SECTION 1

Freeze Protection

by

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FREEZE PROTECTION

Note: Some excellent references are available dealing with freeze protection. For a recent publication, refer to Barfield, et al. (1990).

Warnings

Fact: Irrigation has been successfully and widely used in California for freeze protection with orchards and vineyards.

Fact: During a Florida advective freeze in 1962, over-tree sprinkler systems (applying less than 0.1 in/hr, or 45 GPM/acre) caused considerably more damage to citrus groves than frost alone in non-sprinkled groves.

Fact: There are a number of theoretical models that can be used to predict the required sprinkler application rates to maintain a certain plant temperature. However, these models all provide different answers. The exact effects of under-tree vs. over-tree, sprinkler nozzle size/pressure relationships, and other factors are still unknown.

Fact: The information presented in this section cannot be guaranteed to be the final answer for design. However, this section, plus additional reading, should assist designers in providing better, although not foolproof, sprinkler design.

Note: Irrigation system designs should not guarantee protection against freeze damage, since there is still so much "art" involved in freeze protection by sprinkling, and because windy arctic air masses can be impossible to protect against.

Terms

1. Dew point temperature. The temperature at which vapor in the air will condense. Dew will form on a cold surface (at or below the dew point temperature) as moisture-laden air passes over that surface.
2. Relative humidity. The ratio of the actual vapor pressure in the air to the saturation vapor pressure, times 100. At a relative humidity of 100%, the air can hold no more water vapor at that temperature.
3. Wet bulb temperature. The temperature recorded by a thermometer that is swung around through the air, with a wet wick over the bulb. This is also the temperature to which the air will drop when sprinklers are turned on. If the air has a low relative humidity, the wet bulb temperature is much lower than the dry bulb temperature.
4. Dry bulb temperature. The air temperature.
5. Inversion layer. A layer of cold air is near the ground surface, while air several tens or hundreds of feet higher is warmer.

Types of Freezes

Radiant Freeze

Radiant freezes are associated with clear, cloudless skies and little or no wind. The temperature drops because the heat in the soil and plants is lost to the atmosphere in the form of long wave radiation. Radiant frost is characterized by heat leaving the plants. The plant surfaces cool the air, rather than vice versa.

Radiant frosts are frequently accompanied by an inversion layer. The air near the ground surface becomes cool as the soil and plants lose heat into the atmosphere in the form of long wave radiation.

Frost appears on plant surfaces because the temperature of those surfaces drops below freezing. Specifically, it drops to the dew point temperature, which in this situation is below 0°C (32 deg. F).

Sprinklers can be effective in preventing damage during radiant freezes.

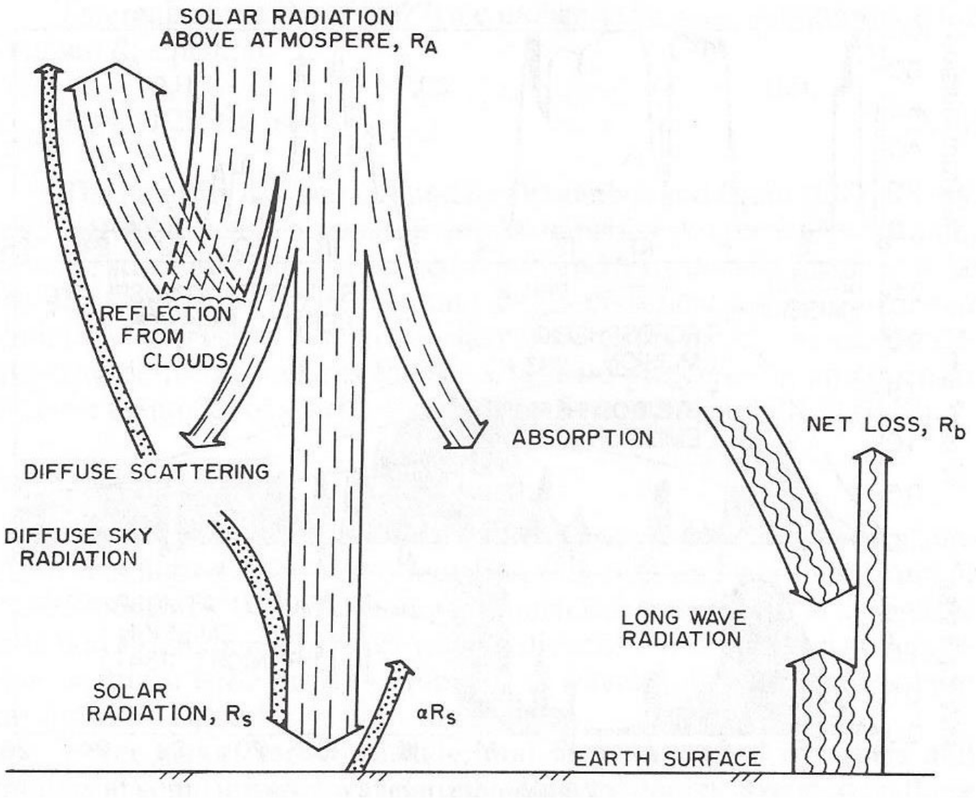


Figure 1-1. Radiation balance diagram (Jensen and Allen, 1990)

Advective Freeze

Advective freezes are associated with wind. If the sky is clear, there is still long wave radiation loss into the sky. However, the freeze is much more severe because (i) the wind carries away convective heat from the orchard, and (ii) the wind brings in cold air from the surrounding area. The wind may originate from a cold polar air mass and be extremely cold. It is very difficult, and often impossible, to protect against advective freezes with sprinklers.

Sensitivity of Crops to Freezing

The freezing resistance of crops depends upon the crop variety and stage of growth. Also, there is no one temperature at which all buds or blossoms will experience damage; rather, research has shown that at a particular stage of growth, a certain temperature will result in a probable percentage of damage. Unfortunately, the exact temperatures and percentages are not well researched for many crops.

During the dormant, or "rest" cycle of growth, vines and trees are able to withstand temperatures below 0 deg. F. However, the time for freeze protection occurs during late winter or early spring during bud break and blossoming, or during early vegetative shoot growth.

Table 1-1 represents estimates of damage likely to occur based on temperature durations of 30 minutes. Longer durations of cold will produce more damage. These are estimates, only.

Table 1-1. Critical temperatures for almond fruit and blossoms (Univ. of Calif. Ext., 1979). Guidelines, only.

		Temperature (deg. F) and Percent Damage										
Variety	Bloom Stage	30°	29°	28°	27°	26°	25°	24°	23°	22°	21°	20°
Nonpareil	Popcorn								10	25	35	50
	Full Bloom							20	35	50		
	Small Nuts		25	75	100							
NePlus	Popcorn							60	80	100		
	Full Bloom					25	75	100				
	Small Nuts	25	75	100								
Mission, Merced, and Thompson	Popcorn								25	40	60	
	Full Bloom							25	50	75		
	Small Nuts	25	75	100								

Similar work has been done more recently using both old and new almond varieties (Table 1-2). There is some discrepancy in the data between the two studies, regarding freeze sensitivity at early and full bloom stages. However, the reported damage at the small nut stage is very similar.

Table 1-2. Percentage damage to almonds exposed to 30 minutes at the indicated temperatures during various growth stages. Data obtained from the U.C. almond regional variety trials at the Chico State University Farm (Connell and Snyder, 1991). Field results depend upon vigor of tree.

Variety	Bloom Stage	Temperature (deg. F) and Percent Damage										
		30°	29°	28°	27°	26°	25°	24°	23°	22°	21°	20°
Ne Plus Ultra	Pink Tip						1	10		20		20
	Pink Bud					0	70	90	90	90	90	
	Full Bloom			5	70	90	100					
	Small Nut	1	5	20	50	100						
Sonora	Green Bud						1			5		5
	Pink Bud						20					
	Full Bloom					70	80	70	80	90		
	Small Nut		1	5	60	100						
Peerless	Green Bud						5			5		10
	Pink Bud					1	50	100				
	Full Bloom		0	5	90	100						
	Small Nut		0	5	60	100						
Nonpareil	Pink Bud						20	40	40		50	
	Full Bloom				50	70	90	90	90			
	Small Nut	1	1	40	90	100						
Price	Pink Bud						30	30	30	40		
	Full Bloom				50	70	90	100				
	Small Nut		0	30	80	100						
Carmel	Pink Bud						40	50		70		70
	Full Bloom				60	90	100	100	100			
	Small Nut	1	10	30	70	100						
Butte	Pink Bud					40	80		80	90		
	Full Bloom		0	0	60	90	100					
	Small Nut		1	5	80	100						
Padre	Pink Bud					70	90	90	100			
	Full Bloom		0	1	50	100						
	Small Nut		1	5	30	100						
Mission	Pink Bud						90		90		100	
	Full Bloom		0	1	80	100						
	Small Nut		0	40	90	100						

Mechanics of Freeze Protection

The key processes associated with irrigation freeze protection are described in this section.

Storing of Solar Heat during the Day for Release at Night

A moist soil can store heat during the day. At night, this heat is released from the moist soil buffer. It is generally recommended that the soil be wet to at least a depth of 1.0 foot (0.3 m). This mechanism provides about **1 - 2 deg. F protection**.

Adding Heat to the Orchard/Vineyard in the Form of Warm Water

Well water is often at a temperature of 60 deg. F or warmer. As the water cools, it releases heat into the field. 1 calorie of heat is released for each 1 deg. C (9/5 deg. F) drop in water temperature of a gram of water.

Table 1-3. Heat changes of water

	Heat change	
Action	BTU/gallon	calorie/gm
1 deg F drop in water temp	8.3	0.56
Water --> Ice @ 32 deg. F	1,200	79
Water --> Vapor @ 32 deg. F	9,000	592
Vapor --> Ice @ 32 deg. F	10,200	671

Release of Heat by Water as it Converts from a Liquid to a Solid (i.e., Freezing)

As liquid water freezes, it releases the "latent heat of fusion", which is equivalent to 79 calories for each gram of water (at 32 deg. F). This is most effective when the phase conversion (change from liquid to ice) occurs on the plant surface itself. **Ice does not act as an insulating material. With over-vine sprinkling, the continuous phase change on plant surfaces provides the protection. This is the most effective freeze protection mechanism of all those listed. Plants can be protected to temperatures of 10-15 deg F below freezing if the plant surfaces always have liquid water on them (or on the outside of the ice encrustation).

Figure 1-2. Ice from sprinklers, on grape vines. Photo courtesy of Wade Rain.

Adsorption of Heat by Water as it Converts from a Liquid to a Vapor

As liquid water vaporizes, it must absorb the "latent heat of vaporization", which is equivalent to 592 calories for each gram of water at a water temperature of 32 deg. F. This heat is responsible for the drop in air temperature when sprinklers are turned on.

Interception of Long Wave Radiation Loss by Water Droplets or Mist in the Air

Up to 50% or so of the heat loss from an orchard or vineyard may be prevented if a fog is over the plants. This is the principle of the Mee fogger system, which uses extremely high pressures and small nozzle sizes to create a dense fog. Part of the protection supplied by wet soil, under-tree sprinklers, and misters is due to this fogging benefit. The small water droplets intercept the long wave radiation that would normally exit into the sky.

Condensation of Vapor on Plant Surfaces

Water vapor that condenses on plant surfaces releases the latent heat of vaporization plus the latent heat of fusion when it forms frost.

Orchard Floor Management

The maintenance of the orchard or vineyard floor itself has a large impact on sensitivity to low temperatures. A weed-free, firm, moist soil can add 1 to 4 degrees of protection during a radiant freeze. Soils that are dry, freshly cultivated, or covered with live or dead grass give the opposite effect.

Table 1-4. Air temperature at five feet above soil surface as influenced by orchard floor conditions. (Powell, 2000)

Orchard Floor	Temperature Ranges
Bare, firm, moist ground	Warmest
Shredded cover crop, moist ground	0.5 degrees F colder
Low-growing cover crop, moist ground	1 to 3 degrees F colder
Dry, firm ground	2 degrees F colder
Freshly disced, fluffy ground	4 degrees F colder
Higher cover crop	2 to 4 degrees F (or more) colder

General Recommendations

It must be emphasized again that determination of proper application rates is still somewhat of an art. This section presents information gleaned from experience and various publications, but is by no means a guarantee of success.

Start and Stop Temperatures

When sprinklers are turned on, the air temperature will drop to the wet bulb temperature. Dewpoint temperatures are often broadcast over the radio.

Table 1-5. Air temperatures at which sprinklers should be started to prevent the initial air temperature from dropping below 32 deg. F.

Dewpoint Temp, deg. F	Starting Temp, deg. F
26 and above	34
24-25	35
22-23	36
20-21	37
17-19	38
15-16	39

After sunrise, with no wind, sprinklers can be turned off if the air temperature is 32 deg. F. If there is some wind, wait until 34 deg. F. It is not necessary to wait until all the ice is melted (Kasimatis et al., 1975).

Reservoir Capacity

It is generally assumed that a water supply must be available for sprinklers to operate 10 hours per night, for 3 or 4 nights in a row. Local weather data must be consulted to determine the actual number of hours and sequential days. Well capacities will determine how much can be supplied from a reservoir and how much directly from wells. In general, surface water supplies (i.e., irrigation districts) are not available in California during the freeze protection season.

Figure 1-3. Vineyard with a dual irrigation system. Drip is used for irrigation; over-vine sprinklers are used for freeze protection. Reservoir is in the background. Located east of Paso Robles.

Uniformity

There is one consideration that is rarely mentioned in the freeze protection literature – that of the effect of Catch Can Uniformity (CCDU) and Flow Rate Uniformity (GPMDU). For under-tree sprinklers and foggers, CCDU (such as is computed in the SPACE computer program of CIT, Fresno) does not appear to be very important. However, the GPMDU is quite important. A GPMDU indicates that every nozzle in the orchard is discharging the same flow rate (an impossibility). A high GPMDU means that less water must be applied, on the average, to obtain adequate freeze protection at the weakest spot in the system.

For over-vine sprinkling, the Catch Can Distribution Uniformity (CCDU) is extremely important. The mechanism of over-vine freeze protection relies on direct water contact with the leaves. A high CCDU (plus a high GPMDU) decreases the required average application rate because the leaves that get the least amount of water will not be grossly under-irrigated, as compared to the average.

For over-vine sprinkling, the overall system Distribution Uniformity is:

Over-vine System DU = CCDU x GPMDU

For example, a typical over-vine sprinkler system has a CCDU of about .70 (due to very wide spacing - also note that DU is not the same as the Christiansen's Coefficient of Uniformity, which is larger than the DU), and a GPMDU of about .85.

System DU = .70 x .85 = .60

If the **<u>system</u>** DU can be raised to .75, the amount of water that must be applied can possibly be the following ratio of the original amount:

$$\text{Reduction factor} = \frac{\text{Old System DU}}{\text{New System DU}} = .60/.75 = 0.8$$

That is, the more uniform system might only need 80% as much water as the conventionally designed system.

For under-tree or fogger systems,

UT Sprinkler System DU = GPMDU

Over-Vine Sprinklers

Over-vine sprinklers provide the majority of their protection by applying water on the plant surfaces, to provide a continuous release of the latent heat of fusion. A theoretical approach is available in a BASIC microcomputer program called FROSTPRO (Perry, 1986). Table 1-5 shows results obtained with this program.

Table 1-6. Irrigation rates, in inches/hour. Relative humidity = 70%, critical temperature = 28 deg. F. Temperatures are air temperatures (from Barfield et al., 1990). Probably assumes 100% Distribution Uniformity of water.

	Wind speed (miles/hour				
deg. F	0.5	1	2	4	8
28	.07	.10	.14	.19	.24
26	.09	.13	.18	.25	.32
22	.13	.18	.26	.35	.48
20	.15	.21	.28	.41	.55

A Rain Bird reference (Fry, 1977) recommends an application rate of 0.12 inches/hour (54 GPM/acre) for dewpoints of 25 deg. F or higher. It recommends an additional 0.01 inch/hour for each degree of dewpoint below 25 deg. F. These recommendations are for fast rotation (15–40 sec) wedge drive sprinklers. If the sprinklers rotate more slowly (60 sec), an additional 0.02 inches/hour is recommended.

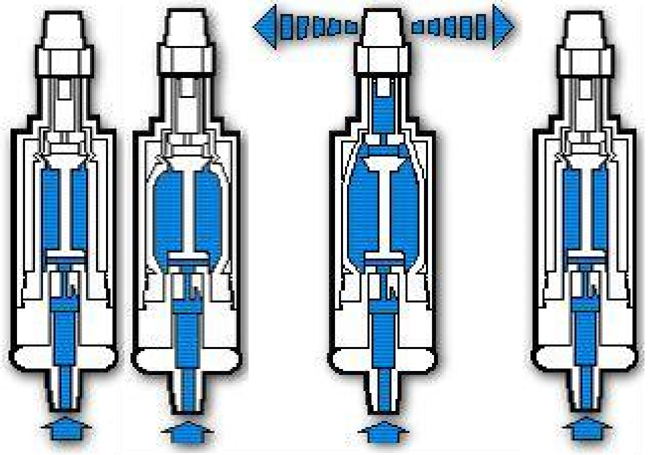
Pulsator® Micro-Sprinklers on Grapes

Along the Central Coast of California, many vineyards use Pulsators® (see Figure 1-4) for freeze protection. These are micro-sprinklers with a special accumulator chamber under them, the action of which is explained in Figure 1-5 below. Beyond the design of the microsprinkler unit itself, the major point of interest is that the intent is to direct the spray pattern so that it only covers the grape vines. Because the freeze protection effectiveness is primarily dependent upon formation of ice directly on the plant, the idea is that effective freeze protection can be obtained with about 1/3 the water – compared with sprinklers that wet the complete vineyard.

There are practical difficulties with these units, such as making certain that the spray pattern is directly aligned with the vine row. Another difficulty occurs at the edges of a field, where the cold air entering a vineyard will sometimes freeze the micro-tubes that supply the Pulsators®.

This problem is generally solved by installing Pulsators® of double the flow rate at the edges of a field. Some freeze problems on the sprinkler itself can also be solved by using brass parts that transfer heat from the water to the sprinkler body – preventing excess ice accumulation on the microsprinkler. New designs utilize two, 180° hydraulically-efficient directional nozzles to increase the throw distance and also allow for higher flow rates per microsprinkler – thus reducing some of the problems with supply tube freezing.

Figure 1-4. Pulsator® accumulator with microsprayer and directional spray plate. Photo courtesy of Wade Rain.



A constant flow into the PULSATOR® is provided by the flow control located in the base of the unit. As the flow enters the PULSATOR®, the diaphragm expands, resulting in a pressurized condition. The diaphragm continues to expand until the discharge seal opens, releasing a full burst of pressurized water to the jet. This represents one cycle of pulsed flow. Following release, the diaphragm retracts and reseals the chamber. The diaphragm refills and the process repeats for the next pulse.

Figure 1-5. Explanation of Pulsator® concept. Courtesy of Wade Rain.

Under-Tree Sprinklers

Under-tree sprinklers provide protection through a combination of mechanisms, but are less effective than over-vine sprinklers because they do not apply water to the plant surfaces themselves. High pressures enhance long wave radiation interception through fogging. The warm water adds heat to the orchard, and water applied the days before a freeze will act as a buffer. In addition, the air receives heat as ice forms on the ground surface. Fry (1977) recommends an application rate of 0.089 inches/hour (40 GPM/acre), with high pressures and closely spaced sprinklers. This is supposed to provide **4–5 deg. F protection**, if the dewpoint is above 32 deg. F. More recent measurements by Connell and Snyder (1991) indicate that an assumption of **2–4 deg. F** protection is quite reasonable, with protection inside an orchard sometimes reaching **7 deg. F**. However, during an advective freeze, in which a cold air mass moves into an orchard from surrounding areas, the outer rows of trees on the upwind side may be impossible to protect. If the advective freeze is severe, under-tree sprinklers will not be able to protect the orchard.

As mentioned earlier, under-tree sprinklers can be used prior to a freeze to wet the soil surface to a depth of one foot, to provide a heat buffer. For this portion of protection, it is valuable to have a good Catch Can DU (CCDU).

Figure 1-6. Ice pattern on the ground during freeze prevention. Pistachio trees with microsprayers.

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