Improving Sprinkler Frost Protection In New Zealand Vineyards

Summary Report from 2004 Data

Prepared for:
Hawke's Bay Grape Growers Assn (Inc) and other Stakeholders

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This work has been commissioned at the request of interested parties after the unsatisfactory results from our frost protection methods (more specifically sprinkler applied water), during several frost events in the spring of 2003. These parties include winegrowers (both grape growers and winemakers), Hawke's Bay Grape Growers Assn, irrigation design and installation companies through Hawkes Bay Irrigation Services and irrigation hardware supply companies through NaanDan and Deeco.

Through the HBGGA, the group applied for funding in autumn 2004 but failed in this bid. With the help of considerable in kind finance, and delaying the analysis of results and some minor alterations in method, the design and installation of the trial proceeded, and data were collected during the winter and spring of 2004. Reapplying for finance from Sustainable Farming Fund (SFF) in autumn of 2004 was successful and the project has now been accelerated, and provided assurance of sufficient funds for data analysis and extension work.

Project Team

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Project Site:	Sileni Estates- Keruru Block

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1 SUMMARY

The key question that was asked from this trial in 2004 was how the nine sprinkler configurations monitored performed for frost protection. We conclude that the configurations provide protection as summarised in Table 1.

Table 1 Summary of protected areas for specified sprinkler configurations.

Sprinkler	Pressure (kPa)	Spacing (m)	Est. rate (mm/hr)	Protection (ºC/mm/hr)	Efficiency (ºC/l/hr/m^2)	Protection (ºC)
S Mamkad 445	300	13.2 x 9	4.1	1	1.0	4.0
S Mamkad 445	350	13.2 x 9	4.5	1.1	1.1	5.0
Turbohammer	300	4.4 x 9	6.1	0.8	0.7	4.5
Turbohammer	300, 50%	4.4 x 9	3.0	0.7	0.7	2.0
Flipper, black	300	2.2 x 9	2.2	0.5	0.9	2.0
Flipper, black	250	2.2 x 9	2.0	0.7	1.3	2.5
Flipper, black	300	2.2 x 7.2	2.7	0.4	0.7	2.0
Flipper, black	250	2.2 x 7.2	2.5	0.6	1.0	2.5
Flipper, violet	250	2.2 x 7.2	1.8	0.8	1.4	2.5

Key results from Table 1 are the protection efficiency (ºC/l/hr) and protection (ºC), where in each case higher values are better. For modest protection, the violet NaanDan Flipper (spaced at 7.2 metres and operated at 250 kPa provides the highest protection efficiency of 1.4 ºC/l/hr/m^2 for protection down to -2.5 ºC. The Super Mamkad at 350 kPa on a 13.2 by 9 metre grid provides the best protection, down to at least -5 ºC, but water use is higher.

We also draw attention to the influence of factors that can significantly compromise the performance of a sprinkler frost protection system. These factors will be explained further in future reports, in the light of findings from the 2004 and subsequent in-vineyard trials.

1. Air movement which distorts sprinkler distribution patterns and hence alters application depth, especially mid-way between targeted sprinklers.
2. Sprinkler alignment – affects targeted systems in a similar manner to air movement.
3. Shading of buds and florets by ice-encased wires, buds and vines.
4. Startup temperature is frequently incorrectly set, and as well as allowing frost damage if set too low, may also allow damage if too high, as well as unnecessary use of water.
5. Freezing of irrigation laterals may occur at stagnation points, but only affects a small portion of a vineyard.

2 INTRODUCTION

Frost damage to crops has long plagued mankind’s efforts to expand the range of crops grown for food or fibre. Some of the earliest accounts of frost protection go back as far as AD77, and it seems likely that the practise dates back even earlier than this. By the late 1800’s, frost protection for horticultural crops (including grapes) was well established in Europe and in the USA.

In New Zealand, areas such as Central Otago regularly experience damaging frosts, and frost protection has been practised since the early 1930’s. Some of the earliest reported New Zealand research into frost protection techniques was undertaken in Auckland vineyards in the late 1940’s (Palmer, 1949).

Nearly all the horticulturally significant frosts in New Zealand are of the radiation type. Radiation frosts occur on nights with clear skies and little or no wind. As heat is radiated away from the surface of vegetation (or other objects) the surface cools and draws heat from the plant material and the surrounding air. If suitable conditions remain long enough, the temperature of the object falls to a point where irreversible damage takes place to the plant tissue. For grapes, the most sensitive period for frost damage is at the point where the new buds and florets are emerging in the early spring. Damage to these buds occurs if temperatures fall to zero and substantially reduces the subsequent flower set and hence directly influences the subsequent crop. Losses of up 30% in total yield due to frost damage are not uncommon.

2.1 Frost Protection Methods

A wide range of methods is presently used to protect horticultural crops against frost damage. These can be loosely grouped into three main methods which are summarised as follows.

Directly heating the orchard area by means of specially designed burners fuelled by oil, natural gas, LPG or by special solid fuel blocks or candles made from wax, compressed wood-waste or other similar materials. Orchard heaters are probably one of the oldest form of frost protection ever used. Their use in NZ is presently restricted to relatively small areas because of the relatively high fuel costs and the large labour input required to operate the system. Fully automatic systems are in use in some parts of the world but the high capital cost of such systems has so far precluded their use in New Zealand.

The second general class of protection methods utilises the inverted temperature gradient that exists under radiation frost conditions (the type experienced in spring in New Zealand). Under these conditions, the air temperature rises with increasing height above the ground up to a limiting height, which is dependent largely on topography and the climate of the area concerned. In many horticulturally important areas of New Zealand the temperature 15 metres above the ground is often three to four degrees warmer than the temperature one and half metres above the ground. By mixing this warmer air from above the orchard with the lower air, the overall temperature within the fruiting area can be increased sufficiently to provide protection against damage.

Two methods are commonly used to perform the required mixing operation - wind machines and helicopters. A wind machine is essentially a large fan (with a horizontal axis) which rotates around the top of a 10 metre high tower located in the centre of the area to be protected. The ‘jet’ of air produced by the fan entrains the warm air above the orchard and mixes this into the colder air closer to the ground. The area protected is circular in shape although this can be significantly distorted by even low wind speeds. Other problems include high noise levels (which can cause problems with neighbouring properties) and the dependence of a strong enough inversion to allow significant warming to be achieved. Flying a heavily laden helicopter at relatively slow speed across the orchard area can achieve a similar effect. By flying in a pre-determined pattern of closely spaced tracks, areas of almost any shape can be protected. However, this method is also relatively noisy, requires considerable forward planning to ensure availability of machines and pilots, and is similarly dependent on the presence of a sufficiently developed inversion condition. Despite these problems, the last decade has seen widespread use of both of these methods in various parts of New Zealand.

The third, and probably most common method utilises the heat released when water changes state from a liquid to a solid. By spraying water at the correct rate onto a crop under frost conditions, a layer of ice slowly develops over the plants. Provided the surface of this ice layer is kept wet, the temperature of the enclosed plant tissue will generally be greater than minus half a degree, even though the surrounding air may be at a much lower temperature. The method requires a continuous supply of water (typically 3 to 4 mm/hr) all of which ultimately ends up on the ground. Unless good drainage is available, the potential for water-logging the soil with subsequent plant health problems is high. Although high levels of reliable protection can be obtained, the use of this method is largely confined to those areas where adequate water is available, and soils are free draining.

2.2 Frost Monitoring

There are a number of useful measurements for characterising frost conditions, but when assessing frost for damage to plant tissue, it is most appropriate to measure the exposed temperature of the plant tissue itself, or an object that has similar radiative and convective characteristics to the plant tissue. Since most damage to NZ grapevines arises during spring when buds are swelling or bursting, or florets are exposed, a temperature sensor several millimetres in diameter has been shown (eg Hamer, 1980) to replicate bud or florets quite well. Under frost conditions, the temperature of a bud will typically be 1 or 2 degrees lower than air (screen) temperature, depending predominantly on wind speed (Trought et. al., 1999).

For these reasons, the trial block measurements were made using artificial buds, comprising precision thermistors moulded to form 8 mm diameter plastic cylinders (Figure 3).

2.3 Objective and Scope of the Project

The intent of the project is detailed in the application by Hawkes Bay Grape Growers Assn. (Inc) to the Sustainable farming Fund (SFF); “Improving sprinkler frost protection in New Zealand vineyards”. An extract outlining the essential elements is given below.

“The intention of the project is to evaluate and quantify the performance of existing configurations of sprinkler frost protection systems to define bounding conditions for effective frost protection. This information will:

1. Provide a key set of performance data for identifying deficiencies in current installations
2. Allow tighter specifications on the performance of new installations
3. Identify local characteristics of different frost conditions
4. Provide better recommendations on trigger temperatures for starting frost protection
5. Enable savings in water use by optimising the use of low application rate systems and investigating pulsing.
6. Standardise a risk analysis procedure enabling growers and designers to make informed decisions trading-off likely damage rates against system cost and/or water use, and providing confidence in the frost protection system.

Project phase 1 involves an extensive, on-going trial within a particular vineyard. A large trial block will include a control section, at least 15 sprinkler configurations, and a phenology/physiology block where vines will be unprotected from just one frost event. The trial will continue through winter (when frost protection is unnecessary) to provide data from a wider range of frosts than normally experienced during the critical growth stages. The physiological response of the vines to each treatment will be monitored using the assistance of the viticulture staff of the participating companies and any adjustments to the engineering of the project will be made accordingly. Trial outputs will be delivered to the industry through seminars, field days and articles in industry publications.

Phase 2 of the project has the goal of transferring results directly to individual growers through analysis of their vineyard and frost protection system. The outcomes will include promotion of (currently non-existent) standardised temperature measurement and recording, sensor placement, and tailoring system parameters to individual sites for optimum frost management. Apart from the preparation of data sheets and check lists that can be used by individual growers, much of this grower-targeted knowledge transfer phase is expected to be funded directly from growers or regional grower associations."

3 EXPERIMENTAL DETAILS

3.1 Overview

The key aspect of the project is real-time monitoring of temperature and other frost-related weather parameters over an extensive trial site on the Keruru block at the Sileni vineyard, using a number of frost protection sprinkler types and layouts. Analysis of the data along with real-time collection of sprinkler distribution patterns and hence application rate distribution is intended to enable relationships to be formed between in-vineyard conditions, real application rates, and the prevailing conditions. A second phase of the project is concerned with technology transfer: ensuring that the knowledge gained is effectively relayed in useable form to vineyard managers. Hence the indicators of success will be:

1. Identify the conditions under which each frost protection treatment fails
2. Provide solutions to rectify or alleviate the failure
3. Provide new frost protection design criteria, and which may be related to prevailing conditions and quantitative measures of risk
4. Transfer knowledge to vineyard managers through analysis of individual vineyards and recommend changes to frost protection systems and/or management.
5. Provide recommendations for on-vineyard monitoring that enable consistent, inter-vineyard comparison of frost conditions and performance of frost protection systems (ie future-proofing).

3.2 Trial design

The trial was conducted at the Sileni vineyard around 20km West of Hastings. Eight rows of the Keruru Block A were used in the trial (Figure 1 and Appendix C).

The concept of the trial was to employ two weather stations, one stationary and one which could be moved around the trial block if required. The weather stations comprised a mast for measurements of air temperature, exposed temperature, wind speed and wind direction at two metres, and air temperature, exposed temperature and relative humidity at 1.2 metres (standard meteorological screen height).

Figure 1 Layout of trial site, Sileni Vineyard, Aorangi Rd, Hastings.

The weather stations (Figure 2) comprised screened (air temperature) and exposed temperature sensors at the standard meteorological height of 1.2 m, and at 0.9m above the canopy (ie at 2m). Wind speed and direction were also measured at approximately 2m, and weather station 1 monitored relative humidity (RH).

Figure 2 Weather station configuration: Screened (air temperature) and exposed temperature sensors at the standard meteorological height of 1.2 m, and at 0.9m above the canopy (ie at 2m). Wind speed and direction (vane in line with view) are also measured at approximately 2m.

Nine in-vineyard stations were used to monitor the effectiveness of different sprinkler frost protection configurations, and could be easily moved throughout the trial block. They comprised a weatherproof box containing the data logger, power supply and connector for data retrieval. The box was fixed to a semi-flexible 5m boom with temperature sensors at 65 cm spacing, and which could be secured along the canopy (Figure 3). The height of these sensors was typically 0.8 m. The data collection equipment also included a sprinkler distribution measurement station comprising eight collecting funnels (0.5 by 0.5 m) complete with stands (2 groups of four in a row) which could be positioned alongside the canopy to monitor application rate distribution. The system provided a time resolution of 2 minutes and sensitivity of 0.02 mm (ie equivalent to 0.6 mm/hr). Further details of the data logging systems are provided in Appendix B.

Figure 3 In-vineyard bud temperature sensor with label referring to sensor number and distance from data logger (and hence sprinkler) of 4.7m.

After the 2004 frost recording season, the project was reviewed, and the following changes were made to address some difficulties that arose during 2004.

1. Data loggers. The data logger had been chosen for its large memory capacity and convenience of an internal battery. However the lack of conditional data logging resulted in very large quantities of data (data were recorded continuously), and the loggers were very slow in transferring data to the laptop – a half day exercise for the 12 data loggers. Hence the decision was made to move to the newly available Campbell CR200 loggers for the 2005 frost season, and to construct custom electronics to expand their channel capacity. The CR200 allowed logging only during frost conditions, and data transfer to a laptop was rapid.
2. Site protection. Over-winter grazing of sheep in the vineyard resulted in chewed sensors, so temporary electric fencing was erected to protect the trial site. There were also issues with ants nesting inside the data logger cabinets. This has been addressed by reducing the size of the breather holes and spraying an on-contact insecticide inside the box.
3. Sprinkler distribution measurement. This approach to determining the effect of wind on the distribution pattern of the sprinklers was constrained by data logger issues and moisture entering the cabinet containing the data logger and electronics. The new CR200 data logger and the provision of a cover alleviated these issues.

4 ANALYSIS PROCEDURE

4.1 Background:

In 2004, approximately one million readings were collected during frost events. Programs were written to automatically generate plots based on selectable criteria, and to automatically generate data summaries and time-based plots. Although these tools eased the analysis burden, there remained a significant task of manual assessment and interpretation.

A key aspect was to establish criteria for judging the performance of the frost protections systems. In past studies we have utilised chosen damage thresholds, but in this industry-wide study, it is important that all stakeholders are able to apply their own damage criteria when assessing the performance of a particular configuration. For this reason, we elected to report on performance at four levels.

1. Provide an assessment of each sprinkler configuration as satisfactory or not, and under what circumstances the configuration failed
2. Provide graphical and tabular data supporting the assessment and enabling readers to make their own assessments
3. Enable access to time-at-temperature results, since actual damage is dependent on variety, development stage, air speed, humidity, etc. We envisage these data would be used for detailed comparisons based on crop sensitivity
4. Unprocessed data with sufficient detail for others to analyse in different ways.

Data at level three are provided in Appendix A. Data at level four are not provided in this report, but available from Lincoln Ventures Ltd. A small charge may apply for providing level four data.

Sileni Vineyard has allowed the project full access and discretion over the trial plot, operation of the frost protection trial continued through the 2004 and 2005 winters, providing a broader range of frosts than would otherwise be the case. One example of a temperature record for a winter frost event and one sprinkler configuration (NaanDan Mamkad full cover) is shown in Figure 4. Although the frost is more severe than the usual damaging spring frosts, the recordings provide the means to compare different configurations and determine under what conditions, the system fails.

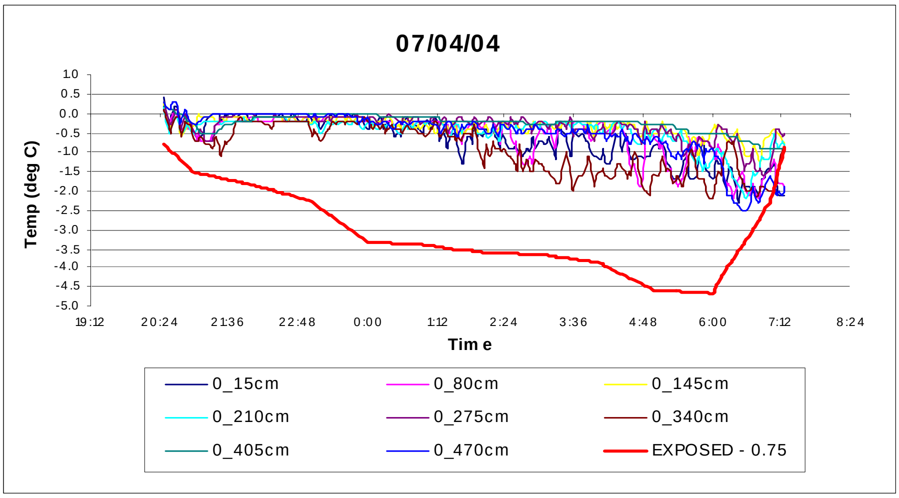

Figure 4 Example time-based trace of artificial bud temperatures in Sileni vineyard on the night of the 4 July 2004protected by a NaanDan Super Mamkad sprinkler operating at 300 kPa.

4.2 Desired Output:

From previous trials conducted by project team members, it was apparent that the rate of change of temperature of temperature sensors resembling grape buds in shape, size and colour, was quite rapid, even when heavily loaded with ice such as shown in Figure 5. Clearly, the rate of change of temperature of the bud can be quite high (eg the sudden drop in the second ice-encased sensor at around 0630).

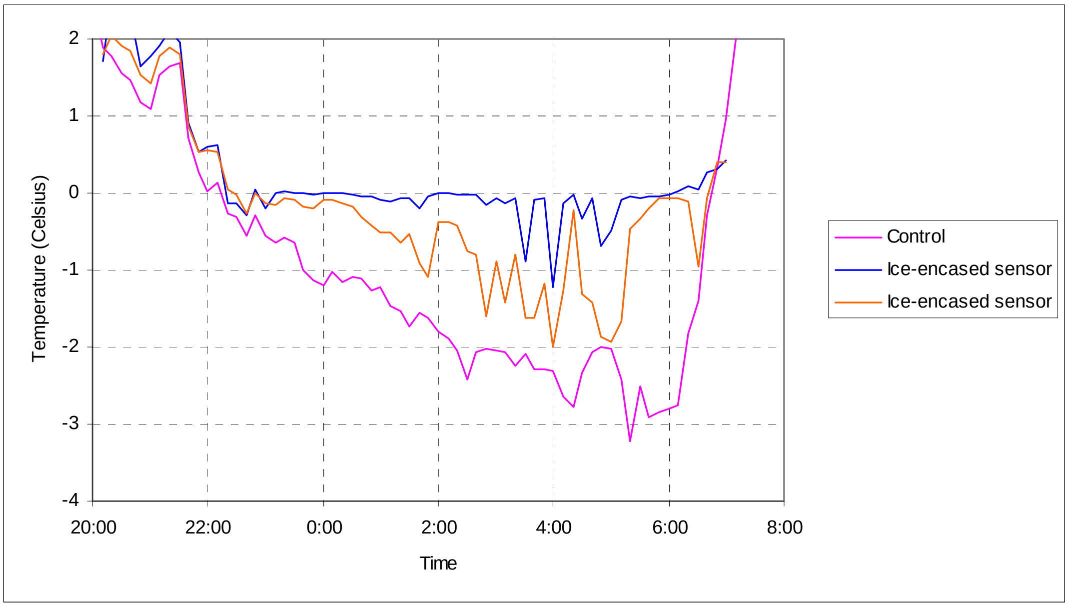

Figure 5 Plot of iced-covered sensor showing dynamic response

Given that the bud temperature may change quickly, a question remains about the rate of freezing of plant tissue. From Rajashekar (1989), it is apparent (e.g. his Fig 1) that ice nucleation at -2.5 ºC causes immediate freezing, and that lowering temperature at 4 ºC/hr results in a gradual increase in the quantity of ice inside the bud. Although not explicitly stated, it implies that there is little thermal lag at the 4 ºC/hr freezing rate. Hence we assume from the implied precision of Fig 1 of Rajashekar (1989) that a freezing rate of 4 ºC/hr causes an error or temperature skew, of less than 1ºC. This leads to the conclusion that the bud will always have reached the temperature of its surroundings and internal freezing will have stabilized, within 60 minutes of a step change in temperature. Hence, in formulating tabular data to enable independent assessment of the performance of different sprinkler configurations according to the frost sensitivity of different cultivars and at different developmental stages (Appendix A), we have elected to calculate time-at-temperature data within the time intervals defined as: 0-2, 2-4, 4-6, 6-8, 8-10, 10-14, 14-20 and >20 minutes.

Decisions were also required on how the data could be most usefully presented to provide the essential information about use of sprinklers and their failure modes. The main variables are listed in Table 2, with column two indicating whether the parameter was sufficiently influential to warrant its inclusion in charts or tables.

Table 2 Frost protection variables

Variable/parameter	**Include?**	**Comment**
Air temperature	No	Screen temperature, barely relevant
Exposed temperature	Yes	The control, unprotected bud temperature
Protected temperature	Yes	The crucial protected bud temperature
Time	Yes	Time at temperature is crucial
Wind speed and direction	Yes	A variable influence
Height	No	Sensors at one height, influences shading
Distance from nearest sprinkler	Yes	An axis on the plots
Distance from next sprinkler	Yes	May be inferred from sprinkler spacing
Shading	Yes/no	Not included in summary plots. Shading will change as vines grow.
Sprinkler type	No	Separate data plots for sprinkler type
Sprinkler flow rate	No	Separate data plots for sprinkler flow rate
Sprinkler spacing	No	Separate data plots for sprinkler spacing

5 REFERENCE DATA

A crucial aspect of the trial is measurement of the effectiveness of frost protection systems and configurations. As described earlier, the measurements of exposed temperatures in the form of artificial buds, which represent the temperature of the vine buds, were referenced to the exposed temperature at two control sites, outside the treatment area. For the 2004 season, the two weather stations providing the reference temperatures and other parameters were located towards the north of the trial block, near the river gully (locations 10 and 11 in Figure 1).

The dominant wind direction during frost conditions was in the easterly quarter, down the river valley, and there was little correlation with frost severity (Figure 6).

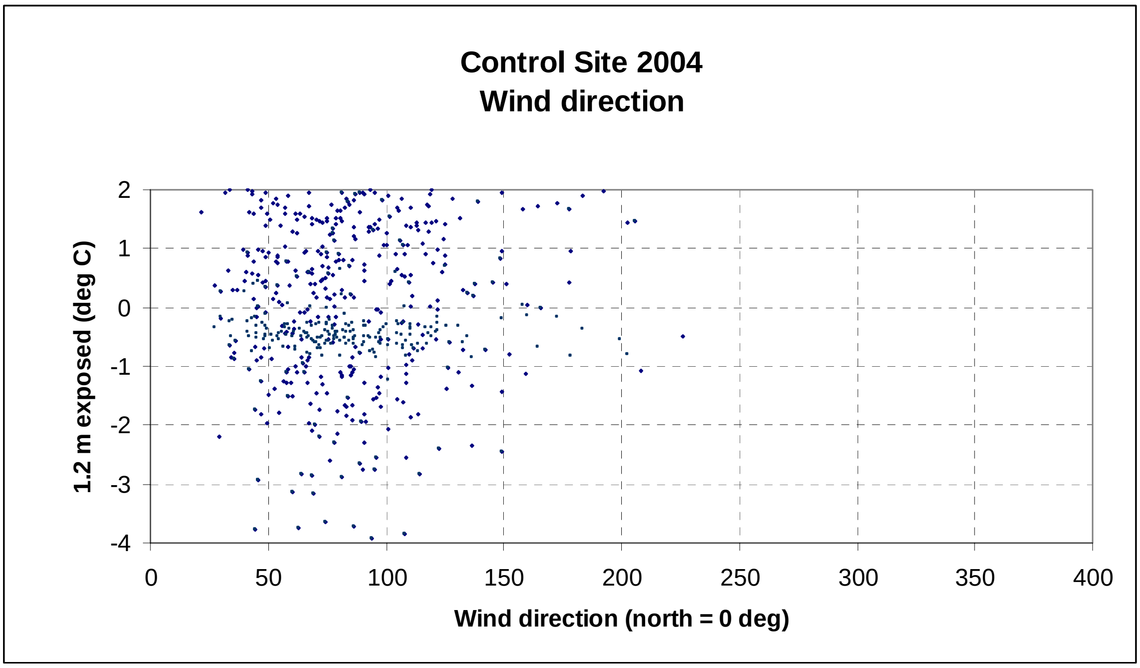

Figure 6 Dominant wind direction during frost conditions – uses 1.2m exposed temperature.

On two occasions, the pump/distribution system failed and hence provided the opportunity to examine the differences in temperature between the exposed temperatures at the control sites and those within the rows.

First, plots comparing site 1 with sites 0, 2, 7 and 8 (and Appendix C) demonstrate that there is no consistent difference in the exposed temperatures (at 77 cm above ground level) over the trial block. The differences at 2.7 ºC and 4.3 ºC were almost certainly due to early morning sun reaching the sensor at site 1 before site 0. The manually inserted line of best fit for the data (excluding the anomalous readings) has a slope very close to 1 indicating that the sites do experience very similar conditions. The comparison between sites 1 and 0 also reveals little consistent difference at two opposite corners of the trial block, although there is more scatter than between adjacent sites 1 and 2. The scatter was distributed throughout the recorded periods, indicating that it was most likely due to air movement, and was certainly of a short-term nature. Hence, we may conclude that without frost protection, there is no substantive difference in frost conditions over the trial block.

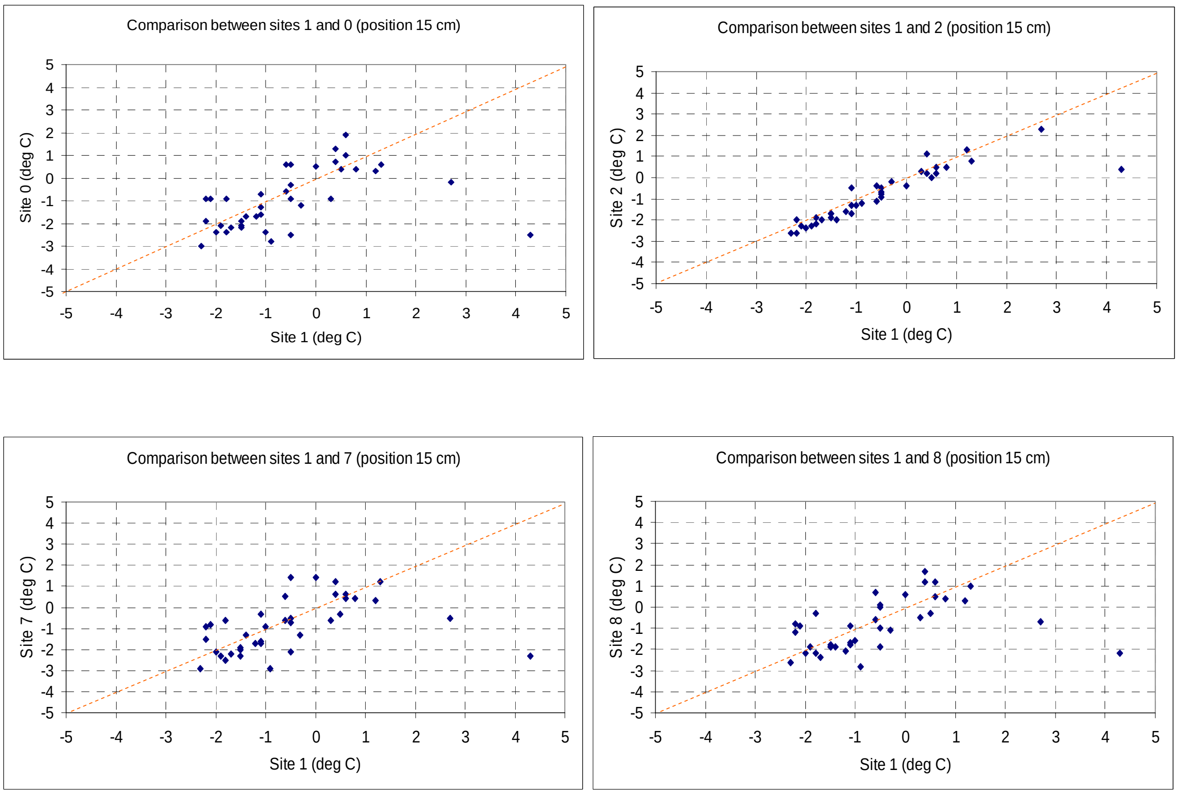

Figure 7 Differences between the 77 cm exposed vine temperatures at sites 1 and 0,2,7 and 8 without frost protection..

Turning now to a comparison of the control sites with the trial block, Figure 8 shows the differences between the mean of the 1.2 m exposed temperatures at the two control sites with the site 2 temperatures. The line through the data is an estimate of the real difference between the sites, and indicates that the mean of the 1.2 m exposed temperatures at each of the two control sites is between half and one Celsius degree warmer than site 2. Figure 8 is very similar to the control site comparisons for all other sites in the trial block, indicating that the control sites are consistently warmer than the trial block by 0.5 to 1 ºC. We attribute this to two factors: the vineyard sensors are approximately 0.8 m above ground level compared with the meteorological standard of 1.2m for the control site, and the proximity of the river gully and lack of canopy around the control site sensors allows greater airflow and hence warming of the exposed temperature sensors. The former factor is quite small, averaging approximately 0.2 ºC over the entire season, as determined by the difference between the 1.2 and 2 m exposed temperatures at the control sites.

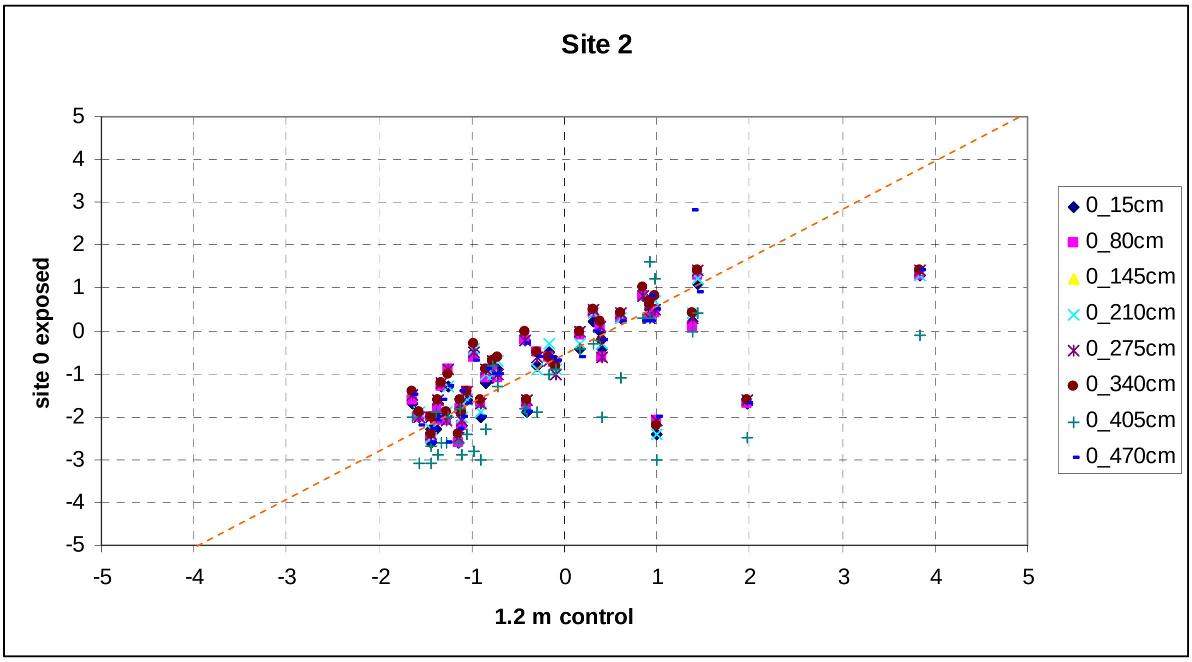

Figure 8 Comparison between the mean exposed temperature at the control sites and within the rows at site 0. The fitted line indicates the estimated difference between the sites (refer text).

During 2004, there were 22 recorded frosts at the Sileni site, and 6 were unprotected. The minimum control site temperatures were -4.2 ºC (uncorrected 1.2 m exposed) and -3.9 ºC (1.2 m screen).

6 SPRINKLER PERFORMANCE RESULTS

The results from each sprinkler configuration described below includes both a plot and tabular values of the mean level of protection. The data use corrected control temperatures consisting of the measured exposed 1.2m control temperature less 0.75 ºC for reasons discussed in §**Error! Reference source not found.**. The percentage protection is calculated as follows:

$$P(\%) = \frac{\sum_{n} 100(t_c - t_p - 1)}{n.t_c}$$

where t_c is the corrected control temperature, n is the number of events and t_p is the protected temperature in the vineyard. The 1 ºC offset is used to define 100% protection when t_p is at -1 ºC, and only data where t_c was cooler than -1 ºC were included. In summary, the percentage protection is a measure of the effectiveness of frost protection, 100% when at or above -1 ºC, and 0% when at the exposed control (unprotected) temperature.

Tabular values of the time that protected sensors were at a particular temperature, expressed as a percentage of the time the unprotected sensor was at or below that temperature have also been prepared. These data are in Appendix A.

In Section 7, the results are discussed and conclusions drawn about the performance of each sprinkler configuration.

6.1 Full Cover, 300 kPa at 13.2 by 9 m

The full cover NaanDan Super Mamkad sprinklers with orange 445 nozzle sprinklers at 300 kPa and spaced on a 13.2 by 9m grid were sited in block 17, and data recorded on data logger 0.

Table 3. Values of mean level of protection (%) provided by NaanDan Super Mamkad sprinklers with orange 445 nozzle spaced on a 13.2 by 9m grid at 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp (°C)	53 cm	118 cm	183 cm	248 cm	313 cm	378 cm	443 cm	508 cm
-1 to -1.5	99	100	99	99	99	100	100	100
-1.5 to -2	99	100	100	99	100	99	99	99
-2 to -2.5	95	99	97	97	96	95	95	97
-2.5 to -3	99	99	99	99	99	99	99	99
-3 to -3.5	86	84	89	88	91	91	88	86
-3.5 to -4	86	89	100	97	100	100	99	89
-4 to -4.5	79	75	84	92	98	92	88	75
-4.5 to -5	76	70	74	86	78	83	76	66

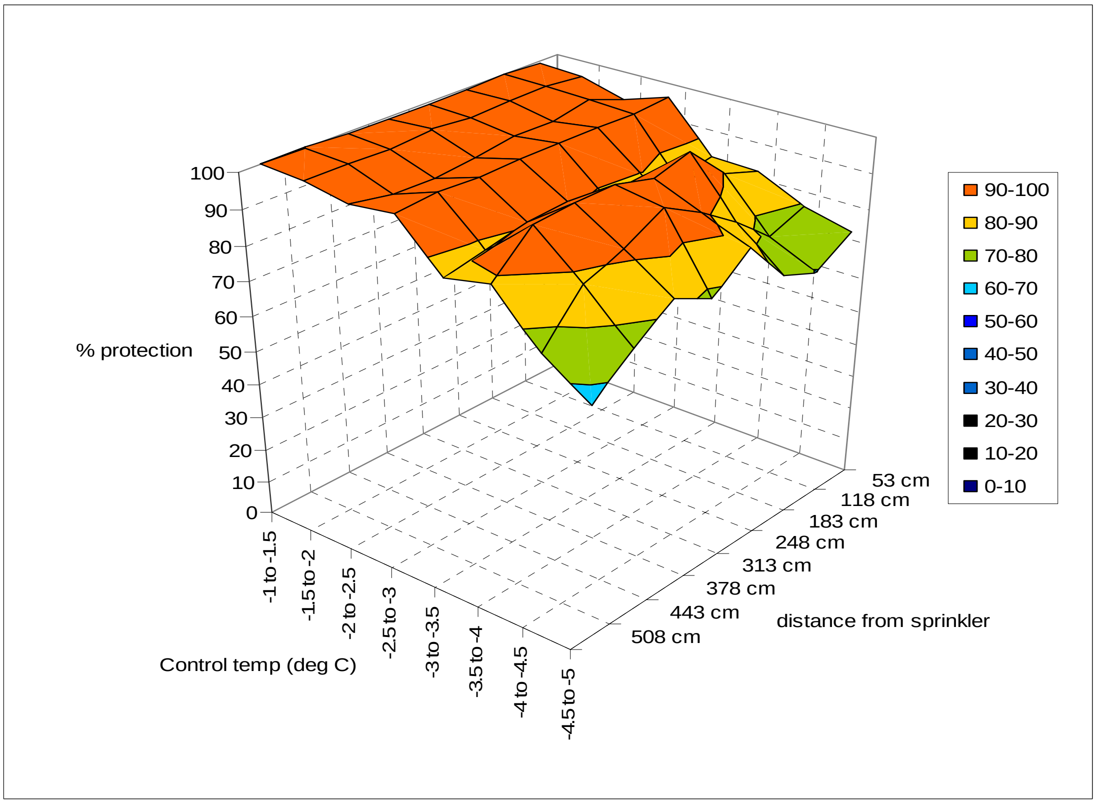

Figure 9. Mean level of protection (%) provided by NaanDan Super Mamkad sprinklers with orange 445 nozzle spaced on a 13.2 by 9m grid and at 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.2 Full Cover, 350 kPa on 13.2 by 9 m grid

The full cover NaanDan Super Mamkad sprinklers with orange 445 nozzle sprinklers located on a 13.2 by 9 m grid and operated at 350 kPa were sited in block 16, and data recorded on data logger 8.

Table 4. Values of mean level of protection (%) provided by NaanDan Super Mamkad sprinklers with orange 445 nozzle sprinklers spaced on a 13.2 by 9 m grid and operating at 350 kPa. Data analysis uses corrected control temperatures (see text).

Control temp (°C)	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	99	99	99	99	99	100	98	100
-1.5 to -2	98	98	98	98	97	98	98	89
-2 to -2.5	88	92	95	93	89	90	92	85
-2.5 to -3	99	99	99	99	99	97	100	98
-3 to -3.5	96	95	97	97	98	93	100	93
-3.5 to -4	97	100	100	100	100	96	100	100
-4 to -4.5	96	98	100	100	100	86	100	100
-4.5 to -5	94	96	100	94	100	75	100	88

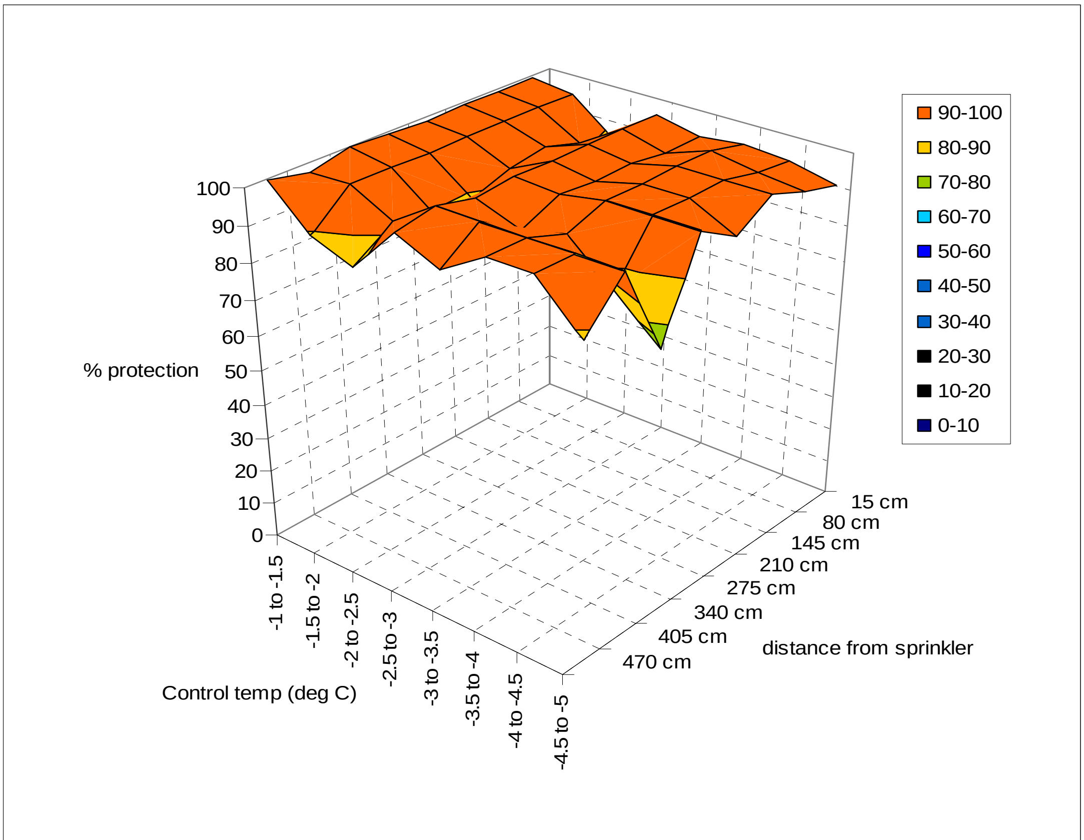

Figure 10. Values of mean level of protection (%) provided by NaanDan Super Mamkad sprinklers with orange 445 nozzle sprinklers spaced on a 4.4 by 9 m grid and operating at 300 kPa. Data analysis uses corrected control temperatures (see text).

6.3 Full Cover, 160 l/hr 300 kPa on 4.4 by 9 m grid

The full cover NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles located on a 4.4 by 9 m grid and operating at 300 kPa were sited in block 13, and data recorded on data logger 6.

Table 5. Values of mean level of protection (%) provided by NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles spaced on a 4.4 by 9 m grid and operating at a line pressure of 300 kPa. Data analysis uses corrected control temperatures (see text). Data in red are interpolated due to defective sensor.

Control temp (°C)	45 cm	110 cm	175 cm	240 cm	305 cm	370 cm	435 cm	500 cm
-1 to -1.5	100	100	100	100	100	100	100	100
-1.5 to -2	100	100	100	100	100	100	100	100
-2 to -2.5	95	95	96	95	96	97	96	95
-2.5 to -3	95	99	99	98	98	99	97	95
-3 to -3.5	91	94	94	94	94	97	92	87
-3.5 to -4	95	97	97	100	100	98	93	88
-4 to -4.5	83	90	100	94	96	91	84	78
-4.5 to -5	73	88	81	87	79	86	78	70

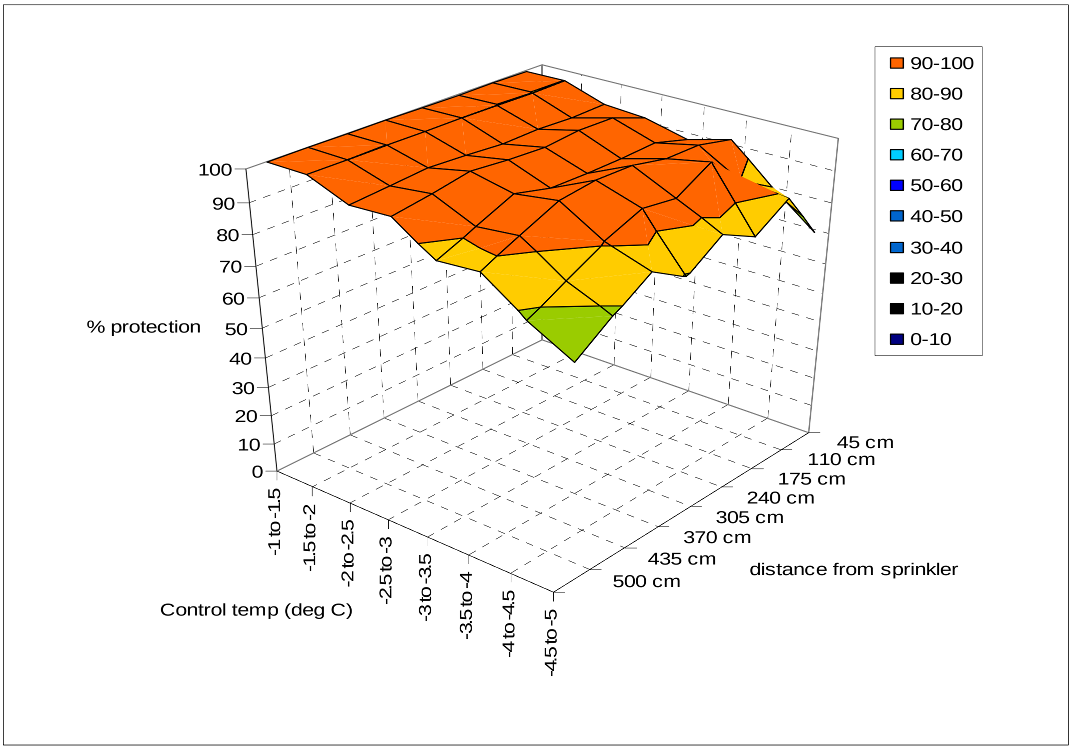

Figure 11. Values of mean level of protection (%) provided by NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles spaced on a 4.4 by 9 m grid and operating at a line pressure of 300 kPa. Data analysis uses corrected control temperatures (see text).

6.4 Full Cover, Pulsed 300 kPa on 4.4 by 9 m grid

The full cover NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles located on a 4.4 by 9 m grid and pulsed at 300 kPa were sited in block 14, and data recorded on data logger 7.

Table 6. Values of mean level of protection (%) provided by NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles spaced on a 4.4 by 9 m grid and pulsed at 300 kPa. Data analysis uses corrected control temperatures (see text).

Control temp (°C)	45 cm	110 cm	175 cm	240 cm	305 cm	370 cm	435 cm	500 cm
-1 to -1.5	99	99	99	100	98	98	99	100
-1.5 to -2	90	89	91	91	93	91	100	94
-2 to -2.5	80	75	79	79	82	81	91	82
-2.5 to -3	72	64	72	76	87	84	93	85
-3 to -3.5	68	61	68	68	77	76	87	84
-3.5 to -4	73	63	69	73	79	77	96	86
-4 to -4.5	72	66	69	80	72	74	93	70
-4.5 to -5	59	54	56	67	62	64	85	55

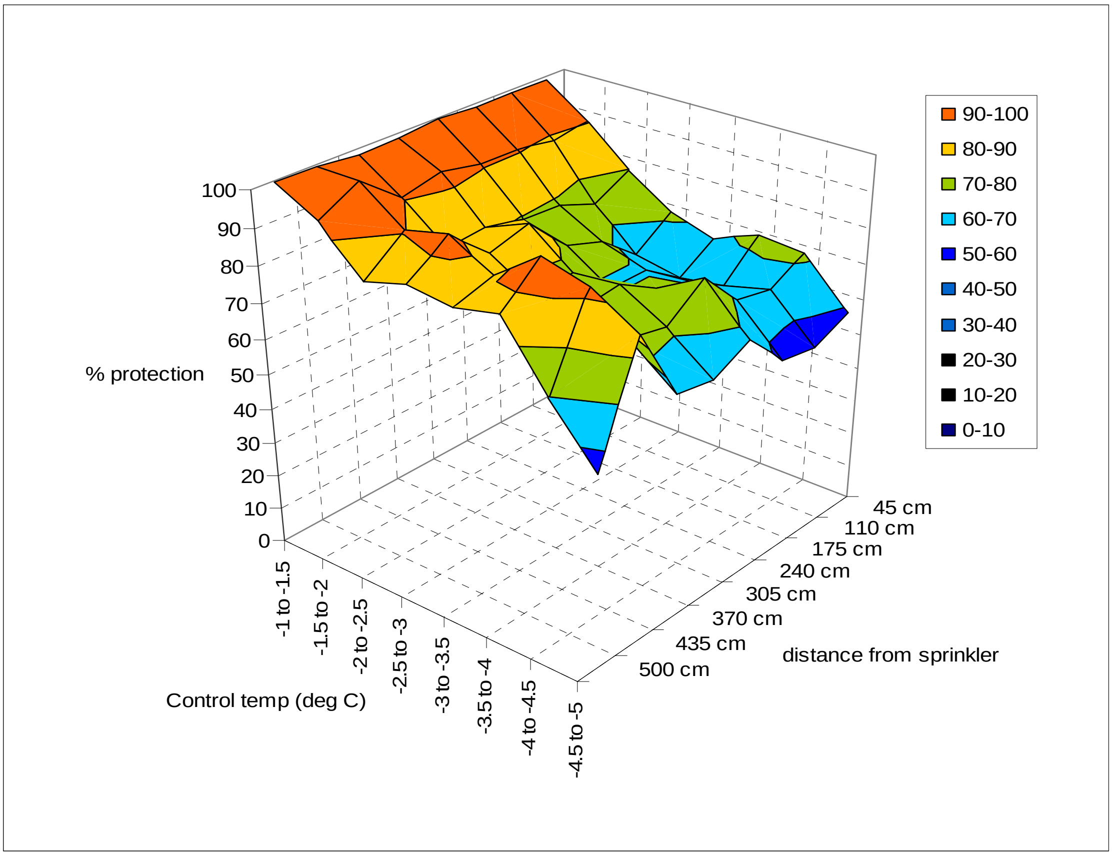

Figure 12. Values of mean level of protection (%) provided by NaanDan 501-U Turbohammer sprinklers with green 160 l/hr nozzles spaced on a 4.4 by 9 m grid and operating at 300 kPa. Data analysis uses corrected control temperatures (see text).

6.5 Targeted, 35 l/hr 300 kPa at 9 m

The targeted NaanDan Flipper with black 35 l/hr nozzles spaced at 9m and operating at 300 kPa were sited in block 1, and data recorded on data logger 1.

Table 7. Values of mean level of protection (%) provided by NaanDan Flipper with black 35 l/hr nozzles spaced at 9m and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text). Data in red are interpolated due to defective sensor.

Control temp (ºC)	36 cm	101 cm	166 cm	231 cm	296 cm	361 cm	426 cm	491 cm
-1 to -1.5	100	100	100	99	99	97	100	100
-1.5 to -2	97	96	95	96	90	90	95	98
-2 to -2.5	90	89	87	88	83	73	85	91
-2.5 to -3	81	77	73	73	66	64	75	84
-3 to -3.5	66	66	68	62	57	57	63	72
-3.5 to -4	63	57	57	58	56	60	63	66
-4 to -4.5	57	54	54	53	51	47	54	61
-4.5 to -5	57	51	50	54	46	45	51	56

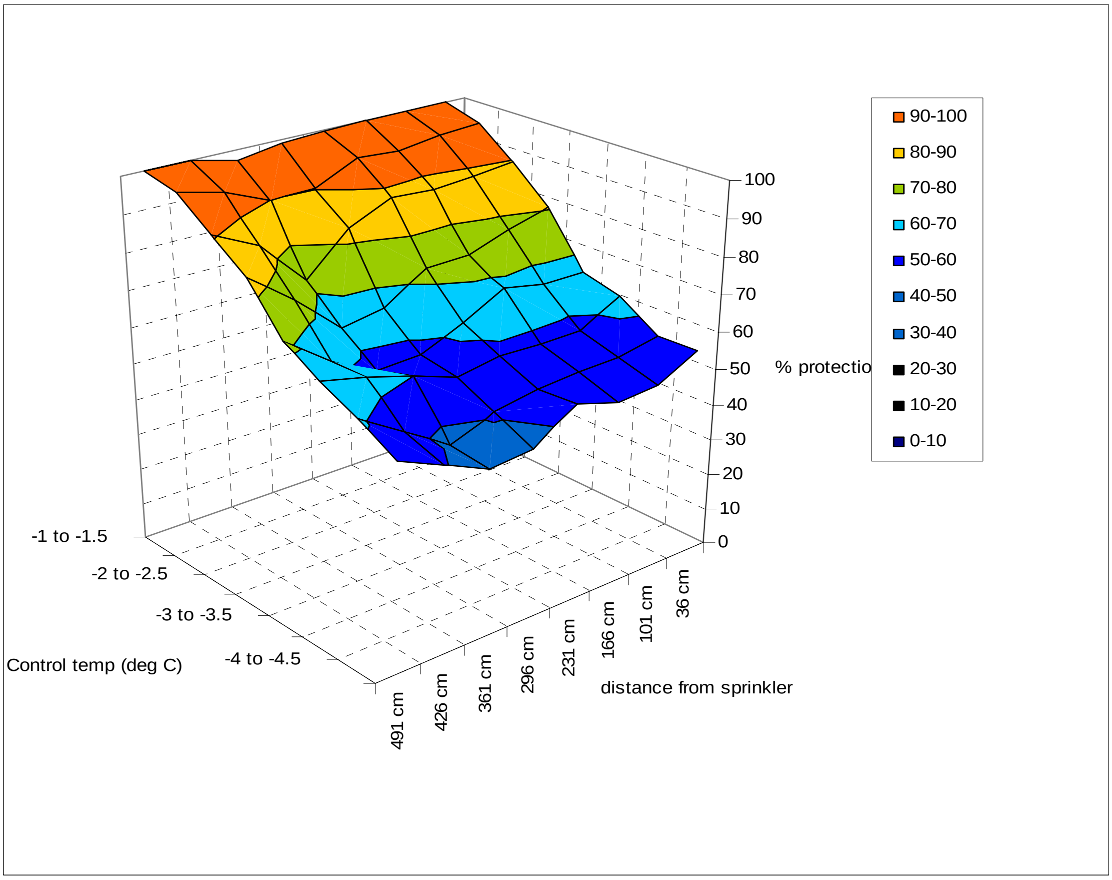

Figure 13. Mean level of protection (%) provided NaanDan Flipper with black 35 l/hr nozzles spaced at 9m grid and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.6 Targeted, 35 l/hr 250 kPa at 9 m

The targeted NaanDan Flipper with black 35 l/hr nozzles spaced at 9 m and operating at 250 kPa were sited in block 10, and data recorded on data logger 5.

Table 8. Values of mean level of protection (%) provided by NaanDan Flipper with black 35 l/hr nozzles spaced at 9 m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp (°C)	45 cm	110 cm	175 cm	240 cm	305 cm	370 cm	435 cm	500 cm
-1 to -1.5	100	100	99	99	100	100	100	100
-1.5 to -2	100	100	99	98	99	99	98	100
-2 to -2.5	97	95	92	93	88	91	95	91
-2.5 to -3	96	91	88	86	82	88	95	90
-3 to -3.5	94	84	87	86	77	83	92	81
-3.5 to -4	90	79	72	73	71	82	87	77
-4 to -4.5	76	70	65	60	63	69	73	69
-4.5 to -5	84	66	74	68	55	61	70	62

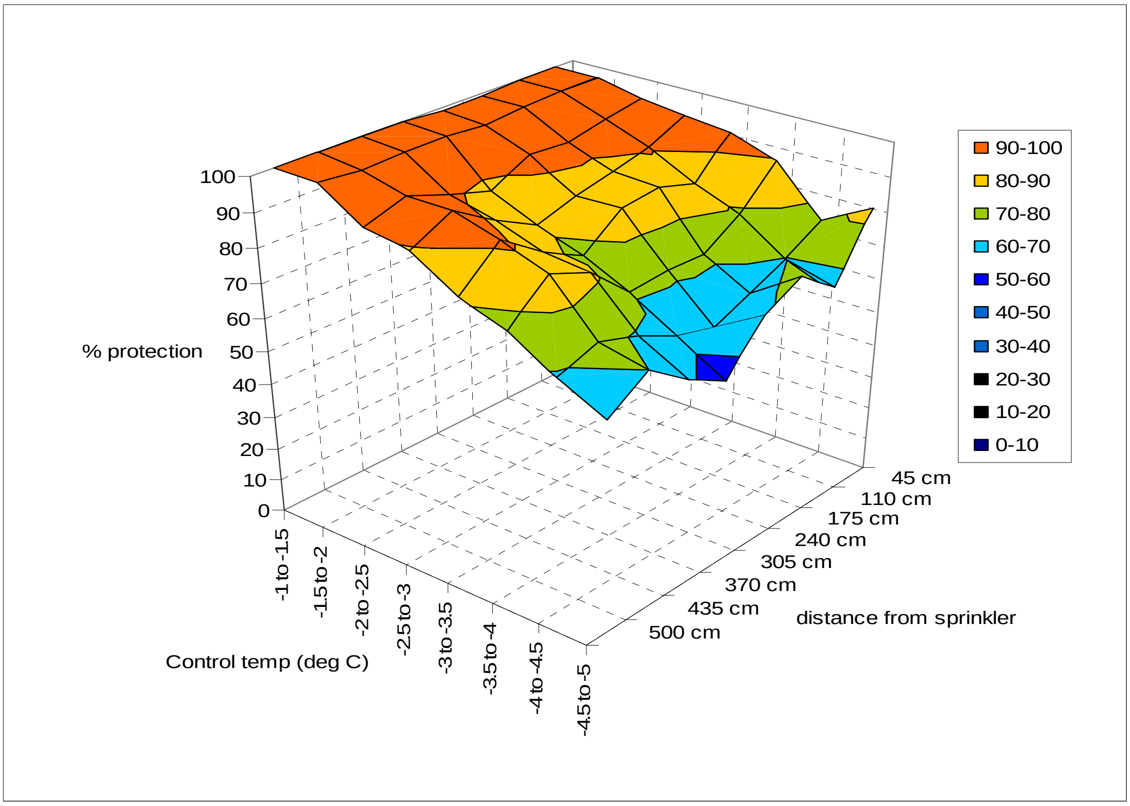

Figure 14. Mean level of protection (%) provided by NaanDan Flipper with black 35 l/hr nozzles spaced at 9m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.7 Targeted, 35 l/hr 300 kPa at 7.2 m

The targeted NaanDan Flipper with black 35 l/hr nozzles spaced at 7.2 m and operating at 300 kPa were sited in block 2, and data recorded on data logger 2.

Table 9. Values of mean level of protection (%) provided by NaanDan Flipper with black 35 l/hr nozzles spaced at 7.2m and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp (ºC)	36 cm	101 cm	166 cm	231 cm	296 cm	361 cm	426 cm	491 cm
-1 to -1.5	99	100	100	100	100	100	100	99
-1.5 to -2	98	99	100	100	100	98	98	98
-2 to -2.5	93	95	97	96	96	89	95	89
-2.5 to -3	93	98	97	96	93	82	97	86
-3 to -3.5	94	91	91	97	93	78	91	75
-3.5 to -4	97	99	99	98	93	74	86	86
-4 to -4.5	92	96	99	100	82	63	88	57
-4.5 to -5	85	85	86	87	75	66	87	57

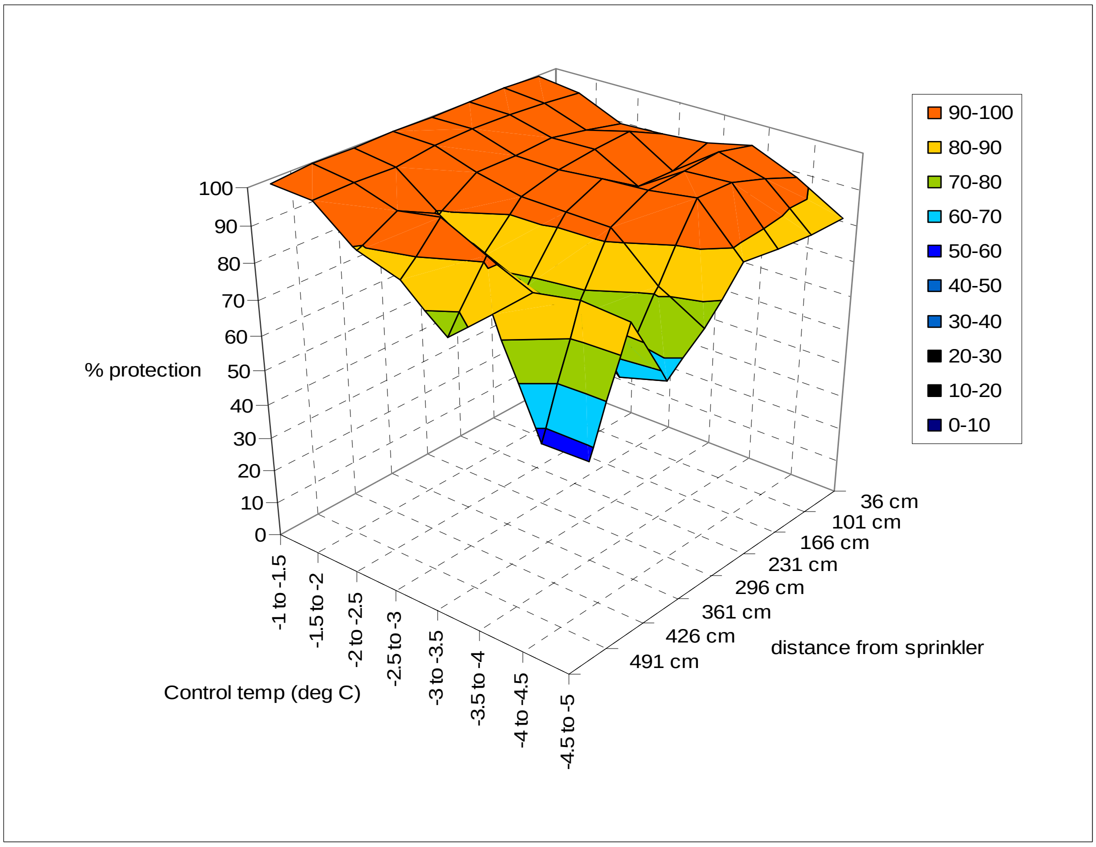

Figure 15. Mean level of protection (%) provided by NaanDan Flipper with black 35 l/hr nozzles spaced at 7.2m and 300 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.8 Targeted, 35 l/hr 250 kPa at 7.2 m

The targeted NaanDan Flipper with black 35 l/hr nozzles spaced at 7.2 m and operating at 250 kPa were sited in block 11, and data recorded on data logger 4.

Table 10. Values of mean level of protection (%) provided by NaanDan Flipper with black 35 l/hr nozzles spaced at 7.2 m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp (°C)	36 cm	101 cm	166 cm	231 cm	296 cm	361 cm	426 cm	491 cm
-1 to -1.5	100	100	100	100	100	100	100	100
-1.5 to -2	99	100	100	99	100	99	98	99
-2 to -2.5	94	95	93	94	96	92	94	98
-2.5 to -3	93	92	94	98	100	94	100	95
-3 to -3.5	86	89	89	92	100	95	92	86
-3.5 to -4	80	90	84	100	100	99	100	84
-4 to -4.5	75	75	90	96	100	97	100	75
-4.5 to -5	62	70	65	77	100	88	100	63

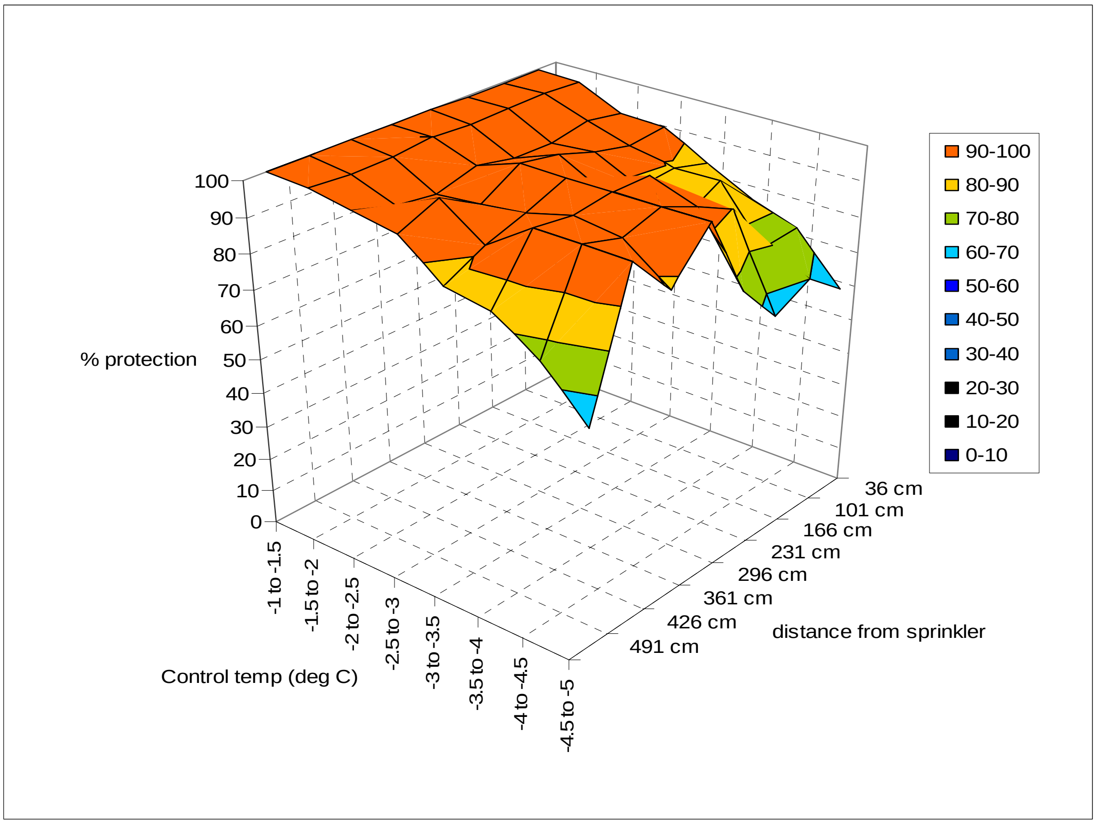

Figure 16. Mean level of protection (%) provided by NaanDan Flipper with black 35 l/hr nozzles spaced at 7.2m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

6.9 Targeted, 25 l/hr 250 kPa at 7.2 m

The targeted NaanDan Flipper with violet 25 l/hr nozzles spaced at 7.2 m and operating at 250 kPa were sited in block 8, and data recorded on data logger 3.

Table 11. Values of mean level of protection (%) provided by NaanDan Flipper with violet 25 l/hr nozzles spaced at 7.2 m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text).

Control temp (°C)	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	99	98	99	100	99	99	99	98
-1.5 to -2	95	94	95	97	94	96	98	95
-2 to -2.5	87	85	82	88	84	85	86	82
-2.5 to -3	80	74	69	88	85	90	94	78
-3 to -3.5	79	70	68	93	93	88	83	73
-3.5 to -4	80	63	59	93	100	93	86	74
-4 to -4.5	79	65	61	79	100	88	75	70
-4.5 to -5	72	55	52	80	100	87	75	65

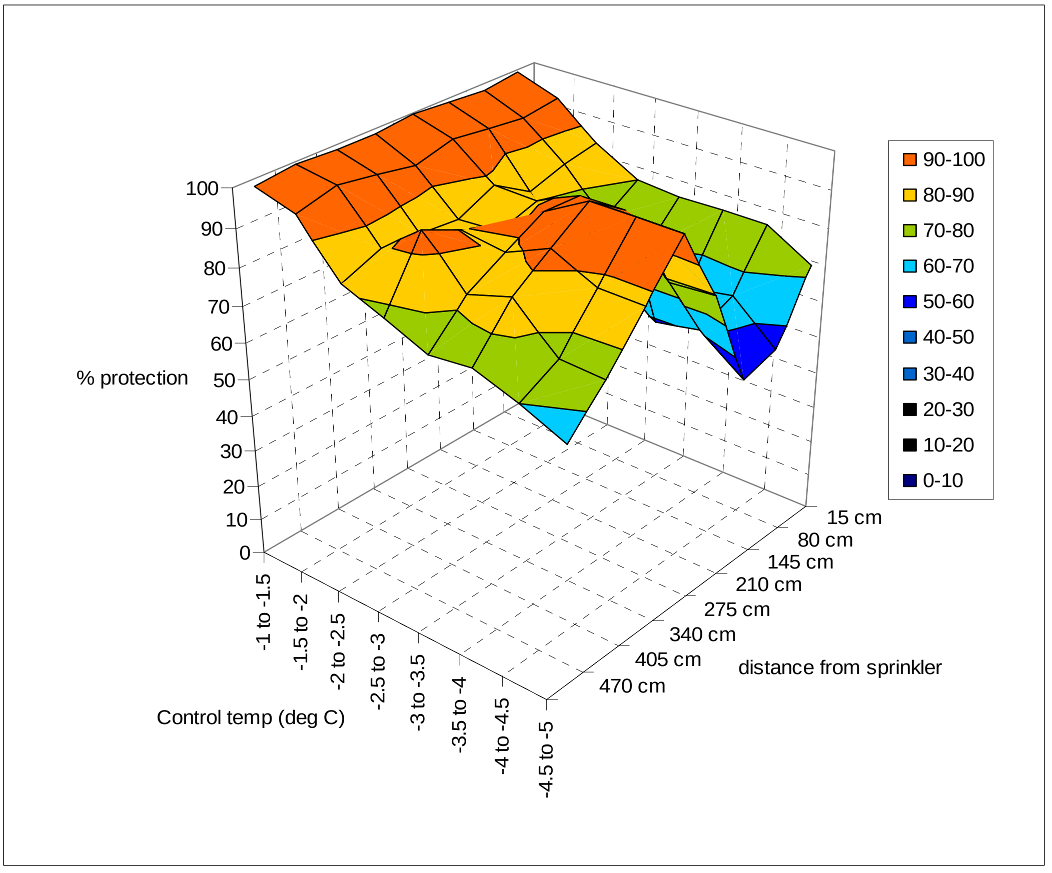

Figure 17. Mean level of protection (%) provided by NaanDan Flipper with violet 25 l/hr nozzles spaced at 7.2m and 250 kPa line pressure. Data analysis uses corrected control temperatures (see text)

7 DISCUSSION

To assist with comparison between different sprinkler types and configurations, estimates of the effective application depth and water use for each configuration is provided in Table 12. These data will be used below in discussing the merits and performance of each configuration

Table 12 Configuration of sprinklers and their resultant water use and effective application depth.

Sprinkler	Pressure (kPa)	Spacing (m)	Flow rate (l/hr)	Cover/sprinkler, m^2 (incl inter-row)	Rate, l/hr/m^2 (incl inter-row)	Est. rate (mm/hr)
SMamkad orange	300	13.2 x 9	490	118.8	4.1	4.1
SMamkad orange	350	13.2 x 9	529	118.8	4.5	4.5
501-U t'hammer	300	4.4 x 9	160	26.4	6.1	6.1
501-U t'hammer	300, 50%	4.4 x 9	80	26.4	3.0	3.0
Flipper, black	300	2.2 x 9	43	19.8	2.2	4.3
Flipper, black	250	2.2 x 9	39	19.8	2.0	3.9
Flipper, black	300	2.2 x 7.2	43	15.8	2.7	5.4
Flipper, black	250	2.2 x 7.2	39	15.8	2.5	4.9
Flipper, violet	250	2.2 x 7.2	28	15.8	1.8	3.5

Assumes half row spacing is covered

7.1 Full Cover, 300 kPa and 350 kPa on 13.2 by 9 m grid.

Both these sprinkler configurations use the NaanDan Super Mamkad sprinklers with orange 445 nozzle, and provide good frost protection and few instances where the temperature falls below the protection level of -1 ºC. A line pressure of 350 kPa pressure provided a little more protection at lower temperatures (**Figure 9** and **Figure 10**) than 300 kPa. Reference to Appendix C shows the orientation of the data logging booms with respect to the sprinkler patterns, and places the results in Sections **6.1** and **6.2** in context (the measurements are along a row between the sprinklers). Application from at least two and in some instances four sprinklers, means that water is applied to the vines from several directions, reducing the likelihood of interception by ice-laden spurs, branches or support wires, and this is supported by the quite uniform frost protection down to quite low temperatures. Good protection (>80%) is obtained for temperatures down to about -4 ºC at 300 kPa and -5 at 350 kPa for an application depth of around 4 mm/hr, but since they are full cover sprinklers, the water use is also quite high at around 4 l/hr/m^2.

There is a lack of protection at 53 cm and 300 kPa, and to some extent at 508 cm, and both are attributed to some shading. The 53 cm sensor in particular, is occluded from two sprinklers due to the angle of the sensor and partially due to the data logger box. The 340 cm sensor at 350 kPa is similarly occluded, causing poor protection at lower temperatures. These effects are typical of real conditions in vineyards where some buds get inadequate water and damage to those buds occurs. It is rather surprising that the small increase in water pressure and flow rate dramatically improves the performance of the Super Mamkad on a 13.2 by 9 m grid at low temperatures (below -4 ºC), but since the manufacturer's distribution pattern data is only available for one pressure, investigation into the likely reasons for this would require our own sprinkler tests. Nevertheless, performance of both configurations is sufficiently good that further investigation of the reasons for this is barely warranted.

In this configuration, the Super Mamkad sprinklers provided protection of approximately 1 ºC/mm/hr at 300 kPa, and approximately 1.1 ºC/mm/hr at 350 kPa.

7.2 Full Cover, 300 kPa on 4.4 by 9 m grid.

This configuration uses NaanDan Turbohammer sprinklers with green 160 l/hr nozzle and provides good frost protection (>80%) down to -4.5 ºC. Despite the higher application rate for this sprinkler configuration, the protection is inferior to that of the Super Mamkad at 350 kPa, although it is better than the Super Mamkad at 300 kPa. As would be expected for an application depth of around 6 mm/hr and water arriving from several sprinklers, protection is good along the monitored portion of the row, but fails below -4.5 ºC (**Figure 11**). Note (Appendix C) that there is no sprinkler at the logger end of the monitoring boom so the configuration is skewed, although this is not apparent from the level of protection (**Figure 11**).

The performance of the pulsed Turbohammer was a little worse than expected, only providing protection down to a mean level of -2 ºC. One of the better traces (Figure 18) suggest that -2.5 ºC is possible, yet at 3 l/hr/m2, the water consumption is only slightly less than the 4.1 l/hr/m^2 of the Super Mamkad on a 13.2 by 9 m grid, which provides protection down to -4 ºC. The results suggest that the 3 minutes on and 3 minutes off pulsing periods chosen for the trial should be reduced, since high resolution time-temperature plots show several instances of 1 ºC fall during the 3 minute off period, with quite slow recovery. Pulsing has proved successful from other trials (John et. al., 1987), so will be discussed further when additional data from 2 minute pulsing periods are available. Naturally, lower sprinkler efficiency due to additional time operating at reduced (transitional) line pressure and possible hydraulic issues mean that choosing the maximum time consistent with reasonable protection, is desirable.

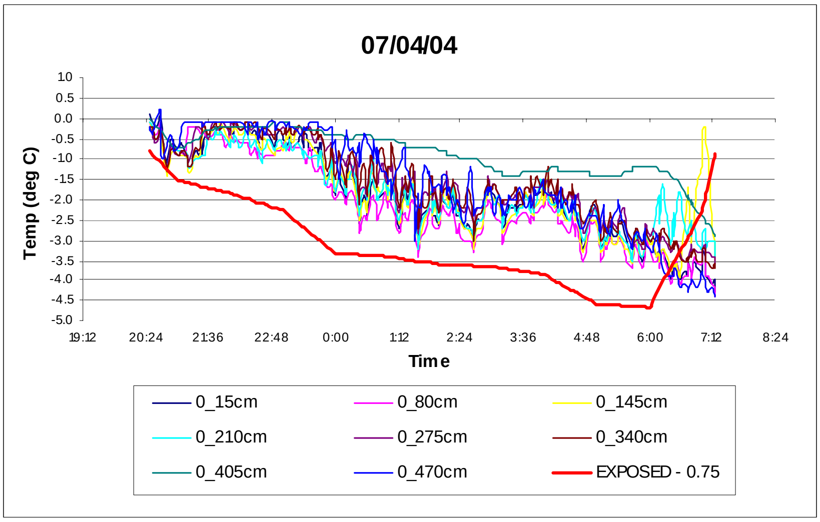

Figure 18 Plot of temperature from pulsed trial demonstrating protection down to approximately -2.5 ºC

In this configuration, the Turbohammer sprinklers provided protection of approximately 0.8 ºC/mm/hr at 300 kPa, and 0.7 ºC/mm/hr when pulsed. It is apparent that a strategy of pulsing until the temperature falls below -2.5 ºC would have resulted in considerable savings in water, especially for milder frosts. Future reports will analyse the likely savings throughout a frost-fighting season.

7.3 Targeted, 35 l/hr at 9 m spacing.

Targeted NaanDan Flipper sprinklers with black 35 l/hr nozzles operating at 250 kPa and 300 kPa at 9 m spacing provide an interesting comparison with the full cover sprinklers. Here the 300 kPa configuration only gave adequate protection down to -2 ºC, but the 250 kPa faired somewhat better, protecting to -2.5 ºC. We attribute the better performance at low pressure to a larger droplet size, a characteristic we have observed in previous trials. Since the effect was apparent along the whole span of the sprinkler throw, it appears not to be a trajectory factor but rather due to the size of the droplet alone. An overlap pattern for the Flipper (Figure 19) was generated from NaanDan data, but the depth information from the data was incorrect, so the scale is left uncalibrated. As would be expected, the shape of overlap pattern (Figure 19) resembles the extent of protection at -5 ºC (**Figure 14**).

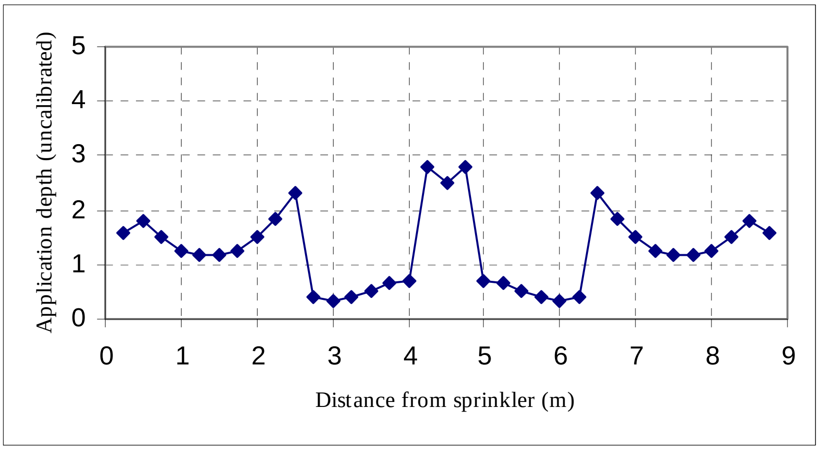

Figure 19 Overlap pattern of 35 l/hr Flipper operating at 250 kPa and spaced at 9 m, using distribution data from the NaanDan specifications.

Using an application width of 1.1 m, the 35 l/hr Flipper spaced at 9m provides protection of approximately 0.7 ºC/mm/hr and 1.3 ºC /l/hr/m^2 at 250 kPa and 0.5 ºC/mm and 0.9 ºC /l/hr/m^2 at 300 kPa.

The above results and the overlap pattern demonstrate that Flippers spaced at 9m provide inadequate frost protection, especially when considering that the quantity of water used (l/hr/m^2) is similar to the Super Mamkad configurations discussed in §7.1 that provide protection down to at least -4.5 ºC. There is evidence that air movement has slightly distorted the distribution pattern since the level of protection at 4.35 cm (**Figure 14**) is no better than at 45 cm, yet the application depth (Figure 19) is slightly greater there. However, the effect is rather small and firm conclusions cannot be formed yet. Note that the maximum recommended spacing issued by the manufacturer is 6 m.

Due to the poor level of sprinkler distribution data from the manufacturer, including a lack of information relating to wind distortion, some independent tests are being conducted to provide the missing information. NaanDan have also produced a new sway (flipper) for the sprinkler, and this will be tested in 2006.

7.4 Targeted, 35 l/hr at 7.2 m spacing.

Increasing the overlap from the 9 m spacing discussed in §7.3 to 7.2 m provided better frost protection. Targeted NaanDan Flipper sprinklers with black 35 l/hr nozzles operating at 300 kPa with 7.2 m spacing providing very good protection down to -5 ºC at up to 1.5 m from the sprinkler, but worsened for greater distances from the sprinkler.

Overall, the 300 kPa configuration only gave adequate protection down to -2 ºC, but the 250 kPa protected to -2.5 ºC. As for the results from the 9 m spacing, there are quite significant differences between performance at 250 and 300 kPa. In this case, the performance is only marginally better at 250 kPa than at 300 kPa, but is distinctly different and is much more closely aligned with the overlap pattern (Figure 20) which quite closely resembles the extent of protection at -5 ºC (**Figure 16**). The overlap pattern for the Flipper (Figure 20) was generated from NaanDan data, but the depth information from the data was incorrect, so the scale is left uncalibrated.

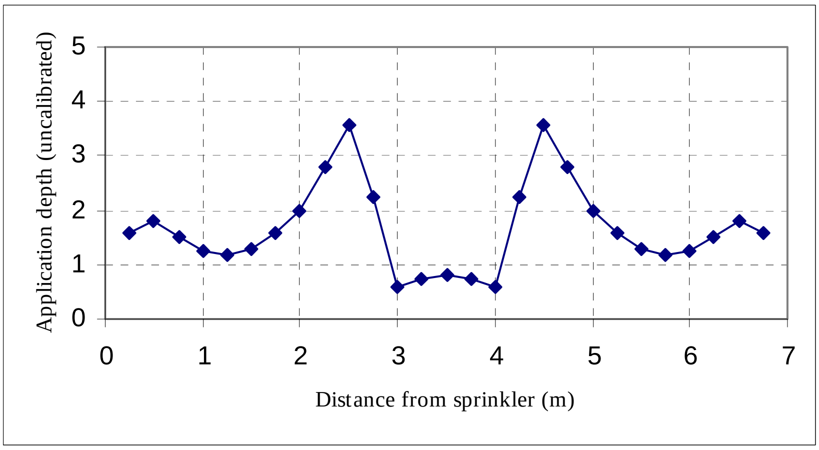

Figure 20 Overlap pattern of 35 l/hr Flipper operating at 250 kPa and spaced at 7 m, using distribution data from the NaanDan specifications.

Using an application width of 1.1 m, the 35 l/hr Flipper spaced at 7.2 m provides protection of approximately 0.6 ºC/mm/hr and 1 ºC /l/hr/m^2 at 250 kPa and 0.4 ºC/mm/hr and 0.7 ºC /l/hr/m^2 at 300 kPa,.

As for the 9 m configuration, there is a little evidence to support air movement distortion of the distribution pattern since the 4.9 m protection should then have been better than that indicated. Rather, the observed variability may be due to the smaller droplet size distribution than at 250 kPa coupled with some wind distortion. It will be necessary to obtain the distribution pattern for a line pressure of 300 kPa to further analyse these influences. These data are currently being obtained from independent testing, so firm conclusions cannot be formed yet.

7.5 Targeted, 25 l/hr at 7.2 m spacing.

Reducing the Flipper size to the violet 25 l/hr nozzle and retaining the 250 kPa line pressure and 7.2 m spacing also provided protection to -2.5 ºC. It is apparent that there is insufficient water to provide adequate protection, although interestingly, there is very good protection down to -5 ºC at 275 cm (**Figure 17**), approximately corresponding to the peak in application rate on the overlap pattern (Figure 21) at 2 m.

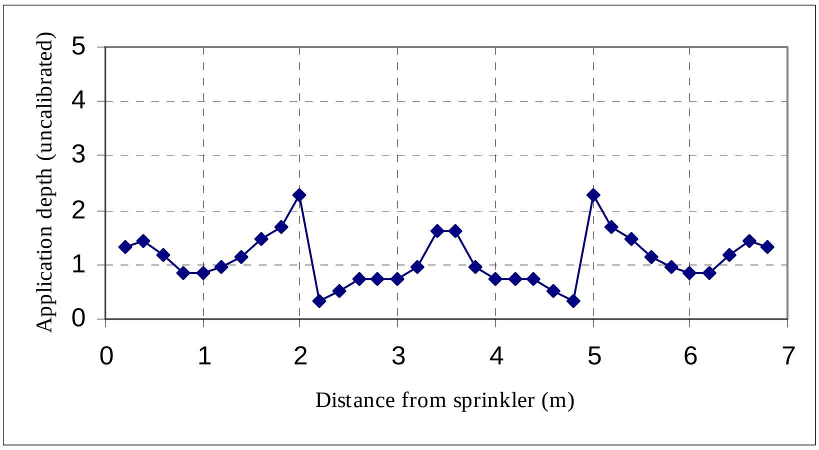

Figure 21 Overlap pattern of 25 l/hr Flipper operating at 250 kPa and spaced at 7 m, using distribution data from the NaanDan specifications.

Using an application width of 1.1 m, the 25 l/hr Flipper spaced at 7.2 m provides protection of approximately 0.8 ºC/mm/hr water at 250 kPa. This configuration also provided the best protection efficiency of 1.4 ºC /l/hr/m^2.

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APPENDIX A: DETAILED FROST PROTECTION DATA

The data in this appendix is, tabulated by protected temperature and time at temperature, the number of frost protection failure events. The frequencies are cumulative, so that a score in a particular temperature bin is also counted in bins of higher temperature.

Table 13. Super Mamkad 300 kPa with orange nozzle on 13.2 by 9 m grid. Shows number of protection failures classified by protected temperature and time at that temperature. Frequencies are cumulative, so a score at a particular temperature is also counted at higher temperatures.

2 min	53 cm	118 cm	183 cm	248 cm	313 cm	378 cm	443 cm	508 cm
-1 to -1.5	3	3	3	7	3	4	3	3
-1.5 to -2	3	2	2	4	2	3	2	2
-2 to -2.5	3	2	2	1	1	2	2	2
-2.5 to -3	3	1	2	1	1	1	1	2
-3 to -3.5	2	1	1	0	1	0	0	2
-3.5 to -4	1	0						0
-4 to -4.5								
-4.5 to -5								
4 min								
-1 to -1.5	4	4	5	8	3	5	3	4
-1.5 to -2	4	2	3	4	2	4	3	3
-2 to -2.5	4	3	2	2	1	3	2	3
-2.5 to -3	3	2	3	1	1	2	2	3
-3 to -3.5	2	1	1			1	0	2
-3.5 to -4	0	0						0
-4 to -4.5								
-4.5 to -5								
6 min								
-1 to -1.5	4	5	5	8	3	6	4	4
-1.5 to -2	5	3	3	4	3	4	3	4
-2 to -2.5	5	3	2	1	1	3	2	3
-2.5 to -3	4	3	3	1	2	2	2	3
-3 to -3.5	2	0	2			1	1	2
-3.5 to -4								1
-4 to -4.5								
-4.5 to -5								
8 min								
-1 to -1.5	5	5	5	7	3	6	4	4
-1.5 to -2	5	4	3	3	2	4	3	4
-2 to -2.5	5	4	2	1	1	3	2	4
-2.5 to -3	4	3	3	1	2	2	2	3
-3 to -3.5	2	0	1			1	0	2
-3.5 to -4								
-4 to -4.5								
-4.5 to -5								
10 min								
-1 to -1.5	4	5	5	8	3	5	5	4
-1.5 to -2	5	3	3	3	2	4	3	5
-2 to -2.5	4	4	3	1	1	3	2	4
-2.5 to -3	4	3	3	1	2	2	2	4
-3 to -3.5	2	1	1			1		3
-3.5 to -4								
-4 to -4.5								
-4.5 to -5								
14 min								
-1 to -1.5	5	4	4	8	3	6	5	4
-1.5 to -2	5	4	3	2	3	3	3	5
-2 to -2.5	5	4	3	1	2	2	2	4
-2.5 to -3	3	3	3	1	2	2	2	4
-3 to -3.5	2	1	1			1		3
-3.5 to -4								
-4 to -4.5								
-4.5 to -5								
20 min								
-1 to -1.5	4	3	4	5	3	5	5	4
-1.5 to -2	4	3	2	2	2	3	3	5
-2 to -2.5	4	4	3	1	2	2	2	4
-2.5 to -3	3	3	2	0	2	2	2	4
-3 to -3.5	1	1						3
-3.5 to -4								
-4 to -4.5								
-4.5 to -5								
> 20 min								
-1 to -1.5	3	3	4	4	2	3	4	4
-1.5 to -2	4	3	1	1	2	2	2	5
-2 to -2.5	4	4	2	1	2	2	2	4
-2.5 to -3	3	2	2	1	1	1	1	4
-3 to -3.5	1							
-3.5 to -4								

Table 14. Super Mamkad 350 kPa with orange nozzle on 13.2 by 9 m grid. The data are the number of protection failures classified by protected temperature and time at that temperature. The frequencies are cumulative, so that a score in a particular temperature bin is also counted in bins of higher temperature.

2 min	15 cm	80 cm	145 cm	210 cm	275 cm	340 cm	405 cm	470 cm
-1 to -1.5	2	2	2	1	1	2	0	1
-1.5 to -2	2	1	0	1	0	2	0	0
-2 to -2.5	1	0	0	0	0	1		1
-2.5 to -3	0	0		0	0	1		0
-3 to -3.5	0			0		0		
-3.5 to -4						0		
-4 to -4.5								
-4.5 to -5								
4 min								
-1 to -1.5	4	2	2	1	1	3	0	1
-1.5 to -2	2	1	1	1	0	2	0	0
-2 to -2.5	1	1	0	0	0	1		1
-2.5 to -3	0	0		0	0	1		0
-3 to -3.5	0			0		0		
-3.5 to -4						0		
-4 to -4.5								
-4.5 to -5								
6 min								
-1 to -1.5	4	3	2	1	2	3	0	1
-1.5 to -2	2	1	0	1	0	3	0	0
-2 to -2.5	2	1	0	1	0	2		1
-2.5 to -3	0	0		0	0	1		0
-3 to -3.5	0			0		1		
-3.5 to -4						1		
-4 to -4.5								
-4.5 to -5								
8 min								
-1 to -1.5	3	3	2	1	1	3	0	1
-1.5 to -2	2	1	0	1	0	3	0	1
-2 to -2.5	2	1	0	1	0	2		1
-2.5 to -3	0	0		0	0	1		
-3 to -3.5				0		0		
-3.5 to -4						1		
-4 to -4.5								
-4.5 to -5								
10 min								
-1 to -1.5	3	3	2	2	1	3	0	1
-1.5 to -2	2	2	0	1	0	3	0	1
-2 to -2.5	1	1		1	0	2		1
-2.5 to -3	0	0		0	0	1		
-3 to -3.5				1		1		
-3.5 to -4						1		
-4 to -4.5								
-4.5 to -5								
14 min								
-1 to -1.5	3	3	2	2	1	3	0	2
-1.5 to -2	2	2	0	1	1	3		1
-2 to -2.5	1	1		1	1	2		1
-2.5 to -3	0	0		0	0	0		
-3 to -3.5						1		
-3.5 to -4						1		
-4 to -4.5								
-4.5 to -5								
20 min								
-1 to -1.5	3	2	1	1	1	3	1	1
-1.5 to -2	2	1	0	1	1	3		1
-2 to -2.5	1	0		1	1	2		1
-2.5 to -3		0		0	0	0		
-3 to -3.5						1		
-3.5 to -4								
-4 to -4.5								
-4.5 to -5								
> 20 min								
-1 to -1.5	3	1	0	1	0	3	1	1
-1.5 to -2	1	1	0	1	0	2		1
-2 to -2.5	1	0		0	1	1		1
-2.5 to -3		1				1		
-3 to -3.5						1		
-3.5 to -4								
-4 to -4.5								
-4.5 to -5								

Table 15. Turbohammer with green 160 l/hr nozzle at 300kPa on 4.4 by 9 m grid. The data are the number of protection failures classified by protected temperature and time at that temperature. The frequencies are cumulative, so that a score in a particular temperature bin is also counted in bins of higher temperature.

2 min	45 cm	110 cm	175 cm	240 cm	305 cm	370 cm	435 cm	500 cm
-1 to -1.5	1	2	2	2	2	2	0	1
-1.5 to -2	1	1	1	1	1	1		2
-2 to -2.5	1	1	1	1	1	1		1
-2.5 to -3	1	1	0	0	0	0		1
-3 to -3.5	1	0	0	0	0			1
-3.5 to -4	0							0
-4 to -4.5	0							
-4.5 to -5								
4 min								
-1 to -1.5	2	2	4	3	2	2	0	2
-1.5 to -2	2	2	2	1	1	1		2
-2 to -2.5	1	2	1	2	1	1		1
-2.5 to -3	2	1	0	0	0	1		1
-3 to -3.5	1	0	0	0	0			1
-3.5 to -4	0							0
-4 to -4.5								
-4.5 to -5								
6 min								
-1 to -1.5	2	3	4	3	3	3	0	3
-1.5 to -2	3	2	2	1	1	1		3
-2 to -2.5	1	2	1	2	1	1		1
-2.5 to -3	2	1	0	1	0	0		2
-3 to -3.5	2	0	0	0	0			2
-3.5 to -4	1							1
-4 to -4.5								
-4.5 to -5								
8 min								
-1 to -1.5	2	3	4	3	3	3	0	3
-1.5 to -2	3	2	2	1	2	2		3
-2 to -2.5	2	2	1	1	1	1		2
-2.5 to -3	2	1	1	1	1	1		3
-3 to -3.5	2	0	0	0	0			2
-3.5 to -4	1							1
-4 to -4.5								
-4.5 to -5								
10 min								
-1 to -1.5	3	3	5	3	3	3	0	3
-1.5 to -2	3	2	2	2	2	2		3
-2 to -2.5	2	2	1	1	1	1		2
-2.5 to -3	2	1	1	0	1	1		3
-3 to -3.5	1	1	1	1	1			2
-3.5 to -4	1							
-4 to -4.5								
-4.5 to -5								
14 min								
-1 to -1.5	3	3	5	3	2	3	0	4
-1.5 to -2	4	3	2	2	2	2		3
-2 to -2.5	2	2	1	1	2	1		2
-2.5 to -3	2	2	1	0	1	0		4
-3 to -3.5	1	1	1		1			1
-3.5 to -4								
-4 to -4.5								
-4.5 to -5								
20 min								
-1 to -1.5	3	3	4	3	2	3	0	3
-1.5 to -2	3	3	2	2	2	2		3
-2 to -2.5	2	2	1	1	2	1		1
-2.5 to -3	2	1	1	0	1	0		3
-3 to -3.5	1		1		1			1
-3.5 to -4								
-4 to -4.5								
-4.5 to -5								
> 20 min								
-1 to -1.5	3	2	3	2	2	2	0	3
-1.5 to -2	2	3	2	1	2	1		3
-2 to -2.5	2	2	0	1	1	0		1
-2.5 to -3	1	1	1	1	1			3
-3 to -3.5	1							1
-3.5 to -4								
-4 to -4.5								
-4.5 to -5								

Table 16. Pulsed turbohammer with green 160 l/hr nozzle at 300kPa on 4.4 by 9 m grid. The data are the number of protection failures classified by protected temperature and time at that temperature. The frequencies are cumulative, so that a score in a particular temperature bin is also counted in bins of higher temperature.

2 min	45 cm	110 cm	175 cm	240 cm	305 cm	370 cm	435 cm	500 cm
-1 to -1.5	4	4	4	5	3	4	0	4
-1.5 to -2	4	3	4	5	4	6	0	4
-2 to -2.5	7	5	6	7	5	6	0	4
-2.5 to -3	4	5	4	5	4	3	1	3
-3 to -3.5	4	5	4	5	3	3	1	3
-3.5 to -4	4	5	4	2	2	3	1	2
-4 to -4.5	5	5	3	2	1	2	1	3
-4.5 to -5	3	4	3	2	2	2	0	1
4 min								
-1 to -1.5	5	5	5	6	5	6	1	5
-1.5 to -2	6	5	6	8	5	7	1	6
-2 to -2.5	9	7	8	8	5	6	1	4
-2.5 to -3	6	7	5	6	4	4	2	4
-3 to -3.5	5	7	6	6	5	4	2	3
-3.5 to -4	5	8	6	2	3	4	1	4
-4 to -4.5	7	6	5	3	2	3	2	6
-4.5 to -5	6	7	5	3	3	3	1	2
6 min								
-1 to -1.5	5	6	6	7	5	6	1	5
-1.5 to -2	6	5	6	8	6	6	1	5
-2 to -2.5	9	8	9	8	4	6	1	4
-2.5 to -3	6	10	6	6	4	4	2	4
-3 to -3.5	4	9	6	6	4	3	2	3
-3.5 to -4	6	11	6	3	4	5	2	5
-4 to -4.5	8	8	7	2	3	5	3	7
-4.5 to -5	3	3	3	3	1	1	1	1
8 min								
-1 to -1.5	6	7	7	8	6	7	2	6
-1.5 to -2	8	6	8	9	7	8	2	6
-2 to -2.5	9	9	10	10	5	7	2	5
-2.5 to -3	6	10	7	7	4	5	3	4
-3 to -3.5	5	9	7	5	5	4	3	3
-3.5 to -4	6	11	6	4	5	6	3	6
-4 to -4.5	9	7	7	2	2	6	4	9
-4.5 to -5	2	4	4			2	2	2
10 min								
-1 to -1.5	7	7	7	8	7	8	2	6
-1.5 to -2	9	7	8	10	8	9	2	7
-2 to -2.5	9	9	9	11	5	7	2	5
-2.5 to -3	7	10	7	7	5	6	4	3
-3 to -3.5	5	8	7	6	5	5	4	4
-3.5 to -4	7	12	7	4	6	6	4	6
-4 to -4.5	8	8	6	3	3	5	5	11
-4.5 to -5	2	2	5			2	2	2
14 min								
-1 to -1.5	6	8	8	9	7	7	2	6
-1.5 to -2	8	7	9	9	8	8	3	7
-2 to -2.5	8	10	7	10	6	7	2	4
-2.5 to -3	6	11	7	6	4	5	4	3
-3 to -3.5	5	6	7	5	6	5	5	4
-3.5 to -4	7	12	7	3	4	7	4	6
-4 to -4.5	7	7	7	4	4	4	6	11
-4.5 to -5	3	3	6			3	3	3
20 min								
-1 to -1.5	5	7	7	8	6	8	3	6
-1.5 to -2	9	7	9	9	8	8	3	6
-2 to -2.5	7	9	7	8	5	6	3	4
-2.5 to -3	5	9	7	5	4	5	5	3
-3 to -3.5	6	6	6	6	5	6	6	4
-3.5 to -4	9	11	5	2	5	7	5	6
-4 to -4.5	4	4	4	4	4	2	7	9
-4.5 to -5	3	3	3				3	3
> 20 min								
-1 to -1.5	4	6	6	7	6	6	3	5
-1.5 to -2	7	7	9	9	8	8	3	5
-2 to -2.5	7	8	7	7	5	5	3	2
-2.5 to -3	5	6	6	5	3	4	6	3
-3 to -3.5	6	7	7	6	3	6	7	3
-3.5 to -4	9	7	3	3	6	6	6	7
-4 to -4.5	2	5	5	5	2	2	7	5
-4.5 to -5							4	

Table 17. Targeted flipper with black 35 l/hr nozzle at 300kPa at 9 m spacing. The data are the number of protection failures classified by protected temperature and time at that temperature. The frequencies are cumulative, so that a score in a particular temperature bin is also counted in bins of higher temperature.

2 min	36 cm	101 cm	166 cm	231 cm	296 cm	361 cm	426 cm	491 cm
-1 to -1.5	3	5	4	4	4	5	3	3
-1.5 to -2	3	4	3	4	4	5	3	3
-2 to -2.5	4	4	4	4	6	6	4	3
-2.5 to -3	5	6	5	5	5	7	4	3
-3 to -3.5	5	6	6	6	6	7	3	3
-3.5 to -4	5	7	7	7	6	7	4	4
-4 to -4.5	6	9	11	11	10	9	4	2
-4.5 to -5	1	4	8	6	6	8		
4 min								
-1 to -1.5	5	6	5	6	6	7	5	4
-1.5 to -2	4	5	5	6	6	8	4	4
-2 to -2.5	6	6	5	6	8	8	6	4
-2.5 to -3	6	9	8	8	7	12	5	4
-3 to -3.5	7	7	8	8	9	10	5	5
-3.5 to -4	8	11	11	11	9	11	7	6
-4 to -4.5	9	13	15	17	16	12	4	2
-4.5 to -5	2	4	8	6	6	11		
6 min								
-1 to -1.5	6	7	4	7	7	9	6	5
-1.5 to -2	6	6	5	7	6	9	6	5
-2 to -2.5	7	8	7	8	9	11	7	5
-2.5 to -3	7	9	8	9	8	13	6	4
-3 to -3.5	7	8	9	8	8	12	5	5
-3.5 to -4	9	11	12	13	11	12	9	6
-4 to -4.5	7	13	15	16	17	12	6	3
-4.5 to -5	1	3	3	4	6	9		
8 min								
-1 to -1.5	7	7	4	7	7	10	7	5
-1.5 to -2	5	7	6	8	7	9	7	6
-2 to -2.5	8	8	8	10	10	12	8	6
-2.5 to -3	8	11	10	10	8	14	6	4
-3 to -3.5	7	8	9	8	9	12	7	7
-3.5 to -4	9	11	14	11	11	15	7	6
-4 to -4.5	5	12	16	20	19	12	6	2
-4.5 to -5	2	2	2	4	6	6		
10 min								
-1 to -1.5	6	6	5	7	7	10	7	5
-1.5 to -2	6	7	6	8	8	11	8	6
-2 to -2.5	9	9	9	11	10	13	8	6
-2.5 to -3	8	12	11	11	9	14	6	5
-3 to -3.5	7	10	10	9	10	11	9	7
-3.5 to -4	9	12	11	12	10	13	9	6
-4 to -4.5	2	6	11	17	17	14	5	3
-4.5 to -5		2	2	2	2	5		
14 min								
-1 to -1.5	6	7	5	7	8	12	8	6
-1.5 to -2	7	7	6	8	9	11	9	6
-2 to -2.5	9	9	9	11	11	15	8	6
-2.5 to -3	9	12	11	12	9	16	7	6
-3 to -3.5	9	9	11	10	9	13	9	7
-3.5 to -4	7	12	13	10	7	15	11	5
-4 to -4.5	2	7	11	15	17	13	6	4
-4.5 to -5			3	3	3			
20 min								
-1 to -1.5	5	5	4	7	8	12	8	6
-1.5 to -2	7	6	5	7	9	11	9	6
-2 to -2.5	8	9	7	9	10	14	9	6
-2.5 to -3	7	10	10	10	9	15	7	5
-3 to -3.5	8	7	7	8	6	13	8	6
-3.5 to -4	6	10	11	9	7	14	10	2
-4 to -4.5	2	7	7	9	13	11	4	4
-4.5 to -5				3	3			
> 20 min								
-1 to -1.5	5	5	4	6	7	10	7	5
-1.5 to -2	6	6	4	6	7	9	8	5
-2 to -2.5	7	8	6	9	8	13	8	5
-2.5 to -3	6	9	8	8	8	12	7	4
-3 to -3.5	5	7	6	7	6	9	7	4
-3.5 to -4	4	9	9	10	7	11	7	3
-4 to -4.5		5	5	2	7	5	5	
-4.5 to -5								

Table 18. Targeted flipper with black 35 l/hr nozzle at 250 kPa at 9 m spacing. The data are the number of protection failures classified by protected temperature and time at that temperature. The frequencies are cumulative, so that a score in a particular temperature bin is also counted in bins of higher temperature.

2 min	45 cm	110 cm	175 cm	240 cm	305 cm	370 cm	435 cm	500 cm
-1 to -1.5	2	2	3	3	3	2	1	2
-1.5 to -2	2	2	2	2	3	2	0	2
-2 to -2.5	2	1	2	2	3	2	0	1
-2.5 to -3	1	2	2	2	2	2	0	1
-3 to -3.5	0	1	2	3	2	2	0	1
-3.5 to -4	1	1	1	1	1	1	0	1
-4 to -4.5	0	0	0	1	1	0		0
-4.5 to -5			0	0				
4 min								
-1 to -1.5	2	3	4	5	5	3	1	3
-1.5 to -2	3	3	4	4	5	3	0	3
-2 to -2.5	3	2	3	3	4	3	0	2
-2.5 to -3	1	3	3	4	3	2	0	1
-3 to -3.5	0	2	3	4	2	3	0	2
-3.5 to -4	1	1	1	2	2	1	0	1
-4 to -4.5	1	1	1	1	1	1		1
-4.5 to -5								
6 min								
-1 to -1.5	3	3	5	5	6	4	2	3
-1.5 to -2	4	3	4	5	6	4	1	4
-2 to -2.5	4	2	4	4	5	3	0	3
-2.5 to -3	2	3	4	4	4	3	1	2
-3 to -3.5	1	2	4	4	3	3	0	2
-3.5 to -4	1	2	1	2	3	1	1	2
-4 to -4.5	1	1	1	1	1	1		1
-4.5 to -5								
8 min								
-1 to -1.5	3	4	6	6	7	5	2	4
-1.5 to -2	4	3	5	5	6	4	1	4
-2 to -2.5	4	3	4	4	5	4	1	3
-2.5 to -3	2	4	4	5	4	3	1	2
-3 to -3.5	1	2	4	4	4	5	0	2
-3.5 to -4	1	1	1	2	3	1	1	1
-4 to -4.5	1	1	1	1	1	1		1
-4.5 to -5								
10 min								
-1 to -1.5	4	4	6	7	7	5	3	4
-1.5 to -2	5	3	5	5	7	5	1	4
-2 to -2.5	4	3	4	5	5	5	1	4
-2.5 to -3	2	4	5	6	4	4	1	3
-3 to -3.5	1	2	4	4	4	4	1	2
-3.5 to -4	1	2	2	2	4	2	1	2
-4 to -4.5		2	2	2	2	2		2
-4.5 to -5								
14 min								
-1 to -1.5	4	4	6	8	7	5	3	5
-1.5 to -2	5	3	5	5	7	5	1	5
-2 to -2.5	4	4	5	6	5	4	1	4
-2.5 to -3	2	4	5	5	5	4	1	3
-3 to -3.5	1	2	4	4	5	4	1	2
-3.5 to -4	1	2	2	2	4	2	1	2
-4 to -4.5		2	2	2	2	2		2
-4.5 to -5								
20 min								
-1 to -1.5	4	4	5	6	7	4	4	5
-1.5 to -2	5	3	6	5	7	5	1	4
-2 to -2.5	3	4	5	6	5	3	1	4
-2.5 to -3	2	3	5	5	4	4	1	3
-3 to -3.5	1	1	4	4	5	3	1	2
-3.5 to -4	1	2	2	2	5	2	1	2
-4 to -4.5			2	2	2	2		
-4.5 to -5								
> 20 min								
-1 to -1.5	4	4	5	6	7	4	4	5
-1.5 to -2	5	3	5	5	7	4	1	5
-2 to -2.5	2	3	5	5	4	2	1	3
-2.5 to -3	2	3	5	5	4	3	2	2
-3 to -3.5	2	1	2	3	4	2	1	2
-3.5 to -4	1	3	3	3	3	3	1	1
-4 to -4.5								
-4.5 to -5								

Table 19. Targeted flipper with black 35 l/hr nozzle at 300 kPa at 7.2 m spacing. The data are the number of protection failures classified by protected temperature and time at that temperature. The frequencies are cumulative, so that a score in a particular temperature bin is also counted in bins of higher temperature.

2 min	36 cm	101 cm	166 cm	231 cm	296 cm	361 cm	426 cm	491 cm
-1 to -1.5	3	3	2	2	3	4	1	4
-1.5 to -2	2	2	2	2	2	4	0	3
-2 to -2.5	2	1	1	1	3	4	0	3
-2.5 to -3	2	1	1	1	2	3	0	2
-3 to -3.5	1	0	0	1	2	3		3
-3.5 to -4	1	1	0	1	1	6		3
-4 to -4.5	0			0	1	2		2
-4.5 to -5						0		0
4 min								
-1 to -1.5	4	5	3	3	4	5	1	6
-1.5 to -2	4	3	2	2	3	5	1	5
-2 to -2.5	3	2	1	1	4	6	0	4
-2.5 to -3	3	1	1	2	3	5	0	3
-3 to -3.5	2	1	0	1	3	6		4
-3.5 to -4	2	1	1	1	2	9		5
-4 to -4.5	1			1	1	2		4
-4.5 to -5								
6 min								
-1 to -1.5	6	5	4	4	5	7	2	8
-1.5 to -2	4	3	2	3	4	7	1	6
-2 to -2.5	4	3	2	2	4	8	1	5
-2.5 to -3	4	1	1	2	4	6	0	4
-3 to -3.5	2	1	1	1	4	7		5
-3.5 to -4	2	1	1	1	1	5		7
-4 to -4.5	1			1	1	2		4
-4.5 to -5								
8 min								
-1 to -1.5	6	5	4	4	5	8	2	8
-1.5 to -2	5	3	3	3	5	8	2	6
-2 to -2.5	4	2	1	2	5	8	1	6
-2.5 to -3	3	1	1	2	4	7	0	5
-3 to -3.5	2	1	1	1	4	7		7
-3.5 to -4	1	1	1	1	1	6		8
-4 to -4.5	1				1	2		2
-4.5 to -5								
10 min								
-1 to -1.5	6	5	5	4	5	8	3	9
-1.5 to -2	5	3	3	3	5	8	2	7
-2 to -2.5	5	2	2	2	5	8	1	7
-2.5 to -3	3	1	1	1	4	8	0	5
-3 to -3.5	2	1	1	1	4	7		8
-3.5 to -4	2	1	1	2	2	6		8
-4 to -4.5	2					3		3
-4.5 to -5								
14 min								
-1 to -1.5	7	4	5	5	6	8	3	9
-1.5 to -2	5	3	3	3	5	9	3	7
-2 to -2.5	5	2	2	2	4	9	1	7
-2.5 to -3	2	1	0	2	3	8	0	6
-3 to -3.5	2	1	1	1	2	7		7
-3.5 to -4	2	1	1	1	2	5		10
-4 to -4.5						2		4
-4.5 to -5								
20 min								
-1 to -1.5	5	4	4	4	5	7	3	9
-1.5 to -2	4	2	2	2	4	9	3	6
-2 to -2.5	4	2	1	2	3	8	1	8
-2.5 to -3	2	0	0	1	3	6	0	6
-3 to -3.5	1	1	1	1	2	6		7
-3.5 to -4	2	1	1	1	2	5		9
-4 to -4.5								4
-4.5 to -5								
> 20 min								
-1 to -1.5	4	3	2	3	4	8	4	8
-1.5 to -2	3	1	2	2	3	7	3	6
-2 to -2.5	3	2	1	2	3	7	1	6
-2.5 to -3	2	1	1	2	3	5	1	5
-3 to -3.5	2	2	2	2	2	5		4
-3.5 to -4	3			1	3	3		6
-4 to -4.5								5
-4.5 to -5								

Table 20. Targeted flipper with black 35 l/hr nozzle at 250 kPa at 7.2 m spacing. The data are the number of protection failures classified by protected temperature and time at that temperature. The frequencies are cumulative, so that a score in a particular temperature bin is also counted in bins of higher temperature.

2 min	36 cm	101 cm	166 cm	231 cm	296 cm	361 cm	426 cm	491 cm
-1 to -1.5	1	1	1	1	0	2	0	1
-1.5 to -2	1	1	1	1	0	1	0	1
-2 to -2.5	1	1	1	1	0	1		1
-2.5 to -3	2	1	1	1	0	1		2
-3 to -3.5	1	1	1	1	0	1		1
-3.5 to -4	1	1	0	0		0		1
-4 to -4.5	0	1	1					
-4.5 to -5								
4 min								
-1 to -1.5	2	2	2	2	0	2	0	1
-1.5 to -2	2	2	2	1	0	2	0	2
-2 to -2.5	2	2	1	1	0	2		2
-2.5 to -3	2	2	2	1	0	1		3
-3 to -3.5	2	1	2	1	0	2		2
-3.5 to -4	1	2	1	1		0		1
-4 to -4.5		1	1					
-4.5 to -5								
6 min								
-1 to -1.5	2	2	2	2	1	3	0	2
-1.5 to -2	3	2	2	2	0	3	0	2
-2 to -2.5	3	3	2	2	0	3		2
-2.5 to -3	2	3	2	1	0	1		3
-3 to -3.5	2	2	3	1	0	1		3
-3.5 to -4	2	2	1	1				2
-4 to -4.5		2	1					
-4.5 to -5								
8 min								
-1 to -1.5	2	3	2	2	1	4	0	2
-1.5 to -2	3	2	2	2	0	3	0	3
-2 to -2.5	3	3	2	2	0	3		2
-2.5 to -3	3	3	3	1	0	1		3
-3 to -3.5	2	2	3	2		1		4
-3.5 to -4	2	3	1	1				2
-4 to -4.5		2	1					
-4.5 to -5								
10 min								
-1 to -1.5	2	3	3	3	0	4	0	2
-1.5 to -2	3	3	3	2	0	4	0	3
-2 to -2.5	4	4	2	2	0	3		2
-2.5 to -3	3	3	3	1	0	1		3
-3 to -3.5	3	3	4	2		1		4
-3.5 to -4	3	3	1	1				2
-4 to -4.5		3	2					
-4.5 to -5								
14 min								
-1 to -1.5	2	3	3	2	1	4	0	2
-1.5 to -2	4	3	3	2	0	4	0	3
-2 to -2.5	3	4	3	2	0	3		3
-2.5 to -3	3	3	4	1	0	2		3
-3 to -3.5	2	3	5	1		1		4
-3.5 to -4	3	2	1	1				2
-4 to -4.5		4						
-4.5 to -5								
20 min								
-1 to -1.5	2	3	3	3	1	4	0	2
-1.5 to -2	3	3	3	2	0	4	0	3
-2 to -2.5	3	4	2	2	0	2		3
-2.5 to -3	2	3	3	1		1		3
-3 to -3.5	3	2	4	1		1		3
-3.5 to -4	2	2	1	1				2
-4 to -4.5		2						
-4.5 to -5								
> 20 min								
-1 to -1.5	2	3	2	2	0	3	0	2
-1.5 to -2	3	3	2	2	0	2	0	2
-2 to -2.5	3	3	2	2		2		2
-2.5 to -3	2	3	2	1		1		4
-3 to -3.5	2	2	2	2		1		2
-3.5 to -4	3	1	1					1
-4 to -4.5								
-4.5 to -5								

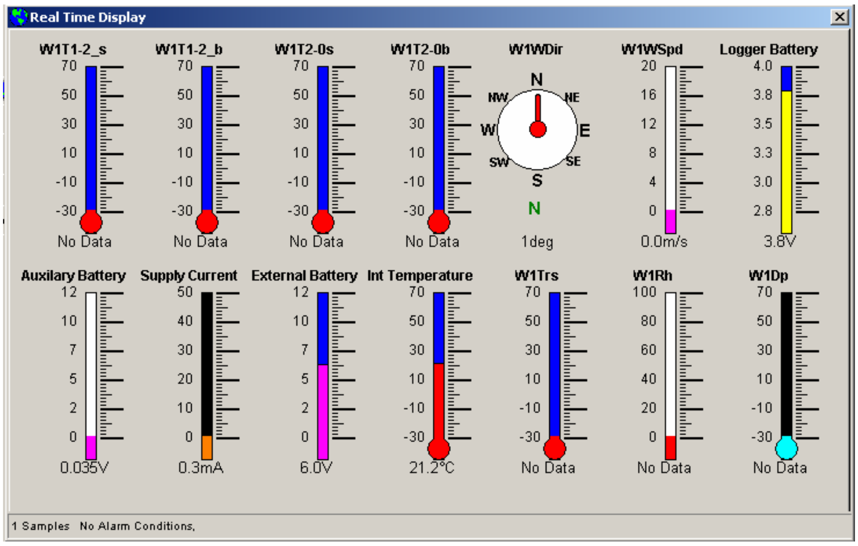
Table 21. Targeted flipper with violet 25 l/hr nozzle at 250 kPa at 7.2 m spacing. The data are the number of protection failures classified by protected temperature and time at that temperature. The frequencies are cumulative, so that a score in a particular temperature bin is also counted in bins of higher temperature.

2 min	36 cm	101 cm	166 cm	231 cm	296 cm	361 cm	426 cm	491 cm
-1 to -1.5	3	3	3	2	1	1	0	2
-1.5 to -2	2	2	2	2	0	0	0	2
-2 to -2.5	3	2	2	2	0	0	0	3
-2.5 to -3	2	3	3	2		0	0	3
-3 to -3.5	1	3	2	2			0	2
-3.5 to -4	1	2	3	0			0	1
-4 to -4.5	2	2	4	1				1
-4.5 to -5		0	1					
4 min								
-1 to -1.5	4	4	4	3	1	1	1	3
-1.5 to -2	3	3	4	3	0	1	1	3
-2 to -2.5	4	4	3	4	0	0	1	4
-2.5 to -3	3	4	4	3		0	1	4
-3 to -3.5	1	4	4	2			0	3
-3.5 to -4	2	4	5	0			1	2
-4 to -4.5	2	2	6	1				1
-4.5 to -5			2					
6 min								
-1 to -1.5	4	5	5	4	1	2	1	4
-1.5 to -2	3	4	4	3	0	1	1	3
-2 to -2.5	4	4	3	4	1	0	1	5
-2.5 to -3	3	5	4	3			1	4
-3 to -3.5	1	5	5	2			1	4
-3.5 to -4	2	5	6	1			1	2
-4 to -4.5	3	3	4	1				1
-4.5 to -5								
8 min								
-1 to -1.5	5	5	6	4	2	2	2	4
-1.5 to -2	4	5	4	3	0	1	1	4
-2 to -2.5	5	4	4	4	1	0	1	5
-2.5 to -3	4	5	5	3			1	5
-3 to -3.5	2	6	6	2			1	4
-3.5 to -4	3	5	7	1			1	1
-4 to -4.5	1	4	5	1				1
-4.5 to -5								
10 min								
-1 to -1.5	5	6	6	4	2	2	2	4
-1.5 to -2	4	5	5	4	0	1	2	4
-2 to -2.5	6	5	4	4	1	0	2	5
-2.5 to -3	4	6	6	3			1	5
-3 to -3.5	2	6	5	2			1	5
-3.5 to -4	2	5	9	1			2	2
-4 to -4.5		3	6					
-4.5 to -5								
14 min								
-1 to -1.5	6	6	7	4	1	2	3	4
-1.5 to -2	5	5	4	4	1	1	2	5
-2 to -2.5	6	5	4	4	1	0	2	6
-2.5 to -3	4	5	6	3			2	5
-3 to -3.5	2	6	5	1			1	5
-3.5 to -4	2	5	9	1			2	2
-4 to -4.5		2	6					
-4.5 to -5								
20 min								
-1 to -1.5	5	5	6	4	1	2	3	4
-1.5 to -2	5	5	5	4	0	1	2	4
-2 to -2.5	5	5	4	3	0	0	2	5
-2.5 to -3	4	5	5	2			1	5
-3 to -3.5	2	4	4	1			1	2
-3.5 to -4	2	6	7	1			2	2
-4 to -4.5		2	4					
-4.5 to -5								
> 20 min								
-1 to -1.5	4	5	6	3	1	2	4	4
-1.5 to -2	4	5	4	3	0	1	2	4
-2 to -2.5	5	5	4	2		0	2	5
-2.5 to -3	3	5	5	2			1	4
-3 to -3.5	2	5	5	1			2	2
-3.5 to -4	1	3	7	1			3	3
-4 to -4.5			2					
-4.5 to -5								

APPENDIX B: INSTRUMENTATION DETAILS

This appendix provides brief notes detailing the instrumentation in the 2004 frost monitoring season.

Weather Station 1, GPMC S/N: 0309503



Analogue Channel		Wiring
1	1.2m temp screen	15k 0.1% R
2	1.2m temp bulb	-
3	0.5m above canopy screen	-
4	0.5m above canopy bulb	-
5	Wind dirn (10 degree dead around N set to local)	Green – sw supply, yellow – wiper/ch, red - gnd
6, 7, 8	n/c	

Other		
Fast Pulse	Wind Speed (TT gain 0.5)	-
RS485	Remote Humidity Sensor	Black – gnd, red – supply, green – rs485a, yellow – rs485b (see notes for setup)

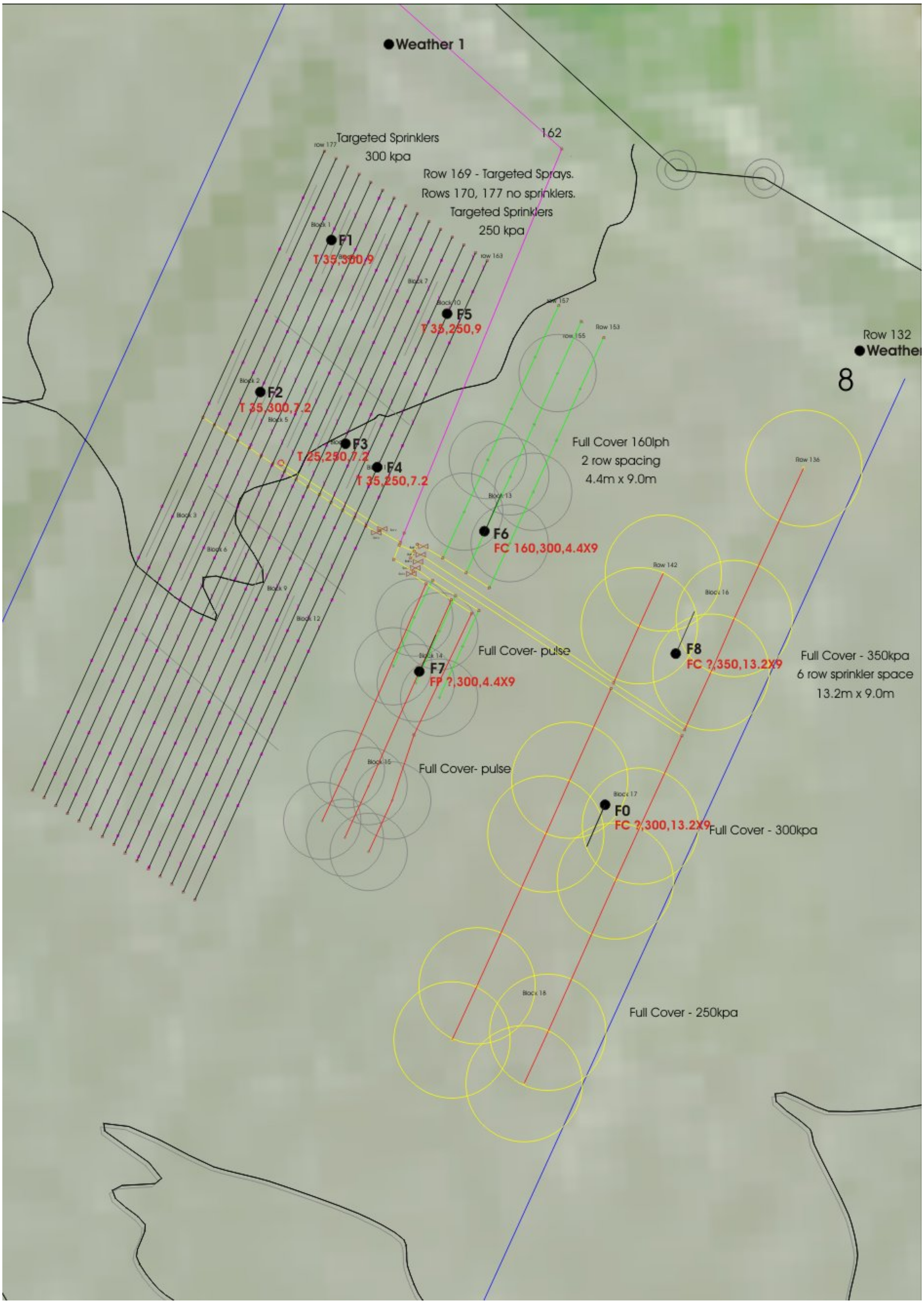
Log: 500,000 12bit samples, 2 minute sample intervals → 24*60/2 = 720 per channel/day logging 10 channels 500,000/7200 = 70 days i.e. collect data every 2 months.
Also log: External Battery, logger battery.

Weather Station 2, GPMC S/N: 0304504 - as station 1 but without humidity.

Serial Cable

9 pin D	default	Bulgin 6
1		Nc
2	Brown	1
3	Red	2
4	Orange	3
5	Yellow	4
6		Nc
7		Nc
8	Purple	5
9	White	6

APPENDIX C: PLAN OF TRIAL SITE



APPENDIX D: GPS COORDINATES OF DATA LOGGERS

sDescription	fLat	fLong	fEasting	fNorthing	fAlt	iColour
frost1	-39.6372	176.6018	2819089	6167948	6040	16711935
frost2	-39.6374	176.6017	2819077	6167926	6017	16711935
frost3	-39.6375	176.6018	2819090	6167915	1718.2	16711935
frost4	-39.6376	176.6018	2819086	6167902	1717.7	16711935
frost5	-39.6373	176.602	2819108	6167935	6011.9	16711935
frost6	-39.6375	176.6022	2819122	6167918	6011	16711935
frost7	-39.638	176.6019	2819091	6167860	3620.7	16711935
frost8	-39.6378	176.6024	2819140	6167879	107.8	16711935
frost0	-39.6383	176.6021	2819112	6167822	3618.7	16711935
weather1	-39.6366	176.602	2819108	6168018	1709.3	16711935
weather2	-39.6371	176.6028	2819180	6167959	106.4	16711935

APPENDIX E: SPRINKLER CONFIGURATIONS

Sileni Frost Trial – Block Detail – as at May 4th 2004

Overall block area 70m x 100m

From northwest corner (row 175) of block running south then east.

Block 1	Targeted Sprinklers 35 1/hr 300 kpa	9.0 m spacing
Block 2	Targeted Sprinklers 35 1/hr 300 kpa	7.2 m spacing
Block 3	Targeted Sprinklers 35 1/hr 300 kpa	6.0 m spacing
Block 4	Targeted Sprinklers 43 1/hr 300 kpa	9.0 m spacing
Block 5	Targeted Sprinklers 43 1/hr 300 kpa	7.2 m spacing
Block 6	Targeted Sprinklers 43 1/hr 300 kpa	6.0 m spacing
Block 7	Targeted Sprinklers 25 1/hr 250 kpa	9.0 m spacing
Block 8	Targeted Sprinklers 25 1/hr 250 kpa	7.2 m spacing
Block 9	Targeted Sprinklers 25 1/hr 250 kpa	6.0 m spacing
Block 10	Targeted Sprinklers 35 1/hr 250 kpa	9.0 m spacing
Block 11	Targeted Sprinklers 35 1/hr 250 kpa	7.2 m spacing
Block 12	Targeted Sprinklers 351/hr 250 kpa	6.0 m spacing
Block 13	Full Cover Sprinklers 160 1/hr 300 kpa	4.4 x 9.0 spacing
Block 14	Full Cover Pulsed Sprinklers 300 kpa	4.4 x 9.0 spacing
Block 15	Full Cover Pulsed Sprinklers 300 kpa	4.4 x 9.0 spacing
Block 16	Full Cover Sprinkler 350 kpa	13.2 x 9.0 spacing
Block 17	Full Cover Sprinkler 300 kpa	13.2 x 9.0 spacing
Block 18	Full Cover Sprinkler 250 kpa	13.2 x 9.0 spacing

Temp Loggers currently located in: @ 4/05/04

Logger 1	Block 1	Weather stations x2 in Northern Headland
Logger 2	Block 2	
Logger 3	Block 8	
Logger 4	Block 11	
Logger 5	Block 10	Tipping bucket array in Block 10
Logger 6	Block 13	
Logger 7	Block 14	
Logger 8	Block 16	
Logger 0	Block 17	