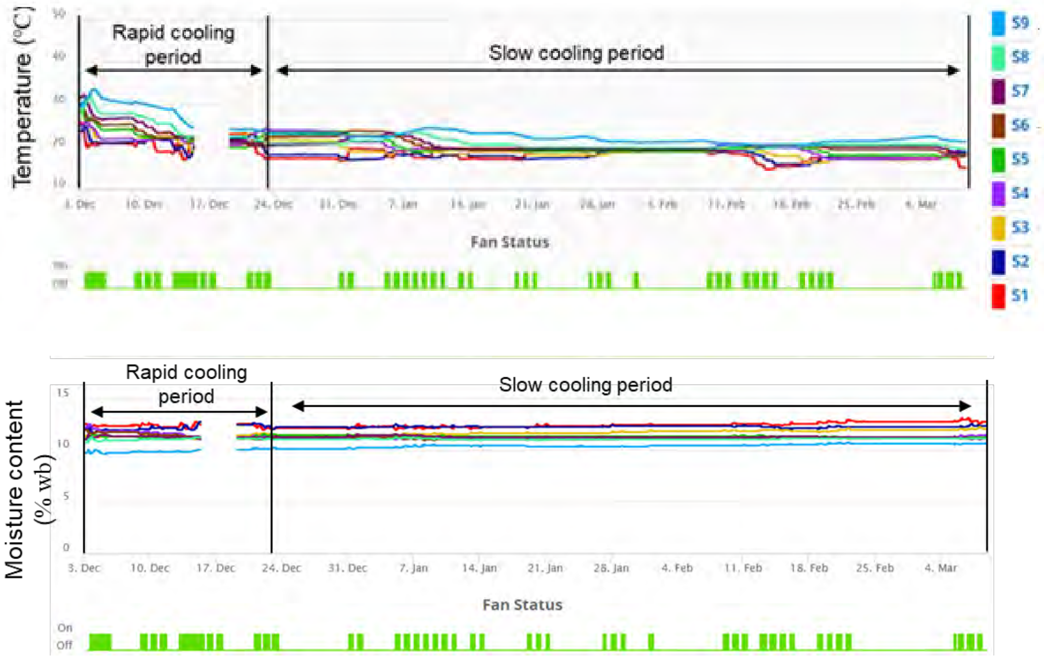


Figure 36. Actual silo performance with various set points during December 2018 to March 2019.

For this control strategy the time to cool barley in a 1,000 t silo was calculated at three air flow rates, as shown in Figure 37.

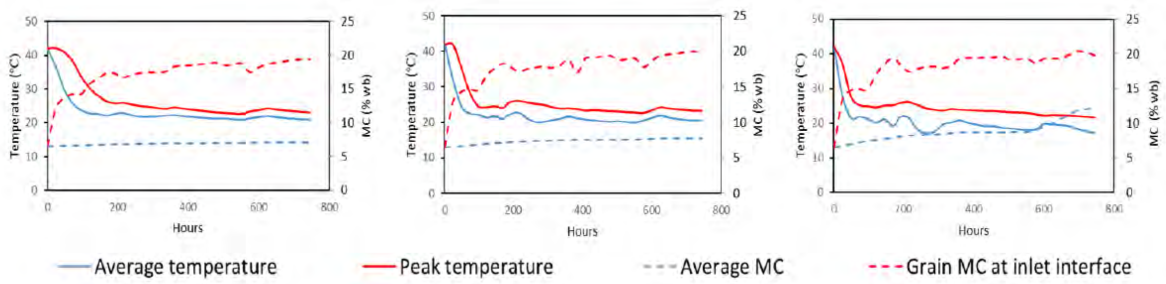


Figure 37. Modelled grain conditions from 20 November to 21 December 2018 with barley in 1,000 t silo. Left = 3 kW fan (0.954 m^3/s); centre = 2 x flowrate (1.9 m^3/s); right = 4 x flowrate (3.8 m^3/s)

For the scenarios of standard 3 kW fan, 5 kW fan (2 x flow) and 4 x flow the modelling showed that for the 4 week period the ambient temperature was less than the lowest grain temperature for 241, 188 and 152 fan operating hours, respectively. As shown in Figure 42, increasing the air flow rate reduced the time to rapidly cool the grain to 25°C. Within the first month none of the scenarios were able to cool the top grain (peak temperature) to below the grain target temperature of 20°C.

The results of Figure 37 showed that in all cases of maximum cooling rate for all fan sizes that the lower grain near the inlet increased in moisture content above the 13.5% limit for barley. This moisture increase shows the need to use ambient humidity as another control parameter.

Recommendation 10. The best fan control strategy is to only run the fan when ambient air temperature is less the grain temperature at the base of the silo and the relative humidity is in a suitable mid range.

8.9. Placement and number of sensors in silo

This work mainly used a central sensor cable to measure temperature and humidity and outer temperature only cables (as shown in Figure 15) with sensors at 1.2 m height spacings.

When placing over dried and hot grain in the silo no extra information was gained from the outer temperature cables. Hence, a single string of sensors would suffice so long as they are more than 500 mm away from the silo wall.

As there is potential to over wet the grain near the air entry to the silo it would be useful to have the sensors located in the grain near the air entry.

Having multiple sensors at 1.2 m spacing was useful to see the grain level in the silo, but for southern Australian grain conditions having only 3-4 sensors at 2 to 3 m vertical spacing in the grain would suffice for monitoring the cooling and conditioning of grain in a silo.

Recommendation 11. A single string of 3 to 4 temperature and humidity sensors is all that is required to monitor the grain condition during aeration cooling and grain conditioning. It would be beneficial to have the lowest sensor near the air entry duct to ensure that over-wetting of the grain does not occur.

9. Details of the OPI silo monitoring and control system

9.1. Sensor cable

It is recommended that the silo be fitted with one sensor cable with combined temperature and relative humidity sensors. Using equilibrium moisture content curves, the grain moisture content can be calculated. These cables are mounted permanently in the silo and are tied to the floor of the silo with string. The sweep auger will cut the string and not damage the cable.

There has been some industry comments of phosphine damaging the sensor cables. During the past 4 years phosphine has been used as a fumigant with the sensors installed without any damage to the sensors.

As an alternative to using the fixed cables, the same sensors can be mounted on spears that are inserted in through the side of the silo via a tank fitting. The sensors can be removed before fumigation and the tank fitting sealed for fumigation. The alternatives are shown in Figure 38.

Figure 38. Example of silo sensors on a fixed cable (left), individual sensors fitted to removeable 1m long spears (centre) and spear inserted into silo above fan entry to silo (right).

9.2. Data transmission

The data is transmitted via solar powered nodes (Figure 39) that can take up to 8 sensor cable inputs. Each sensor string has sensors numbered from 1 at its lowest sensor and then increasing in number up the sensor cable. Hence, for 1 cable per silo, up to 8 silos can be serviced by running wires to a solar powered node.

For the sensor spears inserted through the side of the silo, each spear has individually set sensor numbers that are interconnected to form a virtual sensor cable.

Figure 39. Example of solar powered node to transmit silo data.

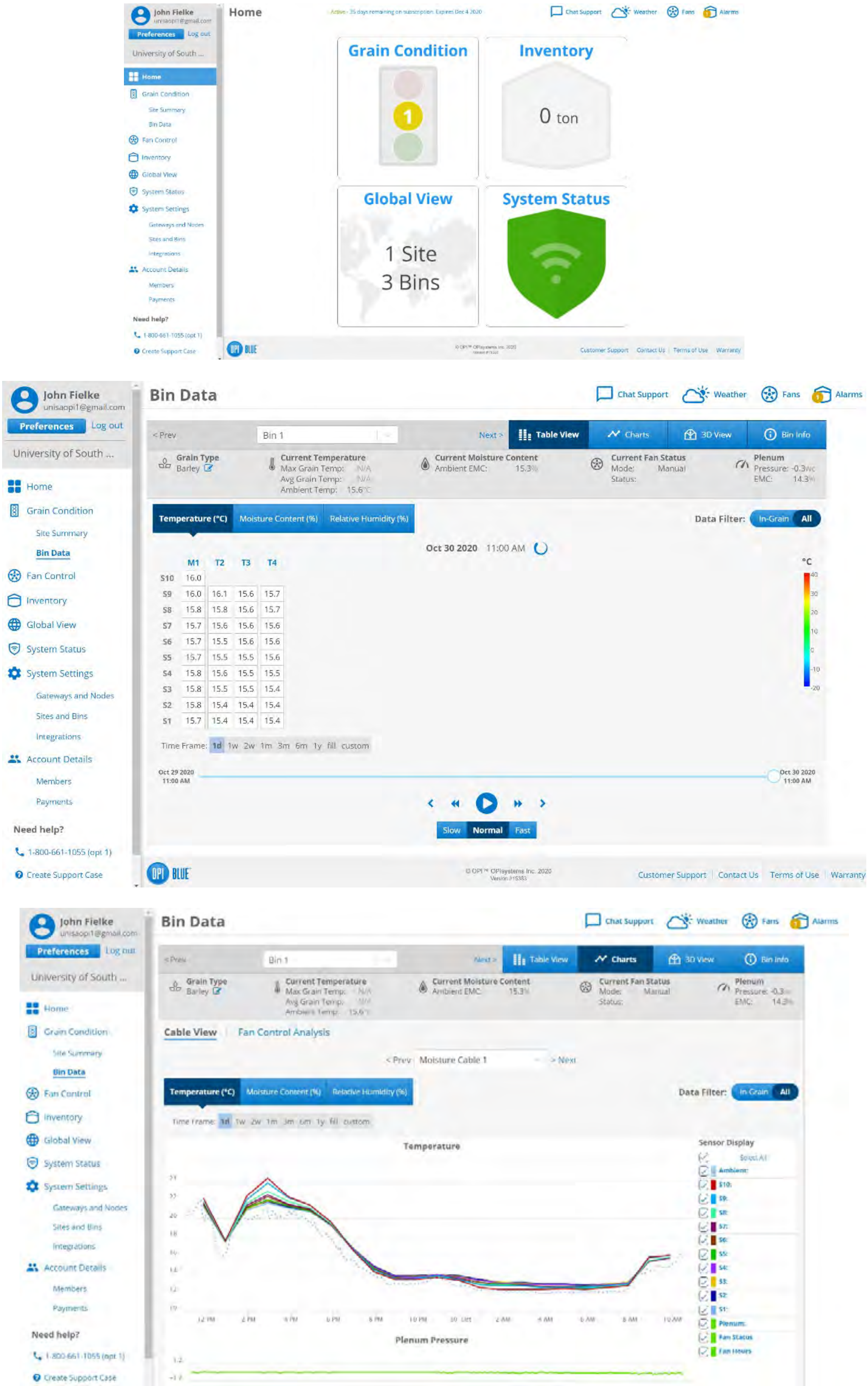
9.3. Data upload to cloud

The data is received by a gateway node and sent via a gateway to the cloud for data storage and access.

Figure 40. Gateway receive node (left) and Gateway control box (right).

9.4. Data access

The data can be viewed as an overview, tables or charts, for temperature, humidity and moisture content, as shown in Figure 41.



	M1	T2	T3	T4
S10	16.0			
S9	16.0	16.1	15.6	15.7
S8	15.8	15.8	15.6	15.7
S7	15.7	15.6	15.6	15.6
S6	15.7	15.5	15.6	15.6
S5	15.7	15.5	15.5	15.6
S4	15.8	15.6	15.5	15.5
S3	15.8	15.5	15.5	15.4
S2	15.8	15.4	15.4	15.4
S1	15.7	15.4	15.4	15.4

Figure 41. Examples of silo status – overview, charts and graphs

9.5. Fan control

Fan control is via a fan control node per fan. The fan control node (Figure 42 left) requires an input of the temperature, humidity and pressure sensors (Figure 42 right) placed in the fan duct to check that the fan is operating as requested.

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Figure 42. Fan control node (left) and fan plenum sensor (right)

Aeration fan control can be based on either a temperature or grain moisture content priority using set points as shown in Figure 43.

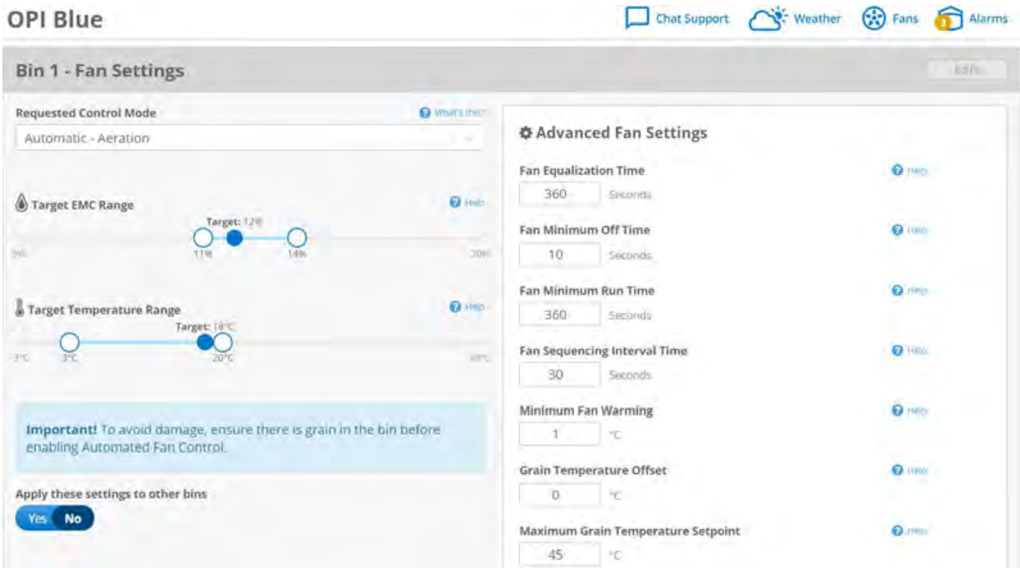

Figure 43. Aeration set points for fan operation.

The ambient weather conditions used for fan control are gained from a local weather station that can be connected to either a fan control node or a gateway controller.

9.6. Indicative pricing for an automated silo controller

Based on 4 silos on a site with 1 cable per silo interconnected to 1 solar node, the costs for the OPIsystems sensors and silo aeration controller are shown in Table 7.

Table 7. Indicative cost to add sensor cables and controllers to 4 silos on the 1 site.

	Cost Per silo	Qty	Cost Per site
Sensor cable	$1,200	4	$4,800
Fan controller	$1,200	4	$4,800
Fan plenum sensor	$700	4	$2,800
8 Channel wireless node			$1,200
Wireless gateway with weather station		1	$3,700
Annual subscription		1	$500
Shipping and installation			$3,000
Total site cost			$20,800

If the silos were of 1,000 t capacity the cost per tonne would be $5.20 per tonne.

With updates from the manufacturer the fan controller could control two fans if the current need for a plenum sensor was removed. This would reduce the total cost, as shown in Table 8.

Table 8. Potential lower costs if the manufacturer made same changes to the system.

	Cost Per silo	Qty	Cost Per site
Sensor cable	$1,200	4	$4,800
Fan controller	$1,200	2	$2,400
8 Channel wireless node			$1,200
Wireless gateway with weather station		1	$3,700
Annual subscription		1	$500
Shipping and installation			$3,000
Total site cost			$15,600

If the silos were of 1,000 t capacity the cost per tonne would be $3.90 per tonne.