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1.0 Introduction

This document is intended as a guide for South East viticulturalists and growers, to help them make informed decisions in relation to frost – risk assessment, irrigation plant, irrigation equipment and management practices.

Water shortages across the nation and an expectation by wine consumers for sustainable viticultural management have placed an emphasis on water use efficiency in irrigated viticultural production. The South East (SE) of South Australia (Coonawarra) is fortunate in having a large, easily accessible, underground water resource. Moves towards a volumetric allocation system in the region, is requiring growers to review their irrigation practices and efficiency of irrigation systems.

Following the severe frosts of spring\summer 2006 and their catastrophic effects on production in Coonawarra, one aspect of irrigated viticultural production, frost protection, has received significant attention.

Frost protection by use of overhead irrigation, functions by the release of latent heat at the point of freezing. This heat is released into vine tissue, preventing freezing and disruption of plant cells, while also releasing some into the surrounding air. While overhead irrigation is an extremely effective and relatively energy efficient form of frost protection, room for efficiency gains has been identified in the region, in the form of a reduction in precipitation rates and improved irrigation management.
2.0 Frost an Overview:

2.1 What is Frost & Why is it Important?

“When air temperature falls below 0°C, sensitive crops can be injured, with significant effects on production...in the USA, there are more economic losses to frost damage than to any other weather related phenomenon” (Snyder et. al., 2005)

The term “frost” is used in various situations to describe types of freezing events. According to Snyder et. al. (2005) a “frost” event is defined as: “the occurrence of an air temperature of 0°C or lower, measured at a height of between 1.25 and 2.0m above soil level, inside an appropriate weather shelter (i.e. Stevenson-screen). Water within plants may or may not freeze during a frost event, a “freeze” occurring only when extracellular water within the plant freezes (i.e. changes from liquid to ice).” This will be the definition adopted for this paper.

A frost event becomes a freeze event, when extracellular ice forms within plant tissue (Snyder et.al., 2005). Subsequently, freeze injury occurs when tissue temperature falls below a critical point (temperature) at which there is irreversible damage (potentially death) of plant cells (Snyder et. al., 2005) due to the rupturing of cell walls (Pudney, 2007). The temperature at which this occurs can vary with humidity (Pocock and Lipman, 2002) (refer to section 3.2.2.2).

2.2 Economic Significance:

Significant work investigating frost and frost protection strategies has been undertaken worldwide, due to the significant production losses incurred by frost damage. Freeze injury as a result of frost, causes serious losses in agricultural crops in Australia (Australian Bureau of Statistics Year Book 2004). Apart from lost productivity and the implications for food and fibre production, frost damage accounts for an annual average of $33 million dollars in lost viticultural production in SA and Victoria alone (Hannink, N., 2008). For the Coonawarra region in 2006, frost accounted for an approximate 70% loss of production (Phylloxera and Grape Industry Board of South Australia, 2007).

2.3 How Does Frost Affect Vines?

Vines are susceptible to damage as a result of frost. Freeze events can cause bud mortality (Trought et. al. 1999), loss of canopy, reduction in flower set and also fruit development (Woodhead et. al. 2007). In frost conditions, buds are typically 1°C to 2°C lower than air\screen temperature depending upon wind speed (Woodhead et. al. 2007) and Young (2007) developed a table of “critical temperatures” for grapevines based on the lowest temperature a tissue can endure for 30 minutes or less without injury (Table 1).

Critical temperature can, however, be many things and has been described as either:

- The temperature estimated to cause 50% bud mortality (Howell, et. al., 1981)
- The temperature at which 10% (T<sub>10</sub>) and 90% (T<sub>90</sub>) of buds are killed (Trought et. al., 1999)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Critical Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.5°C or less</td>
<td>EL3, Woolly bud stage (continued periods can kill the primary bud)</td>
</tr>
<tr>
<td>-2.0°C or less</td>
<td>EL4, Early budburst</td>
</tr>
<tr>
<td>-0.6°C or less</td>
<td>EL5 - EL13, Shoots up to 15cm long</td>
</tr>
<tr>
<td>0°C or less</td>
<td>&gt;EL13, Shoots 15cm and longer</td>
</tr>
</tbody>
</table>

Table 1: Vine critical tissue temperatures (Young, 2007)
The many definitions may lead to confusion, although field observation will ultimately conclude that a certain proportion of buds, shoots or inflorescences are frozen. Apart from the period of time the temperature is below the critical point (Pocock and Lipman, 2002), Trought et. al. (1999) lists several authors and their reasoning for this observation:

- Differences among cultivars (varietal selection relative to region)
- Differences in dew point and surface moisture (high humidity delays temperature drop)
- Pre-freeze conditions
- Stage of bud development\phenology and
- The probability of an ice nucleating event, which can be affected by several factors including: duration of freezing conditions, tissue temperature, the presence of surface ice and presence\absence of ice nucleating bacteria (INB)

Furthermore, young shoots (including shoot tips) and blossoms are more susceptible to damage on the basis of higher water content and thinner cell walls (Pocock and Lipman, 2002).

2.4 Types of Frost
Although many different names are given to particular frost events, ultimately there are only two critical forms: Radiation and Advective frosts.

2.4.1 Radiation Frost:
These frosts generally occur when heat accumulated and stored in the soil during the day, is not adequate to counter radiative heat loss to the sky in the evening (generally on clear, still nights) (Trought et. al., 1999)

Typically during a radiation frost, a temperature inversion forms from the ground up, with air layers close to the soil surface cooler than those above (Sparrow, 2003) (Figure 1).

Radiation frosts are generally more frequent and severe in inland regions (Trought et. al., 1999). Furthermore, relative humidity plays a significant part in frost severity and critical temperature. A basic distinction between frosts on evenings of high and low humidity is given below:

2.4.1.1 Black Frost:
“If there is low humidity leading into a frost event and the dew point is below 0°C, frost will occur without the formation of ice on exposed surfaces” (Pocock and Lipman, 2002)
2.4.1.2 White Frost:
“If there is high humidity leading into the frost event, dew will form on the ground above 0°C. Subsequently, as 0°C is reached, this dew freezes resulting in a coating of ice on exposed surfaces” (Pocock and Lipman, 2002) (Figure 2).

2.4.2 Advection Frost:
These frosts occur as a result of (horizontally) moving cold air masses (Trought et al. 1999) which displace warm air (Sparrow, 2003). As a general rule, beyond wind speeds of 9kph and temperatures to -5°C, very little can be done to protect crops during an advective frost (Loder, 1978).

2.5 Regional Aspects:
“Frost damage can occur in almost any location, outside of tropical zones, where the temperature dips below the melting point of water (0°C)” (Snyder et al. 2005)

The frequency of frost depends on a number of factors: In coastal areas the relatively warm ocean temperatures ameliorate those on land by reducing fluctuations in temperature and humidity (Snyder et al. 2005), while distance from the Equator and elevation above sea level are major cooling influences (Australian Bureau of Statistics Year Book, 2004).

Coonawarra experiences only mild frost conditions based on its relative proximity to the coast. An average of only 6 frost events per season (Pudney, 2007) and an absolute minimum for the last 25 years of -3.6°C (Coonawarra Weather Stn.) attests to this.

2.5.1 Weather Conditions & Frost Forecasts:
In “temperate” latitudes such as is the case for Coonawarra, low pressure systems are generally characterized by a “frontal” line, along which there is a more or less sharply defined boundary between air masses of tropical and polar or sub-polar origin (Arney, 1998). Between the trough of a low pressure system and the central zone of the next high pressure system a stream of cold air generally exists, indicated by strong winds, clouds and/or showers (Arney, 1998). As this “front” passes, conditions may rapidly change, with clouds dissipating and wind decreasing.

Subsequently, conditions which may lead to high frost risk are related to the movement of pressure systems, in particular, the passing of a low pressure system and approach or positioning over a locality of a high pressure system. In this phase: air is cold, RH is low, clear or clearing sky is observed and barometric pressure may be high or rising (Arney, 1998).

Several frost forecasting services are available, generally linked in some way to predictions by the Bureau of Meteorology (BOM). The BOM in particular, has recently updated its service to a user-friendly, “bias corrected consensus forecast” map based system, updated at approximately nine o’clock each morning and evening (refer to Appendix 1, “useful links”). Site-specific forecasts can be produced by use of predictive modelling software (as developed by the United Nations Food and Agriculture Organisation), or one of several rules of thumb may be used as a guide (i.e. 1°C temperature decline per hour after sunset if relative humidity (RH) is moderate to high).
3.0 Frost Protection Methods:

3.1 Passive Methods
Passive methods are critical to achieving satisfactory frost protection. These must be considered from the vineyard design stage and several are detailed as follows.

3.1.1 Site Susceptibility:
An understanding of frost and a proposed vineyard’s susceptibility to frost (on the basis of location) can be critical to avoiding crop failure into the future (Coombe and Dry, 1988). Research into a site’s frost susceptibility should be undertaken prior to vineyard establishment, with Snyder et. al. (2005) recommending the use of historical climatic data, to determine the “statistical probability” of the length of the “frost free” (ultimately “growth”) season for an area.

3.1.2 Site Aspect:
Slope and aspect of a proposed vineyard site, can play a significant role in its frost susceptibility. Due to the flow of denser cold air down slopes, they are generally warmer and provide a longer “frost free” period than lower areas/plains (Coombe and Dry, 1988). Frost “pockets” should be avoided at all costs. Slopes can also provide protection from southerly and westerly winds during advective conditions (Young, 2007).

3.1.3 Trellis Height & Direction:
As frost develops from the ground up, trellis height can play a role in avoiding freeze damage. Pocock and Lipman (2002) site that a difference in trellis height from 0.75m to 1.5m can result in an increase in air temperature of 1°C, while row orientation can be used to aid cold air drainage (oriented down the slope) (Loder, 1978).

3.2 Active Methods

3.2.1 Cultural Methods
Either as a way of avoiding the use of mechanical methods of frost control, or as part of an overall frost protection strategy, vineyard management in itself can play a significant part in reducing a vineyards susceptibility to frost and freeze damage. Cultural methods as per Arney (1998) are listed below:
• Delaying budburst by cultivar selection
• Delaying budburst by late pruning
• Soil and inter-row management aimed at reducing height of cover crop and soil shading. Fig. 4 gives an indication of the temperature profile in an unslashed mid-row
• Avoiding cultivation during the frost period, as large air pockets in soil are poor at storing warmth
• Irrigation aimed at maintaining moderate soil moisture to optimize heat retention
• Spray applications targeted at reducing populations of INB, providing insulation or altering freezing temperature of cell sap.

3.2.2 Frost Protection by Irrigation:

3.2.2.1 Theory:

Frost protection by irrigation functions through the application of water to plant surfaces, which as temperatures drop to the point of freezing, protects plant tissue by the release of “latent” heat energy at the change of state of that water from liquid to ice (Snyder et. al., 2005). Protection remains so long as water is applied and freezing continues. Latent heat is released both into the plant tissue, but also to the surrounding air and is in the order of 80kcal/kg water (Loder, 1978), with 1 calorie being equal to the energy required to raise the temperature of a gram of water by 1°C (Zechori, 2002).

3.2.2.2 Key Factors:

- Bore Design, Construction & Yield:

As per the Agriculture & Resource Management Council of Australia & NZ “Minimum Construction Requirements for Water Bores in Australia” handbook (refer to Appendix 1, “Useful Links”), the landholder is regarded as the “client” in dealings relating to the construction of a water bore. Client responsibilities include:

• Seeking advice on likely water availability and bore yield
• Determining desired yield, purpose and life of a bore
• Obtaining the necessary permit
• Determining materials required
• Investigating geological conditions

Firstly, apart from the requirement to deal with the local authority (the Department of Water, Land and Biodiversity Conservation or DWLBC) to obtain a “Well Construction Permit”, the department can be a useful reference for information relating to geological conditions, relevant “target” stratigraphy, expected yield and subsequent water well design parameters (i.e. casing type and depth, screens, gravel packing, regulatory requirements). Much of this information can be accessed through the department’s web based “Drillhole Enquiry System” (refer to Appendix 1, “Useful Links”). Furthermore, it is important to discuss plans thoroughly with a drilling contractor; the use of local well drillers who are familiar with the area is a clear advantage. Refer to Appendix 2 for an example of a “fact sheet” which can be compiled prior to construction commencing.

Figure 4: Vertical temperature profile in alpine pasture (Tappeiner, 1985)
- Pump Capacity, Pumping Efficiency and System Design

Design of an irrigation system can be complex and is often best left to professional designers. Having said this, it is important to be aware of basic design principles which can have a large influence on factors such as average precipitation and application uniformity.

Once bore construction has been completed, a well test to assess yield is recommended. This can be undertaken either by the drilling contractor or by an irrigation provider. This information is critical to system design, detailing: whether target yield can be achieved, an efficient pumping depth and ultimately the pump and motor specifications required. It also gives a first impression of water quality, which has implications for filtration requirements. Yield will ultimately dictate the number of sprinklers to be operated at a given precipitation rate (refer to section 3.2.2.2 “precipitation rate and sprinkler spacing”).

When purchasing a pump, it is worthwhile ensuring that pump specifications are provided, including performance curves. This will enable assessment of whether the pump is running at its optimum efficiency rating (relative to well test parameters), which can significantly reduce power usage and electricity charges. For systems with irrigation shifts of different sizes, variable speed drives (VSD’s) act to ensure a pump is always running at optimum efficiency. For frost irrigation, it is critical that the system is running at design operating pressure and as the general aim is to protect a maximum given area, it can be assumed that similarly, the pump is running at, or close to its maximum. Refer to Appendix 3 for an example of a performance curve and calculation of pump efficiency.

- Critical Temperatures

Critical temperatures as defined in section 2.3 differ in some ways when speaking in terms of irrigation. Critical temperatures are best referred to as critical start – up temperatures to protect vines, rather than the critical point of 10%, 50% or 90% damage of vine buds. An understanding of the difference, however, can help ease anxiety if there are delays in starting irrigation plant and can explain patterns of damage in unprotected vineyards or if irrigation plant has failed.

i.) Start – up Temperature

Many tables have been developed recommending critical start – up temperatures for irrigation plant, based on relative humidity and dew point (refer to Appendix 4). Ultimately, these tables all recommend similar start – up temperatures, with the critical factor being relative humidity and rate of temperature decline. As a generalisation, to avoid problems with frozen irrigation lines, start up of irrigation at 0.5°C – 1.0°C will be satisfactory for most frost events where there is high relative humidity (Woodhead et. al. 2007). When RH is low, close attention should be paid to critical start – up temperature for two reasons:

- The evaporative cooling effect resulting from irrigation raising RH to 100% prior to freezing (Zechori, 2002)
- The potential for a “black frost” event is very real & will coincide with rapid temperature decline (Loder, 1978)

Tables of critical temperatures are generally only valid for radiation frost events with little or no wind. Degree of protection will be reduced with wind and in extreme situations, ultimately an advective frost, irrigation will provide no benefit.
A recent Coonawarra trial of a frost management strategy concluded that:

On a frost night –

- High RH results in slower temperature decline
- Moderate to high humidity enables later start – up of irrigation plant (lower temperature)
- Low humidity requires earlier start – up of irrigation plant (higher temperature) and results in a profound “chilling effect”

It was noted that the majority of frosts in Coonawarra were on evenings with high RH (ultimately reaching 100%). Relating this to a simplified management strategy which incorporated aspects such as:

- Freezing of irrigation lines below 0 °C (particularly for flipper systems) even though vine critical temperature may be below this
- Programming of automatic (temperature dependent) starters at pump stations removed (some distance) from the vineyard (Fig. 5)
- Inherent variation and (in)accuracy of measuring devices

The following generalisations were made:

- if in the early evening (~10pm) RH humidity is observed as being at or above ~60% and at temperatures above 7 °C, controllers can be programmed to safely start at 0.5 – 1.0 °C
- if in the early evening (~10pm) RH is observed at below 60% and or 4 °C, temperature & RH or temperature and dew point tables should be referred to, to determine whether a higher start up temperature is required
- if RH humidity is low (less than 50%), and temperature is below 7 °C, be extremely wary as the potential for frost is significant and the rate of temperature decline may be accelerated

Refer to Appendix 5 for the flow sheet of this management strategy.
ii.) Shut – Down Temperature
Irrigation plant can be shut down if:

- the temperature measured up – wind from the irrigated vineyard is warmer than the calculated critical temperature (Snyder et. al., 2005)
- after sunrise the temperature is above 0°C and is showing a constant upward trend (Loder, 1978)
- water is observed running between the ice encasement and the plant tissue (providing this occurs after sunrise and conditions are not “advective”) (Zechori, 2002).

iii.) Measuring Critical Temperatures
With new technology, it is much simpler to determine relative humidity and dew point “on the run”. Depending upon budget and degree of accuracy required, a unit costing between $200 and $500 can provide this data to an acceptable level of accuracy (n.b. electronic units use temperature and relative humidity to calculate dew point, which results in a minor error relative to the actual (Fig. 6)).

- Sprinkler Output, Average Precipitation, Coefficient of Uniformity & Distribution Uniformity

i.) Precipitation Rate & Sprinkler Spacing
Different precipitation rates will provide different degrees of protection. A risk assessment must be undertaken for a vineyard and a decision made as to what degree of protection is required (Snyder et. al. 2005). This in turn will determine the average precipitation rate required and the area which can be protected with a given amount of water. Table 2 (pg. 15) gives an indication of average precipitation rates required.

A target precipitation rate can be achieved through sprinkler and nozzle selection, adjustments to system operating pressure (which will also affect droplet size) and sprinkler layout (Fig. 7). Sprinkler layout is critical to achieving average precipitation rates, whilst maintaining a minimum value for Coefficient of Uniformity (CU) of >84% and Distribution Uniformity (DU) of at least 70% (Dept. of Agriculture SA, 1984). An equilateral triangle arrangement generally improves DU (Snyder et. al. 2005).

Coefficient of Uniformity (CU): This relates to a measure of uniformity of water distribution from a pattern of sprinklers and indicates true deviation from the mean (Dept. of Agriculture SA, 1984).
Distribution Uniformity (DU): This is an indicator of the magnitude of the distribution “problem” of sprinklers and represents the average of the lowest 25% of values in the pattern (pers. comm. Denis Sparrow, 2007).

Computer packages enable theoretical models to be developed (Fig’s. 8, 9 & 10), which give an indication of average precipitation. Similar programs enable these to be tested in the field, by use of catch can tests. (Refer to Appendix 1, “useful links”)

**ii.) Droplet Size:**

There is general consensus that large droplets are preferential, in order to reduce the chilling effect at irrigation start – up. Practical experience, however, would suggest that in most cases the fine spray emitted from, in particular, the rear nozzles of impact sprinklers, has greater benefit in improving both DU and CU, than detrimental effects through excessive chilling (pers. comm. Sparrow, 2007). Improved uniformity ultimately contributes to a reduction in water requirement.
iii.) Sprinkler Rotation Time

A final, yet critical aspect of irrigation setup is sprinkler rotation time. This will determine the interval between “wetting fronts” and maintenance of constant water to be frozen. Ultimately, a rotation time of between 40 and 60 seconds is ideal (Loder, 1978), with faster rotation potentially resulting in wasted water (excess water splashing off), while slower rotation time results in reduced effectiveness due to excessive temperature drop between wetting (Fig. 11). Slow rotation time can be countered by increasing the precipitation rate (Snyder et. al., 2005).

Tables detailing degrees of protection relative to precipitation rate are generally based on sprinkler rotation times less than or equal to 60 seconds. In this case, Table 2 highlights the effect of slower rotation time on the degree of protection and application rate.
4.0 Conclusion:
Detailed research into the frost susceptibility of vines and irrigation requirements for frost protection comes as a result of the significant impact of frost on agricultural and horticultural production.

The understanding of frost and frost protection obtained from this research enables sound decisions to be made with regard to water use efficiency. A site specific risk assessment will enable effective decision making, regarding the required sprinkler precipitation rate to provide adequate protection. The three key factors of precipitation rate, application uniformity and time between rewetting (rotation time) need to be within specified limits. Subsequently, if combined with a frost irrigation management plan which takes into account critical temperatures on the basis of temperature and relative humidity or dew point, has the potential to significantly improve water use efficiency, while at the same time maintaining satisfactory protection.

Frost should clearly be taken into account from initial design aspects to ongoing management of a vineyard. Passive methods should be used in conjunction with active methods to achieve satisfactory levels of protection. An understanding of the nature of why damage occurs, degrees of damage, differences between cultivars and the dynamic effects of frost irrigation, can enable logical assessment of risk to be determined, when in the stressful situation of applying frost protection.

Research into frost protection for horticultural crops is ongoing, particularly in the areas of water use efficiency, cultivar susceptibility and ice nucleating bacteria.
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Appendix 1: Useful Links

(Water and The Land: Frost Potential)

(Frost Protection: fundamentals, practice and economics (FAO))

http://biomet.ucdavis.edu/frostprotection/Principles%20of%20Frost%20Protection/FP005.html
(Principles of Frost Protection)

(Elders Weather South East)

(Introduction to Irrigation Management, Evaluating your pressurised system)

(Drillhole Enquiry System)

(Minimum Construction Requirements for Water Bores in Australia)

http://www.nzwine.com/reports/
(New Zealand Winegrowers Research Committee)
Appendix 2: Bore Construction “Fact Sheet”
Shallow Bore Construction Details Fact Sheet

**Introduction:** Water used for drip irrigation and stock purposes on ***** property is sourced from Water Well (****,****). Having recently collapsed, it is necessary to drill a new bore.

**Responsibilities:** Being the “client” requesting bore construction, our responsibilities include, but are not limited to:

- Determine desired yield, purpose and life of the bore
- Obtaining necessary permit
- Seeking advice on likely water availability and bore yield
- Determining materials required
- Investigate geological conditions
- Ensuring reports and water samples are submitted to the licensing authority

**Classification:** The target unit is within the Padthaway frm., which consists of alternating consolidated and unconsolidated fine sand. Target depth is within 20m of surface and high yields of 60L\text{sec} have been observed in bores at 12m. It is subsequently necessary to construct a high-flow screen and gravel packed bore (figure 1).

**Construction:** The bore will be constructed targeting a high yielding, relatively coarse sandstone unit. Factors considered in the design process include:

- Selection of casing size, relative to potential yield and pump size.
- Selection of screen length relative to aquifer thickness
- Choice of gravel pack size and material based on the determined size fraction of aquifer material
- Selection of screen slot aperture (approx. 20\% smaller than gravel pack modal size)
- Hole diameter which will allow for casing and 50 to 100mm gravel pack

**Sampling:** As technical staff at ***** Estate have an earth sciences background, stratigraphic logging aims to ensure optimum bore design and construction.

**Casing, Screens & Gravel Packing:** PVC casing with horizontal slots of predetermined width (by analysis of sand fraction) may be adequate, although stainless steel casing with gravel packing of wire – wound screens would be potentially more economical over time. Stainless steel casing has the advantage of higher resistance to collapse at small hole diameters. This is particularly relevant in an environment of high pressure differential (high yield) and unconsolidated fines.

Careful sampling of the water-bearing formation, followed by sieve analysis of grain size, will enable packing and screen size to be determined, targeting a water entrance velocity of 30mm per second.

**Bore Development:** Bore development consists of the application of appropriate techniques designed to bring a bore to its maximum production capacity. The development process involves both chemical and mechanical agitation techniques.

Development not only increases the productive capacity of a bore, but also stabilises the formation which then acts as a filter to prevent the pumping of sand. Proper development will result in a virtually sand and silt free bore. Figures 2 and 3 display the development process and desired aquifer structure post – development.

**Resources:**


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**Figure 1:** High-yield bore (high-flow screen & gravel packed)

**Figure 2:** Improved bore permeability through Development

**Figure 3:** Commencing Bore Development
Appendix 3: Pump Performance Curve & Calculating Pumping Efficiency
Performance Curve
Calculating Efficiency

Meter readings during the frost season indicate an average flow of 270kL/hr or 75L/sec.

The performance curve is for a Caprari P10CU/6/30/2A, with the above flow marked in red.

The performance curve shows a maximum efficiency of 77.4% occurring at a flow of 68 L/sec.

Comments from Denis Sparrow (Rural Solutions South Australia):

“This is close.

The third curve down, “Efficiency” curve, indicates the operating efficiency at various flow rates. Normal operation (system flow) should always occur near to the point of maximum efficiency 77.4% or slightly before*.

* When a pump first starts it usually pumps at a high flow rate to fill the mains then reverts back to normal operation. The pump must be able to accommodate this extra flow at start-up, hence picking a normal operation point well back from the end of the pump curve.”

Therefore, the optimal point is slightly to the left - hand - side of the maximum efficiency point.

In the case of this pump curve, optimum coverage for frost protection could be achieved at a pressure 50kpa lower than the “specified duty” for irrigation during the growing season.

Pressure was reduced by increasing the number of sprinklers operating, with the effect of shifting the operating point to the right along the hydraulic efficiency line. Care must be taken in doing this, however, as by going too far to the right, high system flow may result in cavitation of the pump and premature wear (pers. comm. Daniel Grosse).
Appendix 4: Tables of Critical Start – Up Temperatures
Air temperature at which irrigation plant must be turned on at slow temperature drop (less than 1.0°C/hour) and very low wind speed (less than 5.5km/hour) (Loder, 1978)
Air temperature at which irrigation plant must be turned on at normal to fast temperature drop (1.0°C/hour or >1.0°C/hour) (Loder, 1978)
Guide to Using Tables

Determining critical temperature at which to start irrigation plant as per Loder (1978)

- Using Table “Fast Temperature Drop” Hypothetical Scenario
  - first observation at sunset

<table>
<thead>
<tr>
<th>Observation</th>
<th>Reading</th>
<th>Critical Air Temp. °C</th>
<th>Temp. at which to turn on irrigation plant °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temp. °C</td>
<td>RH %</td>
<td></td>
</tr>
<tr>
<td>i.</td>
<td>4.0</td>
<td>60</td>
<td>1.7</td>
</tr>
<tr>
<td>ii.</td>
<td>4.5</td>
<td>60</td>
<td>1.6</td>
</tr>
<tr>
<td>iii.</td>
<td>5.0</td>
<td>57</td>
<td>~1.7</td>
</tr>
</tbody>
</table>

Answer: WAIT

- second observation one hour later

<table>
<thead>
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<th>Observation</th>
<th>Reading</th>
<th>Critical Air Temp. °C</th>
<th>Temp. at which to turn on irrigation plant °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temp. °C</td>
<td>RH %</td>
<td></td>
</tr>
<tr>
<td>i.</td>
<td>2.5</td>
<td>69</td>
<td>1.6</td>
</tr>
<tr>
<td>ii.</td>
<td>3.0</td>
<td>67</td>
<td>1.5</td>
</tr>
<tr>
<td>iii.</td>
<td>4.0</td>
<td>62</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Answer: WAIT

- third observation half an hour later

<table>
<thead>
<tr>
<th>Observation</th>
<th>Reading</th>
<th>Critical Air Temp. °C</th>
<th>Temp. at which to turn on irrigation plant °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temp. °C</td>
<td>RH %</td>
<td></td>
</tr>
<tr>
<td>i.</td>
<td>1.5</td>
<td>74</td>
<td>1.5</td>
</tr>
<tr>
<td>ii.</td>
<td>2.0</td>
<td>74</td>
<td>1.4</td>
</tr>
<tr>
<td>iii.</td>
<td>2.5</td>
<td>71</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Answer: Turn on IMMEDIATELY
Using Table “Slow Temperature Drop” & Actual Data for Evening October 7th – 8th
- Observation at 10pm

<table>
<thead>
<tr>
<th>Observation</th>
<th>Reading</th>
<th>Critical Air Temp. °C</th>
<th>Temp. at which to turn on irrigation plant °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temp. °C</td>
<td>RH %</td>
<td></td>
</tr>
<tr>
<td>i.</td>
<td>2.8</td>
<td>96.4</td>
<td>-</td>
</tr>
<tr>
<td>ii.</td>
<td>3.2</td>
<td>98.1</td>
<td>-</td>
</tr>
<tr>
<td>iii.</td>
<td>3.2</td>
<td>97.1</td>
<td>-</td>
</tr>
</tbody>
</table>

Answer: WAIT

In this case, depending upon the specific frost “plan”, a decision may be to set thermometers on automatic starters to an agreed, generic temperature. For example, to compensate for variable vineyard topography (frost pockets) or to prevent freezing of lines, this temperature may be 0°C or 0.5°C.

Although the result at 10pm was “no likelihood of frost”, it is important to remain wary, as conditions can always change. In light of this, with high humidity, it is however possible to assume that the critical temperature will be close to 0°C, even in the case that there may be a faster than expected temperature decline or change in conditions.

- observation at 1am

<table>
<thead>
<tr>
<th>Observation</th>
<th>Reading</th>
<th>Critical Air Temp. °C</th>
<th>Temp. at which to turn on irrigation plant °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temp. °C</td>
<td>RH %</td>
<td></td>
</tr>
<tr>
<td>i.</td>
<td>0.8</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>ii.</td>
<td>0.8</td>
<td>99.2</td>
<td>-</td>
</tr>
<tr>
<td>iii.</td>
<td>0.8</td>
<td>99.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Answer: WAIT

In summary of this scenario:
- at 10pm a result of “no likelihood of frost” was determined
- at 1am a critical temperature of -0.5°C was determined and finally, the lowest recorded temperature for the evening in the three set locations was -0.5°C.

Although in hindsight turning on irrigation plant may not have been necessary until 3.30am, irrigation in this case was activated at 2.30am at a temperature of 0°C (refer to Fig. 5 pg. 12). This is on the basis of a management decision relating to degree of acceptable risk, which takes into account:
- desire to save water
- potential freezing of irrigation lines (diff. of ground temperature Vs thermometer height)
- variability in temperature across the vineyard
- accuracy of thermometers and
- vine growth stage
Temperature & Dew Point

<table>
<thead>
<tr>
<th>Dew Point °C</th>
<th>(Wet Bulb) Temp. °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>-1.0</td>
<td>-0.2</td>
</tr>
<tr>
<td>-1.5</td>
<td>0.1</td>
</tr>
<tr>
<td>-2.0</td>
<td>0.4</td>
</tr>
<tr>
<td>-2.5</td>
<td>0.7</td>
</tr>
<tr>
<td>-3.0</td>
<td>1.0</td>
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<tr>
<td>-3.5</td>
<td>1.3</td>
</tr>
<tr>
<td>-4.0</td>
<td>1.5</td>
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<tr>
<td>-9.5</td>
<td>3.9</td>
</tr>
<tr>
<td>-10.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Air Temp. at which irrigation plant must be turned on using Dew Point
Adapted from Chandler, K., 2007 and Snyder et. al., 2005
Frost Protection Procedure

Measure Temperature 2hrs after sunset
Set Critical Temperature (at ~ 9 - 10pm)

RESPOND TO FROST ALARM
(ALARM SET AT CRITICAL TEMPERATURE)

- Collect computer
- SMS Weather station
  - Temperature
  - Relative Humidity
  - Wind speed

- Input temp. & RH info. for individual vineyards into frost database, including pump details.
- Calculate startup temperature using "Dew Point" or "Relative Humidity" (Ensure start +0°C)

- Ensure pumps are running below critical temperatures

Stop irrigation above calculated critical temperature or after sunrise if the temperature is above 0°C and is showing an upward trend (Temperature Plot). (Ensure temp. measurements are taken upwind from the frost protected vineyard)