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FROST AND FROST CONTROL IN WASHINGTON ORCHARDS

Successful fruit growers are aware that cold weather can reduce yield as well as the quality of fruit and interrupt the annual bearing tendencies brought about by good orchard management.

Methods of preventing frost injury in the central valleys of Washington have greatly changed since 1965.

The 1970 regulations enforced by the County Clean Air Authorities and the Washington State Department of Ecology precipitated greater interest in heater efficiencies and the feasibility of alternatives such as overtree wind machines and overtree sprinkling.

Prior to that time when fuel oil prices remained below 15 cents a gallon, fruit growers had little incentive to abandon their smoky smudge pots.

A second phase of change was brought into focus as the OPEC oil boycott forced fuel prices up. This brought about a more rapid acceptance of the energy-saving techniques.

FACTORS AFFECTING FROSTS AND FREEZES

RADIATION FROSTS AND ADVECTIVE FREEZES

There are basically two kinds of frosts which can reduce the temperature in the orchard to the critical point. The two types are not distinct, and many nights have characteristics of both.

The most common is the radiation type, which occurs on cloudless nights with little or no wind. After sundown, heat from the earth, trees, and fruit buds is lost as radiation into the sky. Since air does not radiate its heat as quickly as solid particles, it is chilled by contact with the colder trees, buds, and ground. This causes it to become heavier than the warmer air above. As the radiation loss continues, the colder air drifts along the surface to the lowest parts of the ground.

The radiation of heat from the ground, trees, foliage and fruit buds is greatest on clear nights. The rate of heat loss is also influenced by the amount of humidity in the air—the drier the air, the faster the radiation rate.

The second kind of frost is called an advective freeze. It occurs when an arctic cold air mass moves into the region.

The factors controlling a radiation frost are also active during this freeze. However, the cold
HEDGEROWS SHOULD RUN DOWNWARD WITH THE SLOPES TO ALLOW AIR DRAINAGE

ORCHARD SITE AND CULTURAL PRACTICES
INFLUENCE FROST HAZARD

Temperature surveys can be made on lands contemplated for new orchard development. With today's high cost of orchard development, at least one season's survey is essential. Two would be better.

Some assessment can be made by judging the lay of the land. Orchard sites sloping toward lakes and rivers are usually more frost free than flat land away from these bodies of water. Sloping ridges are milder due to free air circulation. Benches exposed to large rocky cliffs will benefit from the heat radiated at night. Beware of draws or narrow valleys carrying cold air drainage from higher ground.

Consider species and varieties. Whether you plan to buy or already own an orchard, you should recognize the important variation in susceptibility of different tree fruits to frost damage. This is especially important in replanting programs. Apricots, peaches, cherries, and pears develop earlier in the season than apples and may be hurt more easily. Apple varieties vary in hardiness. The tenderness of Red Delicious as compared to the hardiness of Rome Beauty is well known. These differences should be taken into consideration when selecting the variety for each site.

Consider cultural practices. Trees themselves can influence air stagnation and frost hazard. For instance, if tree limbs extend so far out that they join or interlock with limbs of other trees, natural air drainage is reduced. Hedgerow plantings, especially, present a problem. Whenever possible, plantings should run downward with the slope to allow air to drain freely. When planting an orchard, it may be advisable to leave an air drainage channel in draws rather than continuing the trees across the draw.

Draws clogged with willows, cottonwoods, and other woody shrubs can retard cold air drainage. These can be kept open as part of your annual pruning chores.

Although the advantages of sod culture outweigh the disadvantages, most fruit growers are aware of the 1 to 2 degree Fahrenheit benefit from a clean-cultivated orchard floor. This difference is not great enough to sacrifice the value of the sod.
arctic air mass has some characteristics that make orchard heating more difficult.

Such cold spells usually last for several days, during which daytime temperatures seldom go above 50°F. (10°C).

Originating in the polar regions, these advective freezes are normal in wintertime. They are characterized by being very dry, and they are accompanied by winds which make it difficult to hold heat in the orchard. Inversion is usually weak with an advective freeze.

These characteristics occasionally account for the advective freeze being severe enough to force temperatures below the protective range of most standard orchard-heating equipment.

INVERSIONS AND CEILINGS

An inversion is a layer of warm air floating over a layer of colder air next to the surface of the ground.

In the daytime, the earth absorbs heat from the sun. The air is heated from contact with the earth. Thus, the air is warmest at ground level, and its temperature becomes cooler as you go up. On a calm, clear night, the earth becomes cold because it radiates heat into the sky. The air in contact with the earth is cooled so that air near the ground is colder than air some distance above the earth—50 to 800 feet (15 to 240 meters).

Thus air temperature increases with elevation above ground level at night and decreases with elevation in the daytime.

Temperatures that increase with elevation are termed an inversion. The height at which the temperature changes from increasing with elevation to decreasing with elevation varies from night to night. The amount of temperature difference from ground level to inversion height may also vary. This is termed the magnitude of the inversion.

Inversions are designated as strong or weak depending upon how much higher the night temperature is at the 50- or 60-foot (15- to 18-meter) elevation than at the 3- or 5-foot (1- to 1.5-meter) elevation.

The actual strength of the inversion can be easily measured over an orchard with electric thermometers set at 5 and 50 feet (1.5 to 15 meters), respectively. The frequency and strength of low-level inversions during periods when frost protection is needed determines the effectiveness of overtree wind machines.

The strength of the inversion layer has an important effect on the performances of heaters on the ground, whether or not overtree wind machines are used.

Hot gasses exhausted from orchard heaters rapidly mix with surrounding air so that when the air stream is some distance from the heaters, its temperature is only a few degrees higher than that of the surrounding air. The temperature of this rising current decreases to become the same as that of the outside air. When this happens, the upward motion of the heated air stops. The height at which the stream from the heater reaches equilibrium is called the ceiling. Heat lost to the ceiling above tree tops can be redistributed into the trees by overtree wind machines.

The ceiling is generally low on nights following warm days. On such occasions, the air volume to be heated and the fuel required for maintaining safe temperatures are relatively small. On the other hand, when the ceiling is high, generally on nights following cold days, the volume of air which must be warmed and the amount of fuel required are relatively high. Following the influx of extremely cold polar air, the ceiling is exceptionally high and the successful performance of an overtree wind machine may require the addition of supplemental heat from heaters on the ground.

WIND

Natural winds mix the colder, ground-level layers with the warmer inversion layers above. As long as the winds blow, the temperature fall will be very slow. Generally, these beneficial winds recede at night and are followed by a more rapid temperature fall. However, when a wind strong enough to mix thoroughly all the air in and above the trees occurs, the temperature within the orchard actually can rise.

There is almost always some air drift on cold nights; however, slow flows of less than 4 miles (6 kilometers) per hour seldom cause widespread mixing.

Winds occurring during an advective freeze will not have this warming effect because colder air is continually moving in.

CLOUDS

The heat lost from the orchard is radiated in long-length waves, which cannot entirely pass through water-vapor clouds. The clouds,
Energy radiated from the ground at night is in the form of long length waves. Long waves are absorbed and radiated back by natural clouds, but pass right through smoke.

if low and of great enough density, will absorb the radiant energy and re-radiate it back into the orchard. Clouds passing over during a frosty night will often check the temperature drop and sometimes reverse the temperature fall. Small, isolated clouds have only a slight effect on the temperature fall.

**SMOKE IS A DETRIMENT**

The smoke emitted from inefficient orchard heaters can become concentrated enough to obscure vision. However, the particles causing this air pollution do not prevent the passage of radiation heat loss from the ground to the sky. This is because the infrared waves radiated from the ground are of the long wave-length. These waves can pass through carbon particles in smoke.

At dawn, however, this particulate matter prevents the penetration of the short-wave radiation from the sun. In the Yakima Valley, prior to the Clear Air Authority regulations, heavy smoke prolonged orchard heating by as much as three hours beyond the normal morning warm-up time.

Thus, smoke worked against the orchardist by polluting the air and creating unpleasant living conditions and, at dawn, forced him to continue heating until the smoke was dispersed by morning winds.

**DEWPOINT**

Dewpoint is the temperature at which moisture will begin to condense out of the air. The higher the dewpoint, the more water vapor present in the air. When the dewpoint is above the critical temperature for the crop, the orchardist benefits by a slower temperature fall than if the dewpoint were several degrees below the critical temperature. This is explained by the liberation of "latent heat of condensation" during the condensation of water vapor to form dew or frost.

A simple method of demonstrating latent heat is to boil water. If a pan of water is placed over a gas flame and a thermometer is placed in the water, an increase in temperature will be observed until the water begins to boil. The heat from the burning gas has been used to raise the temperature of the water. After the boiling point has been reached, the thermometer will show a constant temperature. From that point on, the heat is used up in changing the water from a liquid to a vapor. This heat used to vaporize the water becomes a property of the vapor and is...
liberated as latent heat when the vapor condenses. Thus, water vapor contains a great amount of stored heat, which is given up when the temperature falls to dewpoint and below.

In central Washington fruit districts during the spring-time heating season, the U.S. Weather Service reports that dewpoints of 30°F. (−1.1°C.) are considered high and those of less than 20°F. (−6.6°C.) are considered low. Dewpoints below zero Fahrenheit (−17.8°C.) are rare, but have been recorded at the Yakima Weather Station. Dewpoints in these lower ranges indicate extremely dry air as well as difficult heating conditions.

Low dewpoints carry the potential for a very rapid temperature drop. They may tax the grower’s ability to light up his heating system in time, particularly if the dewpoint is below the critical temperature.

WEATHER MONITORING EQUIPMENT

FROST ALARMS

Frost alarms are an essential part of a well-managed frost-protection system. Reliable electronic alarms have been developed in recent years which permit the orchardist to get his required sleep with confidence that the alarm will ring if needed.

The sensor of any frost-alarm system should be placed in a standard thermometer shelter if you want it to correlate with the standard critical temperatures in this bulletin.

Regardless of the kind of frost-alarm system chosen, it should be checked each season. This inspection should include both the electrical circuitry and the accuracy of the sensor.

The sensor is checked easily by placing it in an ice-water slush and comparing it with an accurate standard orchard thermometer.

THERMOMETERS

One type of thermometer recommended in monitoring frost temperatures is a straight-tube alcohol minimum registering thermometer with the scale etched on the tube. Within the fruit industry, this is called a “standard orchard thermometer.” In recent years electronic thermometers have been developed. These have greater accuracy and faster response than the standard alcohol type thermometers.

A well-managed frost protection system depends on accurate temperature readings. The critical temperature charts have been developed with readings obtained from standard National Weather Service type thermometers placed in standard thermometer shelters.

Thermometers must be properly distributed. At least one is needed for the coldest location in the orchard. The topography and size of your orchard will dictate how many thermometers are needed. There should be enough to keep you posted on the temperature behavior throughout the protected area.

The question is often asked, “Why not place the thermometer in the open like the buds are?” This is because thermometers cannot be left exposed to the sun during the day or the sky during the night. The critical temperatures have been developed from readings taken by sheltered thermometers. Exposed thermometers will register lower temperatures because of radiation cooling. It would be impractical to develop a new set of critical temperatures for exposed thermometers and expect growers to take daily precautions to protect the thermometers from the sun.

The alcohol in the thermometer can become separated if exposed to the sun and give erroneous readings. Separation can also be caused by carrying the thermometer with the bulb end up or jolting the thermometer. If the separation leaves a small amount of alcohol in the upper part of the tube, the readings will be too low. If the separation is near the base, the readings will be too high.

Always watch for these separations. They are usually removed by swinging the thermometer with the base down. If this fails, place the bulb end in a pan of water. Slowly heat the water to give a gradual temperature rise until the separations come together. Then reduce the temperature slowly.

After the frost season, thermometers should
New electronic frost alarms such as the one above are now available for monitoring temperatures with accurate gauges. The circuitry is fail-proof with standby battery power to trigger the alarm at temperatures as low as 25°F. (-3.9°C). Modern electronic thermometers like the one at right have been developed in recent years to be more accurate and quicker to respond to temperature change than the standard alcohol thermometers. Such devices, with remote sensors, are very useful to measure temperatures on high poles to determine inversions.
be stored upright with bulb down and in a cool place.

The National Weather Service will often test thermometers for accuracy in the spring. You must take your thermometers to them prior to the announced deadline date. Clean the thermometers and remove alcohol separations before delivering them to the Weather Service. Check with Weather Service personnel for proper timing and method of tagging for identification.

Meteorologists test the thermometers for accuracy by submerging them in a slurry of water and ice and comparing them with an accurate thermometer in the same bath. The water in the mix will stabilize at 32°F. (0°C.) after stirring for several minutes in insulated containers.

The illustration of the standard thermometer shelter gives the dimensions essential for the basic design. Place the thermometer approximately 5 feet (1.5 meters) from the ground, facing north to avoid direct exposure to the sun's rays.

The thermometer should be mounted with the bulb end ½-inch (1.25 centimeters) lower than the top end. It should be supported with about ½-inch (1.25 centimeters) free space between it and the back of the shelter.

Shelters should be painted white to help reflect daytime heat and to aid in locating them at night.

**SLING PSYCHROMETERS**

Dewpoints are not stable during the night. Some fruit-growing districts in Washington State have special frost-warning radio programs which give the **hourly readings** of dewpoints by the local U.S. National Weather Service meteorologist. Growers living at considerable distances from these weather stations may find it to their advantage to determine their own dewpoint readings with a sling psychrometer.

This instrument consists of a pair of thermometers provided with a handle as shown in the illustration. When the psychrometer is whirled rapidly, the thermometer bulbs are affected quickly by both the temperature and the moisture in the air. The bulb in the lower of the two thermometers is covered with a thin muslin, which is wet at the time of the observation.

It is important that the muslin covering the wet bulb be in good condition. Evaporation of water will leave a deposit of water impurities. These will accumulate to the point where they will interfere with the psychrometer readings. The muslin should be renewed from time to time to avoid this. Your local U.S. National Weather Service meteorologist or your County Extension Agent can tell you where you can purchase a sling psychrometer and a copy of the psychrometric tables for obtaining the dewpoint.

**HEATING EQUIPMENT AND HEATING FUELS**

For years, the principal method of frost prevention was to install many oil-burning heaters in the orchard. Today, the technique of combining overtree wind machines with individual pots has evolved to become the principal method.

Economics is the underlying reason fruit growers choose one system over another. Cost comparative studies were made during the early seventies. These confirmed the assumption that techniques using wind or water were considerably more economical to own and operate even when their capital investments were higher than the fuel-consuming pot systems.

**INDIVIDUAL POT SYSTEMS**

Even though the trend is to overtree wind machines, there will always be isolated parcels of orchard land not effectively reached nor large enough to justify another standard wind machine.

The individual pot systems may be the best technique for those areas. These may include any one of the following systems using oil or Liquid Propane gas fuels. Natural gas has been used with success, but it is not generally available and will not be discussed in this text.

The number of heaters per acre will depend on the orchard with regard to cold spots that require more heat than other areas. Borders on the up-wind side will require more heaters. The number of heaters, regardless of the kind of fuel being burned, will also depend upon the energy output capacity of the heater. As you move from frost-free sites into cold frost pockets, the number of heaters required will
RETURN STACK HEATER

LARGE CONE HEATER

OPEN-POT OIL HEATER WITH COVER

24-INCH STACK HEATER
STANDARD LARGE CONE HEATER CONVERTED TO OIL PRESSURE SYSTEM

A ROW OF HOMEMADE L.P. GAS HEATERS WITH THE GAS LINE BURIED

FOUR DIFFERENT OIL PRESSURE SYSTEMS
vary from none to as many as 100 per acre (247 per hectare).

The amount of protection needed for each site can be determined only by the grower and his years of experience with the frost problem on that site. He may need a pot system capable of delivering as many as five million B.T.U.s per acre per hour (312,424 Kilogram Calories per hectare).

It is a well-proven fact that many small fires are more effective than a few large ones.

Most of the modern orchard heaters have a radiant heat fraction of 20 per cent to 70 per cent of the total heat output. If this radiant heat is to be of value in orchard heating, it should be directed horizontally toward the trees rather than vertically toward the sky.

For this reason, orchard heaters have evolved to the upright stack design. This evolution from the old smoky open pot has been prompted by the need to increase the burning efficiency of the fuel and to reduce the pollution into the atmosphere.

The new centralized fuel systems burning diesel oil, liquid propane gas, or natural gas have greater efficiency in fuel combustion and result in a considerable saving of labor as compared to the individual pot systems.

Briefly, here is a list of the pot-method systems with some of the advantages and disadvantages for each.

THE RETURN STACK HEATER

The return stack heater is the queen of the individual pot systems. If the heater is clean and properly assembled, it will burn approximately 0.3 to 0.6 gallons (1.1 to 2.3 liters) of oil per hour without exceeding the smoke ordinance limitations. The radiant-heat fraction is approximately one-third of the energy output when the heater is operating at its maximum efficiency. It reaches this efficiency level at not more than a one-hole setting.

The larger damper settings are for the light-up period only. After the heater is started, the damper should be turned down to a one-hole setting. With high-speed flame-thrower lighting, the draft holes may be left set at their optimum one-hole setting.

The return stack heater will take in sprinkler water, even when capped and with damper closed. This problem is remedied by using large plastic bag covers when undertree and other sprinklers are in use.

THE LARGE CONE HEATERS

The large cone heater has slightly more radiant ability than the return stack. A second advantage is the lower profile, which makes it easier to take into and out of the orchard. The large cone heater also will resist taking in sprinkler water. However, it will soot up more rapidly than the return stack. This requires more frequent cleanings to prevent a smoky performance.

Special catalytic sprays applied inside the combustion chamber are beneficial in burning out the soot accumulation. Additives to oil to reduce soot or smoke have not been successfully demonstrated in individual pot heaters.

Similar to the return stack heater in lighting procedure, the large cone heater performs more efficiently at a one-hole setting, where it consumes an average of 0.7 gallons (2.6 liters) of oil per hour. Larger openings are prone to waste fuel and reduce the life of the heater.

THE SHORT STACK HEATER

There is a large variety of short stack heaters in use. They have stacks from 6 to 30 inches (15 to 75 centimeters) in length. Generally, the longer stacks will burn quite cleanly at a one-hole setting. However, vent holes in the stack tend to soot up rapidly and cause a smoky performance.

The absence of an adequate combustion chamber in short stack heaters permits unburned, volatilized oil to escape. This fraction of lost energy, in addition to the smoke, contributes to the heaters' low efficiency.

OPEN-POT OIL HEATERS

The advantages are limited to low initial investment cost and a dependable fuel supply. The disadvantages of low combustion efficiency and high labor requirements for firing and filling offset this initial low cost. The radiant fraction is less than 6 per cent of the energy output.

The smoky performance of these trusty old heaters is beyond the tolerance of any known fruit district smoke ordinance.

All of the individual pot heaters have the advantages of dependability (each heater relies upon its own storage reserve), and versatility.
They can be easily moved from one area to another to change the spacing. You can increase or reduce the number of pots at will.

Likewise, these individual stack and open-pot heaters are characterized by a loss of fuel through escaping unburned volatiles. This loss occurs during and after the burning operation. Additional loss is realized from spillage and leakage. All of the above-mentioned heaters have a high labor requirement during operation and for refilling.

PRESSURIZED OIL SYSTEMS

Systems that pipe oil from a central point and jet it under high pressure into the combustion chambers were developed to perfection in the late sixties. They were becoming very popular until the cost of fuel forced reappraisals of energy-saving techniques.

At one time six companies were selling pressurized oil systems. All used the same principles of plastic pipe, brass furnace nozzles, pumps, and filters. The main difference was the design of the combustion chamber.

Diesel oil (No. 2) is delivered through plastic lines from a central control point.

It has been demonstrated that stack heaters and some open-pot oil heaters can be converted to the pressurized systems and will burn cleanly enough to pass smoke ordinance requirements.

Catalyst additives to the oil are effective in keeping the burners clean.

The main advantage of the centralized oil pressure systems (and gas systems) compared to individual pots is the savings in labor and the high burning efficiency. All of these systems when operating properly, will convert nearly 99 per cent of the fuel into usable energy. There is no waste of fuel as long as the system is in good order.

However, the sophistication of the system involves several mechanical things which can go wrong. The failure of any one part of the pump, filter, or motor could result in severe fruit loss. Filters can become plugged, gradually reducing the pressure and causing failure at a time when you need to increase the heat. Pumps and pump motors must be absolutely dependable. Broken pipelines with high pressures can discharge copious amounts of oil, which can be very detrimental to tree growth.

These plastic lines should be thoroughly pressure-tested before being buried. The installation should adhere strictly to the manufacturer's specifications. Underground laterals must be gopher-proof and surface lines mouse-proof.

Proper installation of oil pressure systems is very important. Most main lines are buried, polyvinyl chloride tubing (PVC). These should be buried deeply enough to stand safely pressures of loaded sprayers, tractors, harvest equipment, and gopher-baiting machines.

Experience on sloping ground has shown the practical need for a check valve for each heater. The valves close abruptly when the pump is turned off. The check valve should be located at the “T” where the heater lead pipe is fastened to the lateral line. It should not be located in the nozzle.

PROPANE GAS HEATERS

The use of propane gas as an orchard fuel was proven to be both convenient and economically feasible during the sixties.

Propane fuel has the advantage of allowing the grower to operate the heaters over a wide range of fuel consumption. The lower ranges permit “pilot” standby for gradual increases as the need arises. This convenience prevents over-heating and saves considerable fuel as compared to oil-burning systems.

Propane is the most expensive (on a heat-unit basis) of the orchard heating fuels and offers the most problems in delivery to the orchard and in handling.

Everyone involved in handling or using L.P. gas for orchard heating should have a basic understanding of the properties and behavior of this fuel.

The boiling point of liquid propane is -44°F. (-42°C.). This is the temperature at which the liquid is converted into a gas.

The maximum rate of vaporization or gas conversion of your propane orchard-heating system depends upon the size of the storage tank, the quantity of the liquid within the tank, the outside air temperature, and the total demand of the heaters on your system.

Cooling of the liquid propane will occur if the system is called upon to deliver more than the maximum vaporizing capacity. As the cooling continues, the vaporization capacity can reduce to a point below the peak needs of your heating system.

Normal vaporization is the point at which
This is the suggested arrangement of pot heaters in a tree-crop orchard when heaters are used alone for frost protection. Note the concentration of heaters on the up-drift side of the orchard and in the cold pocket.

Propane lighters hold about 5 gallons of L.P. gas. These units are well adapted to being carried on small tractors or motorbikes, which enables the grower to light up in rapid fashion. Larger models are mounted on a tractor.

For speed and reduced labor, pressurized flame throwers are popular. The fuel used is generally 5 gallons of gas with 8 gallons of diesel oil. The rest of the 25-gallon tank is air-compressed to 110 pounds per square inch.
the tank's peak demand is met by the normal heat transfer from the outside air into the liquid propane within the tank.

Tanks relying upon normal vaporization will have a higher rate of vaporization when the tank is full than when it is only partially full. This is because the liquid contact with the sides of the tank becomes less as the tank is emptied. The liquid has progressively less contact with heat transfer from the outside air.

Some growers have solved the vaporization problem by having extra-large storage capacity to take advantage of normal vaporization.

Most orchard heating systems have a demand too large for normal vaporization. This requires special vaporizing equipment which meets or exceeds all state and local fire codes.

The vapor pressure within the tank is in direct proportion to the temperature of the liquid, as shown by the L.P. pressure/temperature chart.

**VAPOR PRESSURE OF LIQUID PROPANE**

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>F.</td>
<td>C.</td>
</tr>
<tr>
<td>-40° (-40°)</td>
<td>16</td>
</tr>
<tr>
<td>0° (-17.8°)</td>
<td>38</td>
</tr>
<tr>
<td>30° (-1.1°)</td>
<td>66</td>
</tr>
<tr>
<td>70° (21.1°)</td>
<td>124</td>
</tr>
<tr>
<td>90° (32.2°)</td>
<td>164</td>
</tr>
<tr>
<td>100° (37.8°)</td>
<td>187</td>
</tr>
<tr>
<td>120° (48.8°)</td>
<td>240</td>
</tr>
</tbody>
</table>

The specific gravity of propane vapor is 1.5 times the weight of air. This characteristic of L.P. gas is very important and should not be forgotten for safety's sake. Should a leak develop in your orchard heating system, the escaping vapor will flow along the ground to the lower levels.

Growers filling their own propane lighters from their main L.P. tanks should pay particular attention to the safety requirements. Spilled liquid propane around active tank warmers can be explosively dangerous.

The approximate ratio of expansion of liquid propane to vapor is 1 to 269. One gallon of liquid propane will expand to form 36 cubic feet of gas (1 liter expands to .269 cubic meters).

When liquid propane is spilled in the open air, the vapor rapidly expands in all directions as it mixes with the air. If the volume of gas liberated is sufficient, ignition is possible at distances as far as 200 feet (61 meters).

Propane, however, has another property, referred to as “limits of inflammability.” The lower limit is 2 per cent propane vapor to 98 per cent air. The upper limit is 9.5 per cent propane vapor to 90.5 per cent air. The vapor-air mixture has to be within these narrow limits before the mixture will burn or explode. This explains why some of the early homemade propane orchard heaters were difficult to light.

Propane in the pure form is odorless. The familiar odor you smell around L.P. equipment is the additive ethyl mercaptan, which is added at the rate of 1 pound (454 grams) to each 10,000 gallons (38,000 liters) of propane. This additive is heavier than the liquid propane and will gradually settle down to the lower part of the tank if stored for several months without use. This results in a strong odor from the fuel just before the tank runs out.

Because delivery of liquid propane from commercial storage to the farm is more complicated and time-consuming than for oil, it is to the propane user's advantage to share the storage responsibility with the dealer.

Storage capacity on the farm should be large enough to supply fuel for two consecutive nights of firings. Assuming the system burns as much as 40 gallons of liquid propane per acre (373 liters per hectare) per hour at the peak need, two average six-hour firings would consume 480 gallons per acre (4,475 liters per hectare) in the field and approximately 20 gallons (76 liters) in the vaporizer. This would result in a basic figure of 500 gallons storage capacity per acre as a safe minimum (4,675 liters per hectare).

The size of the storage tanks on the farm will influence the efficiency of the vaporizer and the price per gallon of liquid propane from the dealer. Experience in the Yakima Valley has proven the merits of installing 30,000 gallon (113,000 liter) tanks in orchards requiring protection on 60 acres (24 hectares) or more.

In addition to the several excellent commercial propane orchard heaters on the market, fruit growers can make their own by using various pipes, pails, or U.S. army shell casings for the combustion chambers.

*The National Board of Underwriters recommends that a propane tank never be filled over the 82 per cent capacity level to prevent daytime safety valve pressure release.
The overtree wind machines found so frequently in the orchards and groves of the western United States have evolved through trial and error to their present-day form.

Basically, the machine is a tower to hold the propeller 32 to 41 feet (10 to 12.5 meters) above the ground. The motor should be strong enough to drive the air turbulence into the orchard for a distance of 300 to 400 feet (91 to 122 meters). The propeller revolves at approximately 590 revolutions per minute and makes a 360-degree horizontal rotation every 4½ minutes.

The action of an overtree wind machine is to blow air turbulently from the warmer inversion layer into trees. A strong inversion is to your advantage, but you will gain some protection with weak or no inversions. Generally, the fruit buds and small twigs are close to being in equilibrium with the air temperature if the natural winds remain active. These usually die down during the night. Research has revealed that the fruit buds, twigs, and small branches exposed directly to the sky radiate their heat faster than the air about them. They can become 3 to 4 Fahrenheit degrees (approximately 2 to 3 Celsius degrees) colder than the air and, in turn, chill the air, which contracts to become heavier and, in turn, falls to the ground where it accumulates.

The action of the wind machine is to keep those flower parts in the same temperature range as the air around them. A warm air inversion above the trees within reach of the fan is to your advantage and makes the use of the wind machine even more effective. If there is no inversion, or if the air is below the critical temperature, supplemental back-up heat may be needed before dawn.

During an arctic air mass spring freeze, these machines will perform best with supplementary back-up heat supplied by your fuel-burning heaters. If you are planning to purchase a wind machine, your old pot heaters should be held in reserve for the time that you will need them. We can expect such a freeze about one year in five in central Washington. Testimony by growers in the Yakima Valley has indicated that the overtree wind machine is doing the full job of protection about 90 per cent of the time and supplemental back-up heat is required for approximately 10 per cent of the spring season's heating time.

A wind machine can affect 8 to 10 acres (approximately 2 to 4 hectares). Effectiveness decreases as distance from the machine increases. Heaters should border the area and be lightly scattered within the area. The lightest heater concentration should be nearest the tower to minimize vertical current interference with the fan blast.

Basically, the horsepower of these machines...
is rated at the propeller. It is generally required that 10 horsepower be supplied per acre (0.4 hectare) covered for single-motored models.

Grower testimony has revealed that they prefer the motor on the ground for easy access to service.

The standard overtrees wind machines found in the western states have an effective radius of approximately 300 to 400 feet (91 to 122 meters)—depending on the machine's horsepower. The natural air drift over the orchard will shorten the upwind side and lengthen the downwind reach. Effective turbulence with wind machines rarely extends beyond 500 feet (152 meters). Overtree wind machines should not be designed to blow heat from the fan. Warm air is buoyant and results in shortening the radius reach of the fan.

SPRINKLING FOR CONTROL OF FROST

Sprinkling for protection against frost involves three different concepts: (1) Overtree sprinkling for bloom delay up to a certain stage of development and then changing over to (2) overtrees sprinkling during the frost to prevent injury or (3) using undertree sprinkling during the frost to prevent injury. Most growers using sprinklers for frost protection are relying only upon the application of water during the critical hours of frost.

Each of these techniques requires exacting details in the design and operation of the systems.

The bloom delay technique is simply one of cooling the trees with overtrees sprinkling in the late winter and early spring. This technique, still in research-development stages, has several problems and, for many fruit growers, may not be an acceptable method.

For complete description of the bloom delay technique, see EM 4113, "Temperature Modification by Irrigation."

Many growers are using overtrees sprinkling for irrigation, heat suppression, insect and mite suppression, and application of chemicals. As the energy crisis challenges the fuel-burning heating systems, we find growers adopting the overtrees sprinkling method for frost control.

The problem with high salts in irrigation water and the fear of potential sprinkler-oriented diseases (Fire Blight, Coryneum Blight, and Scab) have increased interest in undertree sprinkling and the consideration of its use in frost control.

The physical concept of overtrees and undertree sprinkling is different, and will be discussed separately.

OVERTREE SPRINKLING

The technique of fighting frost with overtrees sprinkling has been tested in nearly every major fruit district in the world. This experience has proven it to be very exacting but practical. There are complications in this technique which account for a greater risk compared to heat application methods. On the other hand, overtrees sprinkling has some distinct advantages.

Enthusiastic supporters for this method agree that the operational costs are lower than with other methods of fruit protection. In addition, it is convenient and clean.

The sprinkling approach to frost protection makes use of a very important physical property of water. When water cools, it gives up a fixed amount of heat for each degree of temperature loss.

One BTU of heat is removed from each pound of water as it cools for each degree of Fahrenheit reduction. (One kilo calorie of heat is removed from each kilogram of water as it cools for each degree of Celsius reduction.)

This heat is given up until the temperature of the water reaches 32°F. (0°C.). It then gives off 144 BTU's of heat per pound (79 kilo calories per kilogram) of water as it turns to ice. This heat energy, called "latent heat of fusion," is available to prevent the plant tissue from going below 31.5°F. (−0.5°C.).

As long as the film of water is maintained by continuous application, the temperature of the plant tissue will remain at or above 31.5°F. (−0.5°C.), even though a layer of ice is steadily being formed. If the water source fails, the ice and plant parts can become colder than the surrounding air because of evaporative cooling. The ice is a very poor insulator.
OVERTREE SPRINKLING USES THE LATENT HEAT RELEASED WHEN ICE FORMS TO KEEP THE PLANT TISSUES AT 31.5°F.

CLEAR-ICE INDICATES ADEQUATE APPLICATION

TREE NEEDS SUPPORT TO HOLD WEIGHT OF ICE
Two very important aspects of this method of preventing freeze injury need emphasis. First, the water film must be maintained continuously as long as the temperatures are low enough to freeze ice or until the ice starts to melt rapidly. Secondly, inadequate application rates or poor distribution can result in a build up of ice. Under long periods of freezing, this can result in excessive weight which must be supported by the tree.

This method only prevents the temperature of the protected flowers and fruit from falling below 31.5°F. (-0.5°C.), which is above the critical temperature of most plant tissues. It does not warm the plant parts, nor does it appreciably raise the air temperature. Therefore, its efficiency cannot be measured by air temperature.

**Water Supply**

Since it is not economically feasible to engineer a flexible-rate sprinkling system, the minimum application rate for protection down to 20°F. (-6.6°C.) is 0.15 to 0.20 inches (0.37 to 0.5 centimeters) per hour, depending on the average dewpoint and wind speed.

Growers experimenting with this technique have shown that an application rate of 0.15 inches (0.37 centimeters) per hour will protect deciduous fruit tree blossoms to 20°F. (-6.6°C.) with a low dewpoint.

This is one of the most important limiting factors of overtree sprinkling as a frost-prevention technique. It should be pointed out that all economically justified heating systems begin to fail at temperatures below 20°F. (-6.6°C.) when accompanied by low dewpoints and wind.

The likelihood of overweighting the trees with ice under these severe conditions is such as to do serious permanent damage to the trees. Weather records, however, show that such severe conditions occur only about once every 10 years during the pre-bloom and bloom season in central Washington.

The higher suggested rate of 0.20 inches (0.5 centimeters) per hour may be used for the upwind side of the orchard where more evaporative cooling occurs.

The application rate of 0.15 inches (0.37 centimeters) per hour requires 67.3 gallons per acre (630 l/hectare) per minute or 4,038 gallons per acre (37,751 l/hectare) per hour. It accumulates 1.5 inches (3.75 centimeters) of water during a 10-hour run.

The supply of water should be adequate to permit continuous operation for several successive nights, each as long as 10 hours in duration. Arctic cold air masses have been known to give Washington growers three successive long nights of orchard heating.

Where irrigation water has not been turned into canals when needed for frost protection, special wells and perhaps holding ponds may be required.

**Equipment**

The installation of an overhead sprinkling system for frost prevention should be carefully engineered to give an even distribution of water over the trees.

A system may be engineered for overtree irrigation and be totally inadequate for adaptation to frost-injury prevention. Turning the entire system on at one time for frost control requires a larger mainline pipe, pump, and motor capacity than turning on a smaller section used in the irrigation rotation.

Growers contemplating installation of overtrees sprinkling should contact reliable dealers or consultants with ability to assist in the engineering layout.

The sprinkler heads should rotate at least one revolution per minute to assure a water film over plant tissue (and ice) at all times. Slower rotation may permit all the water film to freeze. Once the surface of the ice becomes dry, the plant tissue inside may freeze to temperatures below the dry bulb air temperature.

The sprinkler heads should be constructed in a manner that prevents ice build-up around the activator spring. Some growers have experienced ice build-up to the point where the lever action of the head is retarded. This can result in complete stoppage of the revolving head. Some manufacturers have constructed special sprinkler heads for frost prevention.

The pumps must be capable of operating continuously and satisfactorily at temperatures far below freezing. A breakdown could cause the loss of the entire crop of fruit.

**Sprinkler Spacing**

The site to be protected will dictate the spacing according to the wind velocity and di-
rection, the tree spacing and arrangement, and the direction of the traffic pattern in the orchard. Experience in central Washington has demonstrated successful results with overtree sprinklers spaced at 60 by 60 feet (18 by 18 meters). The important thing to remember in the layout design is the application rate of water which you want to achieve with fairly uniform coverage. We cannot recommend spacings in excess of 60 by 60 feet (18 by 18 meters).

The maximum distance between sprinklers is governed by the diameter of throw of the sprinkler and the velocity of the wind. Generally winds of high velocity are rare during the critical frost periods. However, overtree sprinkling is primarily installed for irrigation and should, therefore, be designed for the greater daytime velocities.

In general, the maximum spacing between sprinklers should not exceed 50 per cent of the wetted diameter.

The sprinkler fall-out is lower outside the last sprinkler row because there is no overlap from an adjacent row. This creates a critical area of insufficient water and can cause more damage than good. Special installations should be incorporated to give full protection on the borders.

OPERATION

When a sprinkling system is turned on you may experience a sharp reduction in air temperature due to evaporative cooling. In most systems of overtree sprinkling it will take 5 to 10 minutes to achieve complete fruit bud wetting. The magnitude of the temperature drop during that time will depend upon the relative humidity of the air. Therefore, you should consider this factor in determining when to start sprinkling.

Technically, you should not have to start the sprinklers until the wet-bulb thermometer reading drops to the critical temperature for that stage of bloom. This could also serve as a safe time after sunrise to turn the sprinklers off. If such a guideline were followed precisely, less hours of sprinkling could be encountered.

Since fruit growers are not acquainted with the proper use of wet-bulb thermometers, it is logical for them to rely on simpler methods of determining when to activate sprinklers.

It is appropriate at this time to remind you that the wet-bulb temperature is not the same as the dewpoint temperature. However, you can use the dewpoint temperature when it is readily known via radio with hourly up-dateings as broadcast by the U.S. Weather Service or the correct use of a sling psychrometer.

The following table illustrates the relationship between air temperature, dewpoint, and the wet-bulb temperature:

<table>
<thead>
<tr>
<th>The air temp is:</th>
<th>The wet-bulb temp is:</th>
</tr>
</thead>
<tbody>
<tr>
<td>°F</td>
<td>°C</td>
</tr>
<tr>
<td>32</td>
<td>0.0</td>
</tr>
<tr>
<td>28</td>
<td>-2.2</td>
</tr>
<tr>
<td>25</td>
<td>-3.9</td>
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<tr>
<td>22</td>
<td>-5.6</td>
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<td>18</td>
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<td>14</td>
<td>-10.0</td>
</tr>
<tr>
<td>9</td>
<td>-12.8</td>
</tr>
</tbody>
</table>

Yakima Valley fruit growers with 10 or more years experience have shown that starting the sprinklers at 32°F. (0°C.) or 33°F. (0.5°C.) provides a margin of safety under normal or high dewpoints. Also, water may start to freeze in surface laid laterals and stand pipes if you wait much longer. Experience has revealed these ice crystals can clog the sprinkler nozzles, resulting in an erratic, uneven start for the night.

It is safe to end the sprinkling after sun-up when you see free water running between the ice and the twigs. This means the air temperature is above 33°F. (0.5°C.) in the outside area. It is not necessary to wait until all the ice has melted after the warm sunlight "takes over."

Caution should be exercised with regard to chilling winds that may reverse this situation.

Running the overtree sprinkling system from the time the temperature drops to 33°F. (0.5°C.) until it returns to 33°F. (0.5°C.) after dawn will always commit you to more hours of protection than required for a heating system that burns for only the time the temperature is below critical level.

PRECAUTIONS

The first season of sprinkling may result in considerable spur, twig, and limb breakage or warpage. The apple and pear orchards in the Yakima Valley have shown this NOT to be a problem after the first year. Some modification in the pruning to develop rigid strong branches may be essential to prevent this damage. Older trees with weak crotches are more susceptible to breakage and it may be desirable to install
PER-ACRE OWNING AND OPERATING COSTS
OF VARIOUS FROST PROTECTION SYSTEMS
(10-Acre Block, 1974)

35 Heaters Per Acre

<table>
<thead>
<tr>
<th>Stack Heaters</th>
<th>Oil Pressure Heaters</th>
<th>L.P. Gas</th>
<th>With One Wind Machine</th>
<th>Overtree Sprinkling</th>
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</thead>
<tbody>
<tr>
<td>Capital Investment Per Acre</td>
<td>$756.14</td>
<td>$737.26</td>
<td>$1,016.69</td>
<td>$1,085.11</td>
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<tr>
<td>Operating Costs Per Acre</td>
<td>243.25</td>
<td>225.10</td>
<td>195.46</td>
<td>76.08</td>
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<td>Labor (Total Season)</td>
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<td>17.00</td>
<td>17.00</td>
<td>17.50</td>
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<tr>
<td>Equipment (Total Season)</td>
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<td>3.35</td>
<td>1.25</td>
<td>5.87</td>
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<tr>
<td>Fuel (Total Season Gallons)</td>
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<td>(682)</td>
<td>(455)</td>
<td>(90 oil+32 gas)</td>
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<tr>
<td>Investment Overhead Per Hour</td>
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<td>3.03</td>
<td>3.65</td>
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<tr>
<td>Total Annual Costs Per Acre Hour</td>
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<td>$ 11.67</td>
<td>$ 11.16</td>
<td>$ 5.96</td>
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</table>

28 Oil Pots Per Acre

<table>
<thead>
<tr>
<th>Gas</th>
<th>Wind Machine</th>
<th>Sprinkling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Investment Per Acre</td>
<td>$737.26</td>
<td>$1,016.69</td>
</tr>
<tr>
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<tr>
<td>Fuel (Total Season Cost)</td>
<td>(90 oil+32 gas)</td>
<td></td>
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<tr>
<td>Investment Overhead Per Hour</td>
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</tr>
<tr>
<td>Total Annual Costs Per Acre Hour</td>
<td>$ 11.67</td>
<td>$ 11.16</td>
</tr>
</tbody>
</table>

ropes or some form of branch support.

UNDERTREE SPRINKLING

Fruit growers of central Washington, having heard of the successful use of undertree sprinklers for frost control in California, are asking if this technique has potential in their orchards.

The experience in California has resulted in adequate protection in large blocks where the dewpoints were high (prior to sprinkling). Serious crop loss resulted where the dewpoints were low and more than 3 Fahrenheit degrees (approximately 1 Celsius degree) protection was needed.

Literature for California deciduous fruit growers advises against the use of undertree sprinkling where dewpoints are below freezing.

The success of this technique is based upon the fact that no evaporative cooling will occur if the dewpoint is above freezing. If all the undertree-sprinkled water is frozen, a considerable amount of heat is released as the water turns to ice. An application rate of 0.07 acre inch per hour (17.5 centimeters per hour) will release 2.3 million B.T.U.s per hour per acre (1.42 million kilo calories per hectare). Part of this heat will go into the ground and part into the air. The transfer to fruit buds is by both radiation and convective transfer.

If the dewpoint is low, the evaporative cooling factor could absorb all the heat released by freezing and the resulting crop protection therefore could be minimal.

Additional research and field trials are necessary in central Washington to determine if undertree sprinkling has a general potential for orchardists. Questions unanswered at this time include the rates of application with dewpoints below freezing, the type and spacing of sprinklers, droplet sizes, and the size of the block to be protected.

OTHER METHODS

New techniques of preventing frost injury are being discussed and researched. These include foaming, fogging, chemical sprays, and polarization. Until successful demonstrations of these proposed methods have been made, no recommendations can be advanced.

CRITICAL TEMPERATURES

The key to successful frost protection is knowing when to start. The consequences of error are excessively high operation costs on the one hand, crop injury on the other.

The basis for determining when to start is the "critical temperature." Many critical temperatures for deciduous fruits have been published. The ones we use in Washington have
evolved from U.S. National Weather Service Fruit-Frost Service tables established in the 1920's. Recent experimental work in Washington has provided some new insight into interpretation of critical temperature tables.

By definition, the critical temperature is the temperature, as read on properly exposed orchard thermometers, that the buds, flowers, or fruits will endure for 30 minutes or less without injury. Because of the complex nature of the problem, critical temperatures are often wrong, especially before full bloom. They usually are too high, in order to protect against unusually tender tissues, and as a result frost protection equipment often is operated unnecessarily. Sometimes, on the other hand, buds or flowers become more tender than normal and losses are sustained at temperatures above those shown in the tables. Other factors may contribute to deviations from expected performance. Thermometers may be inaccurate or improperly exposed. Tissue temperatures may differ from air temperature.

To improve our frost protection practices we must improve our understanding of how our fruit crops are affected by low temperatures.

STAGES OF DEVELOPMENT

During dormancy fruit buds of all tree fruits grown in Washington will withstand subzero temperatures. With peaches and cherries, about 6 degrees separate the temperature required to kill 10 per cent of the buds from that required to kill 90 per cent of them. Cold weather below 28°F. to 30°F. (below -2.3°C. to -1.1°C.) increases their hardiness; milder weather reduces it. Bud temperatures are in close equilibrium with air temperatures when they aren't in sunlight.

About the time that visible swelling is observed, some buds become quite tender. Others remain much harder. As a result, the difference between the temperature required to kill 10 per cent of the buds and 90 per cent of them may be as great as 20°F. (-6.9°C.). Cold weather still has the capability of increasing hardiness quite rapidly, so actual critical temperatures may vary drastically from day to day. Bud temperatures are still in close equilibrium with air temperatures.

When the bud scales separate and the blossoms appear, further hardiness is lost. There are fewer hardy buds so the range between 10 per cent and 90 per cent kill is reduced to 10 degrees early in the period and to as low as 3 to 5 degrees later in the period. Cold weather still can cause hardening, but it also kills many of the buds before they can respond. Rapid bud development in warm weather results in less hardy flowers than does slower development in cool weather. As flower parts develop, they give some physical protection from heat loss by radiation. Stone fruits develop an insulating dead air space around the pistil. As the mass of flower parts develops, it takes a little longer for it to cool and freeze. These factors result in an increasingly complex relationship between tissue temperatures and air temperatures.

At full bloom flowers are quite uniformly tender. In some cases, apricot for certain, capability for hardening is still present, but the temperature requirements aren't known. Insulating properties of flower parts are quite well developed, especially in the cherry, where great masses of flowers protect those on the interior quite effectively. Most susceptible are those on the top of horizontal branches, exposed to the sky. Because of radiative cooling, these flowers almost always freeze before those that are more sheltered.

In the small green fruit stage, the freezing point is 29°F. to 31°F. (-1.7°C. to -0.6°C.). The fruit will not survive freezing. It has practically no ability to harden. There is no variability in hardness. The only variability that remains is in temperatures reached in the tree. Low branches get colder than high branches. Foliage provides shelter from radiation to the sky and helps to contain heat from orchard heaters. The rapidly expanding weight of fresh tissue—leaves and fruit—has a correspondingly greater heat capacity of its own. This causes the fruit temperature to lag behind air temperature.

IMPORTANT FACTORS IN USING CRITICAL TEMPERATURES

To use critical temperatures successfully, we must use temperatures from a standard orchard thermometer and, from this, estimate the probability of injury to our crop. There are a good many factors involved in this relationship, most of which are imperfectly understood and/or difficult to measure under orchard conditions.

Be certain that your thermometers are giving reliable and useful information. Have them checked annually. The National Weather Serv-
ice provides this service every spring. Check them frequently to be sure the alcohol column has not separated. Look also for small amounts of alcohol (red) clinging to the sides of the column.

Mount them in shelters that provide protection from radiation to the sky. Such sheltering assures that your thermometer measures the temperature of the air in your orchard. Air temperature is still your most reliable estimate of tissue temperature, even though we know deviations do occur. Don’t rely on thermometers exposed to the sky to give an estimate of tissue temperature. This would be interesting information that you might find useful in conjunction with conventional readings, but don’t rely on it. Don’t rely on wet bulb temperatures. These are not as easy to read as dry bulb temperatures, especially at and below 32°F (0°C), and will frequently give readings that are much too low. Wet bulb readings are for determining dewpoint.

Use several thermometers. Have at least one upwind from the protected orchard and out of range of your protective devices. Be sure thermometers in orchards are not directly affected by heaters. Read all thermometers frequently. Keep a written record of time, location, and both the minimum reading and the present temperature. Such records are very useful during frost protection operations to keep abreast of temperature trends and to determine how effectively you are protecting.

The most important factor determining critical temperature is the stage of development. Temperatures during the 24 hours before the frost have different effects, depending on the stage of development, especially prior to full bloom. Means for providing current information on these effects are being developed.

All buds are not equally hardy. When the range of hardiness values is great, there is little or no hazard in allowing temperatures to go slightly below critical. Small green fruits may be considered to be all the same hardiness. They should not be allowed to go below their critical temperature.

All buds, flowers, or fruits are not the same temperature within a tree. When temperatures in the lower half of the tree go below critical, the upper half is usually still above critical. Flowers or fruits exposed directly to the sky are colder than those that are sheltered. Flower parts and dried shucks, before they fall, provide some protection.

Such variations in hardiness and temperatures within a single tree are very important in saving the crop, particularly at full bloom and earlier.

There are important varietal differences in hardiness. Some are related to differences in stage of development. Lambert blooms later than Bing and is more hardy on any given date. Some are related to variability of bud development within a tree. Some apple varieties, such as Golden Delicious, produce many blossom buds laterally on last year’s shoots. These buds bloom later than the terminal buds on spurs and can make a crop even when all the spur buds are killed. Red Delicious produces most flowers on spurs.

Some varietal differences seem to be in the inherent hardiness of the tissues. Earliir apricot and Chinook cherry both bloom earlier than other varieties but seem to be equally reliable in cropping. Some varieties produce a great excess of bloom, which may increase the chance of having an adequate number of survivors. Redhaven peach is in this category. It often produces a crop even though it may be nohardier than other varieties.

Variateal differences, while quite reliable, can be reversed under some conditions. Reasons for such exceptions are not known nor can they be predicted. Anyone working in frost protection can expect to be surprised.

Similarly, tree vigor has a relatively small but complex effect on critical temperatures. Low vigor trees may show more or less injury than high vigor trees depending upon several circumstances that are still not well understood.

What is the most frost-susceptible tissue? During dormancy, the pistil of stone fruits is usually the most tender. Winter freezes usually result in the death of the pistil and surrounding tissues, followed by sloughing off of the whole bud when warm weather arrives. We see occasionally, especially in the very early stages of spring development, injury to receptacle tissue below the pistil. The flower is not injured but fails to develop normally.

Dormant apple and pear fruit buds are very hardy. Injury to the tree is usually more serious than bud injury at that time.

As stone fruit buds begin to develop, the pistil remains the most tender organ and is usually killed entirely. Just prior to full bloom it
is not uncommon to see the style injured with the ovary uninjured. If this occurs prior to fertilization of the ovule, the fruit will not set.

After the fruit has set, the developing seed is the most tender portion. When the seed is killed, the fruit usually fails to develop and drops. If the skin or flesh is injured, it is probable that the seed also is injured and the fruit will drop. This is the reason frost marks and misshapen fruits are relatively uncommon in stone fruits.

Pome fruits can develop to maturity without all their seeds. They can be partially injured and still mature. Frost rings, misshapen fruit, and russet are the results of partial injury, not great enough to cause fruits to drop. Heating can protect quality by preventing such injury.

Supercooling, cooling the fruit below its freezing point without ice formation, may occur in deciduous orchards. If it does occur, and persists throughout the night, there will be no injury. Ice must form to cause injury. Detached fruits may supercool 10 or more Fahrenheit degrees (5 Celsius degrees) below freezing. Apparently freezing starts in the twigs and branches and then moves along the conducting tissues and into the fruits. We once observed peach trees with no fruit next to trees bearing 10 boxes and more. The best explanation seems to be that the trees supercooled, then something, perhaps a local gust of wind, triggered ice formation in some trees. The ice then spread rapidly throughout the supercooled portion, killing all the fruit. This is not a common situation.

Meteorological factors have a bearing on critical temperatures. Temperature during the 24 hours preceding the frost can have profound effects on hardiness of buds prior to full bloom. The longer term effects are also important, as it has been shown that apple blossoms that developed in cool weather are more frost resistant than those that developed in warm weather.

Humidity, as represented by dewpoint, has a bearing on the problem. Statements can be found in the orchard heating literature claiming more injury at a given temperature with either a high or a low dewpoint. Low dewpoints are associated with conditions favoring radiation to the sky and evaporative cooling. This may cause tissue temperatures to be lower than the air temperature, resulting in more injury at a given air temperature than if the dewpoint is high.

The magnitude of such differences is not well established. It probably varies with stage of development, maybe with species. Tissue temperatures 3 to 4 Fahrenheit degrees (approximately 2 to 3 Celsius degrees) below air temperatures are apparently possible on calm nights. Dewpoint probably has no effect on actual hardiness of the tissue. Finally, of course, very rapid temperature drops can be experienced on low dewpoint nights, so that starting frost protection at above critical temperatures is wise for this reason alone.

Wind of 2 miles per hour or above tends to keep tissue temperatures close to air temperature.

The rate of thawing has been said to increase injury. We think that it is only a very minor factor if it has any influence at all. The same can be said for the effect of ultra-violet light. Buds can be killed by low temperatures in darkness.

The duration of low temperature is important as a factor in tissue-air temperature equilibrium. As such, it is most important in the green fruit stage, unimportant in the dormant bud stage. The minimum temperature is relatively more important than the duration. Remember that air never remains long at any temperature.

Subtle refinements in critical temperatures have been suggested. One idea is that there is a sudden loss of hardiness at each stage of bud development, followed by a gain in hardiness. Our present understanding of hardiness behavior is not sufficiently advanced to support this concept.

To evaluate effects of low temperature, sample carefully and intelligently. Critical temperatures are based on most susceptible flowers. Be aware of crop potential on less fully developed flowers or flowers that stay warmer because they are high in the tree or sheltered from sky radiation.

**CRITICAL TEMPERATURE TABLES**

The accompanying charts are updated slightly from those in the first edition of this bulletin. The old standard temperatures are taken from the 1970 National Weather Service Bulletin (W. J. Rogers, and H. L. Swift, "Frost and the Prevention of Frost Damage"; U.S. Dept. of Commerce, NOAA, Silver Spring, MD, 35 PP.). These figures are the official descendants of the original critical temperatures.
The tables have been changed by including an additional six years' data and by starting our conversion from Fahrenheit to Celsius scales. Some of the numbers are changed, partly because very few figures went into the earlier averages. This serves to emphasize that no critical temperatures are absolute values.

The Celsius figures in the tables for the 10 per cent and 90 per cent levels are from the original research data and the Fahrenheit figures are rounded to the nearest degree.

The average date for the beginning of each stage is for the orchards at the WSU Research Center at Prosser, which has an elevation of 1100 feet, and is an average of the years 1964-1976. The date may serve as a guide to when buds become susceptible and the time intervals between stages.

In addition, average temperatures required to kill 10 per cent and 90 per cent of normal buds are shown. These data come from freezing tests performed at Prosser over the same 1964-76 period. These new values are not replacements for the old standard temperatures. Instead, they provide additional information.

During the early stages of development, there is a wide difference between the critical temperature (temperature endured for 30 minutes without damage) and that required to kill 90 per cent of the buds. With a heavy bud set, many growers might be willing to gamble by using a lower value for the critical temperature, knowing that loss of a certain percentage of buds can be sustained without reducing the crop. After about first bloom, this margin of safety is mostly gone and the risk of too-heavy losses becomes much greater.

The temperature at which a 10 per cent kill is observed varies widely during the early stages of spring development. This reflects day-to-day changes in hardiness, caused mostly by the weather. Such changes can be observed and, perhaps, forecast.

When the first buds on a tree reach a given stage we consider the tree to be at that stage. The data come from samples that included the two or three stages that may have existed on the tree at any one time.

For colored photographs showing each of the bud development stages, see the series of Extension Circulars, "Critical Temperatures for Blossom Buds." Stages for apples are shown in Extension Circular 369, pears in Extension Circular 370, cherries in Extension Circular 371, prunes in Extension Circular 372, peaches in Extension Circular 373, and apricots in Extension Circular 374.

CRITICAL TEMPERATURE TABLES IN °F. WITH °C. IN PARENTHESES

APPLES*

<table>
<thead>
<tr>
<th>Bud Development Stage</th>
<th>Silver Tip</th>
<th>Green Tip</th>
<th>Half-Inch Green</th>
<th>Tight Cluster</th>
<th>First Pink</th>
<th>Full Pink</th>
<th>First Bloom</th>
<th>Full Bloom</th>
<th>Post Bloom</th>
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<td>Old Standard Temp.</td>
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<td>22(-5.6)</td>
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<td>26(-3.2)</td>
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<td>28(-2.3)</td>
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<td>24(-4.7)</td>
<td>26(-3.3)</td>
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*For Red Delicious. Golden Delicious and Winesap approximately 1 degree hardier; Rome Beauty, 2 degrees hardier; except after petal fall, when all varieties are equally tender.

PEARS*

<table>
<thead>
<tr>
<th>Bud Development Stage</th>
<th>Scales Separating</th>
<th>Blossom Buds Exposed</th>
<th>Tight Cluster</th>
<th>First White</th>
<th>Full White</th>
<th>First Bloom</th>
<th>Full Bloom</th>
<th>Post Bloom</th>
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<tbody>
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<td>25(-3.9)</td>
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<td>30(-1.1)</td>
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<td>Ave. Temp. 10% kill</td>
<td>16(-8.6)</td>
<td>19(-7.3)</td>
<td>23(-5.1)</td>
<td>24(-4.3)</td>
<td>26(-3.1)</td>
<td>26(-3.2)</td>
<td>27(-2.7)</td>
<td>27(-2.7)</td>
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<td>0(-17.7)</td>
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<td>9(-12.6)</td>
<td>15(-9.4)</td>
<td>20(-6.4)</td>
<td>20(-6.9)</td>
<td>23(-4.9)</td>
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<td>Ave. Date (Prosser)</td>
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<td>3/24</td>
<td>3/30</td>
<td>4/7</td>
<td>4/12</td>
<td>4/14</td>
<td>4/19</td>
<td>4/27</td>
</tr>
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</table>

*For Bartlett. Anjou is similar in hardness but may bloom earlier and therefore may be more tender than Bartlett at the same date.
## CHERRIES*

<table>
<thead>
<tr>
<th>Bud Development Stage</th>
<th>First Swelling</th>
<th>Side Green</th>
<th>Green Tip</th>
<th>Tight Cluster</th>
<th>Open Cluster</th>
<th>First White</th>
<th>First Bloom</th>
<th>Full Bloom</th>
<th>Post Bloom</th>
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<tbody>
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<td>28(−2.2)</td>
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<td>Ave. Temp. 90% kill</td>
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*For Bing, Lambert and Rainier approximately 1 to 2 degrees hardier through First White.

## PRUNES*

<table>
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<th>Bud Development Stage</th>
<th>First Swelling</th>
<th>Side White</th>
<th>Tip Green</th>
<th>Tight Cluster</th>
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<th>First Bloom</th>
<th>First White</th>
<th>Post Bloom</th>
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<tbody>
<tr>
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<td>—</td>
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<td>27(−2.8)</td>
<td>30(−1.1)</td>
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<tr>
<td>Ave. Temp. 10% kill</td>
<td>12(−11.1)</td>
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*For Italian Prunes and Early Italian Prunes.

## PEACHES*

<table>
<thead>
<tr>
<th>Bud Development Stage</th>
<th>First Swelling</th>
<th>Calyx Green</th>
<th>Calyx Red</th>
<th>First Pink</th>
<th>First Bloom</th>
<th>Full Bloom</th>
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*For Elberta.

## APRICOTS

<table>
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<tr>
<th>Bud Development Stage</th>
<th>First Swelling</th>
<th>Tip Separates</th>
<th>Calyx Red</th>
<th>First White</th>
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<th>In the Shuck</th>
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The authors wish to express appreciation to Claude B. Graves, Jr., and Alan H. Jones, National Weather Service; Ronald B. Tukey, Mel A. Hagood, and Henry Waelti, Washington State University Cooperative Extension Service; and Porter B. Lombard, Southern Oregon Experiment Station, for their help in preparing this publication.
# Temperature Conversion Scales

Source: Handbook of Chemistry and Physics


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