FROST AND FROST CONTROL IN WASHINGTON ORCHARDS
Successful orchardists know the importance of maintaining annual production of high quality fruit. They are aware of the influence of frost in reducing yields, as well as the quality of fruit.

In recent years, the control of frost injury has become more complicated because of increased labor costs, air pollution ordinances, new frost prevention techniques, and high density orchard management practices.

Expansion of orchards into new districts has opened a large market for frost prevention equipment. Fruit growers have been exposed to over 20 new orchard heaters since 1965. The difference between orchard sites and varieties or kinds of fruit play important roles in the evaluation of these new systems.

In addition to the new centralized fuel heaters, the fruit grower must also assess the characteristics of various orchard fuels available, such as petroleum bricks, diesel oil, liquid propane, or natural gas. He must also assess new techniques such as overtree wind machines, overtree sprinkling, fogging, humidification, and chemical sprays.

Some orchards are now planted with as many as 600 trees per acre. These high density hedgerow orchards definitely increase the frequency of frost by retarding air drainage. The new central leader trees are designed to produce fruit on smaller trees, with a larger share of the fruit developing closer to the ground, where the air is naturally colder. The compact hedgerow orchard will definitely affect the distribution of the heat from ground heaters.

The planning and management of these orchards requires special attention to frost prevention techniques.

A basic understanding of the physical laws of nature pertaining to frost is essential if the orchardist is to do a good job in preventing frost injury. An understanding of the weather pattern in his district can help the grower decide which system is best for his needs. For example, he must know what an "inversion" is in order to understand how an overtree wind machine works. He must know his orchard site so he can plant the more frost resistant fruits in the colder areas. He must understand the critical temperatures for each kind of fruit and stage of growth and how weather conditions can change the critical temperatures. He must know the kind of frost confronting him each time the frost alarm rings.

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 most common is the radiation type which occurs on cloudless nights with little or no wind. Heat from the ground is lost as radiation into the sky. The air in contact with the ground is cooled. 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 loss of heat from the ground by radiation on clear nights constitutes a loss of energy from the orchard of approximately 900,000 British Thermal Units per acre hour at its peak. Near sundown, the input is equal to the output. From that time until dawn, the energy loss is variable, according to clouds and relative humidity, but is almost always at its greatest out-
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 benefit from a clean-cultivated orchard floor. This difference is not great enough to sacrifice the value of the sod.
flow just a few minutes before sunrise.

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. The two types are not distinct and many nights have characteristics of both. However, the cold 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.

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.

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 elevation than at the 3- or 5-foot elevation.

The actual strength of the inversion can be easily measured over an orchard. The frequency and strength of low level inversions during periods when frost protection is needed determines the feasibility of overtree wind machines.

The strength of the inversion layer has an important effect on the performance 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 heater, its temperature is only a few degrees higher than that of the surrounding air. When this happens, the upward motion of the heated stream stops. The height at which the stream from the heater reaches equilibrium is called the *ceiling*.

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 which is required are relatively high. Following the influx of extremely cold polar air, the ceiling is exceptionally high and wind has very little effect on increasing the temperature.

**WIND**

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 thoroughly mix all the air in and above the trees occurs, the temperature within the orchard can actually rise.

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

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

**CLOUDS**

The heat lost from the orchard is radiated
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.

Thus, smoke works against the orchardist all night by polluting the air and creating unpleasant living conditions, and, at dawn, forces him to continue heating until the smoke is dispersed by morning winds.

**DEWPOINT**

Dewpoint is the temperature at which moisture will begin to condense out of a particular mass of 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 is several degrees below the critical temperature. This is explained by the liberation of "latent heat" during the formation of dew or frost.

A simple method of explaining 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
THE STATUS OF YAKIMA COUNTY’S ANTI-SMOKE ORDINANCE

The Crop Heating Ordinance of Yakima County was prepared by a committee of growers and homeowners appointed by the Board of County Commissioners during the winter of 1964-65. After much discussion and a public hearing, the county passed the ordinance on December 15, 1965.

Its immediate effect was to outlaw the burning of rubber tires or rubber-based products as a fuel in orchard heating.

This crop heating ordinance designated a grace period of five years for growers to convert the smoky open pots to clean-burning heaters. During these five years, commercial development, research, and grower experimentation resulted in many new types of orchard heaters.

In May, 1970, the Board of Directors of the Yakima County Clean Air Authority adopted Regulation I, which established the use of the Ringelmann smoke chart as a means of measuring the smoke emissions from heaters. Regulation I superseded the existing regulations, but did not change the original intent of the crop heating ordinance.

Regulation I does not describe which type of unit is acceptable or unacceptable. The regulation does, however, depict the amount of visible emissions that will be allowed from any particular unit.

The Ringelmann smoke chart provides four equal graduated shades of gray between black and white. This will be used as a device by which the density of smoke rising from heaters will be judged to determine whether emissions are within the limits of permissibility. A Ringelmann 2 rating is permissible until January 1, 1975, when a reduction to Ringelmann 1 will become effective.

William Cramer, Yakima County Clean Air Authority director, encourages each individual to choose his new heating equipment carefully, because of the many orchard heating units now on the market. When operated efficiently, most of these produce no visible emissions at all. It is the grower’s responsibility to keep the new “smokeless” systems in good order, because it has been demonstrated that they will exceed the smoke tolerance if not operated properly.

Growers are also encouraged to investigate the many conversion units available because of the potential savings possible as compared to a complete new system. For example, the old 5-gallon paint pail will burn clean with a properly adapted oil-pressure jet conversion kit.

A Ringelmann 1 visible emission is not very much smoke. If any visible emissions at all are occurring, they will serve as an excellent visual warning to inform the grower that his equipment can be improved.
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 springtime heating season, dewpoints higher than 30°F. are considered high and those of less than 20°F. are considered low. Dewpoints below zero 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 which may tax the grower’s ability to light up his heating system in time.

Temperature drops of 10 degrees within 15 minutes have been experienced in central Washington orchards.

WEATHER MONITORING EQUIPMENT

FROST ALARMS

Frost alarms are an essential part of a well-managed frost protection system. Reliable 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.

One of the better systems uses mercury thermometer sensors constructed with permanent pre-determined temperature switches. When the mercury column drops below the set temperature, the current is broken and the alarm rings. This procedure safeguards against broken lines between the orchard station and the alarm buzzer. If the line should become broken, the buzzer will sound.

Reliable frost alarms are available at costs of $40 to $150. The more expensive ones have extra conveniences built in.

Some systems have stand-by batteries which are automatically cut in if the commercial electrical power is interrupted.

The electrical thermostat units commonly used in the central valleys of Washington should be protected with dust-proof covers during the off season. Orchard sprays, dusts, and insects can interfere with the bimetal contact points. They should also be checked frequently during the frost season since they do not have the "broken circuit" warning advantage.

The sensor of any frost alarm system should be placed in a standard thermometer shelter.

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 easily checked by placing it in an ice-water slush with at least two check thermometers.

THERMOMETERS

The only 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.”

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 two are needed, one for the coldest location in the orchard, and one nearby outside the heated area for guidance on when to cease firing. 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 in 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 ex-
posed 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. Separations 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 be stored upright with the bulb down and in a cool place.

National Weather Service offices 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.

The meteorologists test the thermometers for accuracy by submerging them in a slurry of water and ice. The water in the mix will stabilize at 32°F, after stirring for several minutes.

The illustration of the standard thermometer shelter gives the dimensions essential for the basic design. Place the thermometer approximately 5 feet 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 lower than the top end. It should be supported with about ½ inch 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. Some growers have added reflective tape to the shelters to make it easier to locate them during the 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 quickly affected 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. Weather Meteorologist or your County Extension Agent can tell you where you can purchase a sling psychrometer.

In addition to this instrument, you will need a copy of the U.S. Department of Commerce psychrometric tables for obtaining the dewpoint. Weather Service Bulletin No. 235, which contains these, is available from the Superintendent of Documents, Washington, D.C. It has some important directions on how to take the dewpoint readings, which becomes more complicated at temperatures at or below 32°F.

HEATING EQUIPMENT AND HEATING FUELS

A frost prevention system must keep the temperature from dropping below the critical level. The system should be adequate to give at least 7 degrees rise in temperature. Requirements may vary from over 40 heaters per acre for one orchard site to 20 heaters or less in another site.

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.

The number of heaters per acre will depend upon the energy output capacity of the heater. However, it is also important to provide heat distribution throughout the protected area. It is a well-proven fact that many small fires are more effective than a few large ones.

The number of heaters per acre is also influenced by the design of the orchard. High density hedgerow plantings, with trees trained from the ground up, may require more heaters per acre than conventional orchards with standard open-center trees.

Commercial heaters available today produce variable rates from as low as 500 BTU's per hour to as high as 300,000 BTU's per hour.

Most of the modern orchard heaters have a radiant heat fraction of 20% to 70% 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 of fuel combustion and a considerable savings of labor as compared to the individual pot systems.

Briefly, here is a list of the orchard heating systems with some of the advantages and disadvantages for each.

INDIVIDUAL POT SYSTEMS

Individual pot heaters range from the return stack heater to the open oil pot.

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 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
RETURN STACK HEATER

LARGE CONE HEATER

OPEN OIL POT WITH COVER

24-INCH STACK HEATER
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 with all holes closed. This problem is remedied by using large plastic bag covers when undertree sprinklers are in use.

**The Large Cone Heater**

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 will also resist taking in sprinkler water. However, it will soot up more rapidly than the return stack. This requires more frequent cleanings in order to prevent a smoky performance.

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

Similar to the return stack heater in lighting procedure, the large cone heater performs most efficiently at a one-hole setting, where it consumes an average of 0.7 gallons 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 in length. Generally, the ones with 24 inch or longer stacks will burn quite clean 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 volatized oil to escape. This fraction of lost energy, in addition to the smoke, contributes to the heaters’ low efficiency.

**Open Oil Pots**

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

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% of the energy output.

All of the individual pot heaters have the advantages of low initial cost of capital investment, 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 have been greatly improved in recent years. These systems use elaborate pumps, filters, plumbing, and nozzles.

The systems deliver the fuel (No. 2 diesel oil) through plastic lines from a central control point. Automatic electric ignition for each heater

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**ON RADIANT HEAT**

Heating is most difficult on nights with small inversions or so-called high ceilings. With a small inversion, the convective heat is largely wasted above the tree tops and radiant heat thus becomes the principal means of protection.—Bulletin 723, “Effectiveness of Orchard Heaters,” Robert A. Kepner, Assistant Professor of Agricultural Engineering, University of California, Davis.
STANDARD LARGE CONE HEATER CONVERTED TO OIL PRESSURE SYSTEM

HOMEMADE OIL PRESSURE HEATER WITH OIL JET BEING EXAMINED BY AUTHOR JIM BALLARD

FOUR DIFFERENT OIL PRESSURE SYSTEMS
has been developed to offer quicker light-ups to save labor. It has been demonstrated that stack heaters and some open oil pots can be converted to the pressurized systems and burn clean enough to pass smoke ordinance requirements.

The main advantage of the centralized oil pressure systems is the great operational efficiency. Most of these systems will convert approximately 99% of the oil into usable energy. There is no waste of oil 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 pressures to 200 pounds per square inch 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. Above all, underground laterals must be gopher proof.

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

There are several commercial oil pressure systems on the market. All use the same principle of jetting the oil through a filtered bronze furnace nozzle. The nozzle should be kept as cool as possible at all times. This is accomplished by having the draft enter near the nozzle, forcing the flame away from it.

Experience on sloping ground has shown that gravity feedback has permitted the flame to continue for several minutes after the system is shut off. This unpressurized flame often engulfs the nozzle and sometimes burns below it, causing damage to the nozzle. This experience shows the practical need for a check valve for each heater. The valves close abruptly when the pump is turned off. This 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.

Reverse pumps have been used to eliminate the gravity-fed flames but have been discarded because they cause faulty nozzle operation.

Off-season storage should follow the directions of the manufacturer. Storing the heaters and plastic pipes in the trees is a sure way to invite faulty operation.

**GAS HEATERS**

The use of liquid propane (L.P.) and natural gas as orchard fuels has proven to be both convenient and economically feasible. Natural gas is the most convenient of all orchard fuels. It requires no tanks, pumps, or filters and burns with a minimum of heater maintenance.

Natural gas is not readily available to most orchards. Growers using this fuel are located where the gas mains run through or next to their property. Natural gas users must bear the continuing meter charge which gas companies require.

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. Propane, however, has some very distinct advantages which account for its increasing popularity. Its use in orchard heating in central Washington has increased steadily since 1966.

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. 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 may reduce to a point below the peak needs of your heating system.
Normal vaporization is the point at which 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 to 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 heats the liquid either by hot water or indirect fire to increase vaporization for the heavy demands.

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.

<table>
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<tr>
<th>Temperature</th>
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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 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.

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.

Propane, however, has another property referred to as "limits of inflammability." The lower limit is 2% propane vapor to 98% air. The upper limit is 9.5% propane vapor to 90.5% 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 to each 10,000 gallons 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 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 per hour at the peak need, two average six-hour firings would consume 480 gallons per acre in the field and approximately 20 gallons in the vaporizer. This would result in a basic figure of 500 gallons storage capacity per acre as a safe minimum.

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 tanks in orchards requiring protection on 60 acres or more.

Growers near railroad sidings can take advantage of tank car delivery for the larger storage tanks.

In addition to the several excellent commercial propane orchard heaters on the market,
A ROW OF HOMEMADE L.P. GAS HEATERS WITH THE GAS LINE BURIED

A SIMPLE HOMEMADE PROPANE HEATER USING SCRAP MATERIAL AND A LITTLE INGENUITY

30,000 GALLON PROPANE TANK WITH HOT AIR WARMER
LIGHT UP EQUIPMENT

An orchard lighting torch is essential for all forms of heaters. This is the standard lighting torch. It is important to keep the asbestos wick in position and replace when necessary. The fuel mix recommended by the manufacturer is $\frac{1}{3}$ gallon gasoline to $1\frac{1}{2}$ gallons diesel oil.

For speed and reduced labor, pressurized flame throwers have become popular. The fuel used in these is generally 5 gallons of gasoline with 8 gallons of diesel oil. The remainder of the 25-gallon tank is air compressed to 110 pounds per square inch.

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.

fruit growers can make their own by using various pipes, pails, or U.S. army shell casings for the combustion chambers.

Propane fuel has the added advantage of allowing the grower to operate the heaters over a wide range of fuel consumption. The lower ranges permit "pilot" standby for gradual increase as the need arises. This convenience prevents over-heating and saves considerable fuel as compared to some other systems using oil or solid fuel.

SOLID FUELS

The use of solid fuel in orchard heating involves wood, compressed sawdust logs, paraffin, and petroleum bricks. Coal and rubber tires have been used but have not proven satisfactory.

Solid fuel has the advantage of letting the grower get into frost protection with a minimum of capital outlay.

This economic advantage may be short-lived, however, if more than two light-ups per season are required.

Growers using solid fuel give testimony that little or no flexibility of temperature adjustment is possible.

Most solid fuels require a longer warm-up period. The labor requirement is excessive for those solid fuels which require additional fueling. Paraffin "candles" have proven very difficult to extinguish.

An exception is the use of petroleum bricks, constructed with fast light-up pads and waterproof coverings. These can be distributed with ease in the orchard with palletized loadings. If the bricks are not used in one season, they can be re-palletized for convenient storage for the following season.

In spite of the several disadvantages of solid fuel, there are three instances where growers should consider its use:

1. Relatively frost-free areas where heating is rarely needed. Solid fuel can be kept on hand as standby insurance against an unusual freeze.

2. Those growers who want supplemental heat to existing systems as insurance against extreme, but rare, cold spells.

3. Those growers who want to hold off another year while deciding which permanent system to install.
HEATING PROCEDURES

With the use of orchard heaters, certain procedures are recommended for a more efficient firing.

When it comes time to light up, your objective is to distribute the heat in a manner that will hold all sections of the heated area above the critical temperature.

Light the borders first on the windward or upslope side. Then light every other heater (with individual pot systems) or every other row (with piped pressure systems). With propane systems, you can light all the heaters and hold on low pilot.

Patrol the orchard after the first lighting to determine if additional heat is needed. If you apply too much heat at first, you can develop a cold air influx that will actually give you a temperature drop, particularly around the borders.

If you need more heat, light additional burners or turn the central control systems up higher.

Alan Jones, meteorologist in charge of the Fruit Frost Service of the National Weather Service at the Tree Fruit Experiment Station, reports on five examples of frost problems common to central Washington valleys:

1. The critical temperature is reached. You've made your first lighting of heaters. Occasional light puffs of wind are noticeable and you observe a sudden temperature rise. This may be delayed air drainage. If erratic, it probably won't last, particularly if it is still several hours before sunrise. You may reduce heat, but patrol the thermometers regularly. Winds occurring several hours before sunrise can quit again. Your thermometers are your guideline for turning the heat up or down.

2. The critical temperature is reached. The first lighting is made and the temperature suddenly rises. This time you observe a cloud drifting over. Leave your heaters as is, unless a solid cloud bank is moving in.

3. The sun has risen after a long, arduous night of firing. Check your outside thermometer before turning the heaters off. It takes time for the natural temperature rise to take over, particularly if the low level air is smoky. If you have a normal cold air drainage into the orchard, you may observe a sudden drop in temperature after sunrise.

4. The frost alarm rings. You prepare to light but the thermometers all read 3 to 5 degrees above the critical temperature. The sky is clear and winds have subsided. The forecaster predicted a low dewpoint of 15°F. with a high ceiling. This means a fast temperature drop. With cold air masses over the district, temperature drops of 9 degrees in 15 minutes have been observed. With an abnormally low dewpoint, you will have trouble holding the temperature above critical. It is better in this case to fire a little early.

5. An advective freeze is upon you. You have done everything right and still the temperature falls. This tells you your heating system is inadequate for future severe situations. For the time being, keep the heat going. You will get some damage but not as much as if you give up and turn the heat off.

WIND MACHINES

Experience with large overtree wind machines in central Washington valleys has proven that usable warm air inversions are prevalent over many orchard sites on most of the frosty nights. The principle of the machine is to mix the warm air in the inversion with the colder air among the trees.

Wind machines which produce and blow supplemental heat from the machine have proved to be less efficient than those that do not create the added heat. Added heat makes the mixed air more buoyant, causing it to rise above the tree tops sooner.

If inversions are too weak or above the reach of the machine, no benefit will be gained by turning it on. Supplemental heat from heaters
During the early 1960's, there was much promotion of low-level ground wind machines coupled with heat generators. They blew out a terrific blast of hot air. The experience of most growers verified what the meteorologists said, "Single, large heaters produce a large hot air mass that rises too fast."

Several growers in Yakima are successfully using small ground fans in conjunction with the pot heaters. Some are electric powered, others gasoline. The mixing action increases the efficiency of the convective heat from standard heaters. It helps prevent the hotter air from rising above the trees. The fans also are beneficial in speeding up the flow of cold air down sluggish valleys or draws.

OVERTREE WIND MACHINE WITH ADEQUATE POWER TO COVER APPROXIMATELY 10 ACRES
placed among the trees in the outer perimeter from machines will be helpful on nights of weak or no inversions.

Experience indicates that it is difficult to predict whether a wind machine will be practical. Temperature measurements of the air up to 50 feet above the ground can be monitored during the frost season by using instant-reading electric thermometers. Three of these thermocouple sensors attached to poles at elevations of 5, 30, and 50 feet will give sufficient information to determine the feasibility of a standard overtree wind machine.

If the orchard site consistently shows an inversion with temperatures that are at least 3 degrees warmer at the 30- to 50-foot zone than among the trees, a wind machine could conceivably be worth trying.

The effective range of a single overtree wind machine will vary from 6 to 10 acres. The area covered will be dependent on orchard site, the size of the machine, and the proximity of other overtrees. Two or more machines will tend to reinforce the effectiveness of each other.

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, overtree sprinkling has some distinct advantages.

If the technique is that risky, the fruit grower may ask, “Why attempt it?” Enthusiastic supporters for this method agree that the operational costs are lower than with any other method 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 Fahrenheit reduction.

This heat is given up until the temperature of the water reaches 32°F. It then gives off 144 BTU’s per pound 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.

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, 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.

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 after dawn. Secondly, the process can build up a layer of ice which can, under long periods of freezing, 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., 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. In fact, the customary air temperature measurements used in regular oil or gas orchard heating may be misleading. For example, a sheltered dry bulb thermometer in the protected area will often read colder temperatures than one outside the sprinkled area. This is due to the evaporative cooling of the air as the water passes through it. An exposed thermometer can be used to indicate the amount of protection as compared to a thermometer outside the sprinkled area.

WATER SUPPLY

Since it is not economically feasible to engineer a flexible-rate sprinkling system, the minimum application rate for protection down to
OVERTREE SPRINKLING USES THE LATENT HEAT RELEASED WHEN ICE FORMS TO KEEP THE PLANT TISSUES AT 31.5° F.

20°F. is 0.15 to 0.20 inches 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 per hour will protect deciduous fruit tree blossoms to 20°F. with a low dewpoint.

This is one of the most important limiting factors of overtree sprinkling as a frost prevention technique. All economically justified heating systems begin to fail at temperatures below 20°F. when accompanied by low dewpoints and wind. Even so, you will likely have some fruit if a diligent heating job is done.

The likelihood of overweighing 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 eastern Washington.

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

The application rate of 0.15 inches per hour requires 67.3 gallons per acre per minute or 4,038 gallons per acre per hour. It accumulates 1½ inches 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. Once you commit yourself to this technique, you are obligated to go all the way. 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 the 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 overtree 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. Two
revolutions per minute is better. 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 if the interruption is long enough.

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 or interruption of only a few minutes 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 direction, the tree spacing and arrangement, and the direction of the traffic pattern in the orchard. The closer spacing of 40 by 40 feet for frost protection would offer better distribution of water and, therefore, better coverage than wider settings.

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. In addition, the area should be isolated by a road or a complete break in the orchard area sprinkled and not sprinkled.

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% of the wetted diameter.

OPERATION

Sprinkling should usually begin when the temperature of the shielded thermometer has dropped to 33°F. Starting at lower temperatures, as indicated by the critical temperature charts, is a greater risk, as temperatures within the sprinkled area will drop during the first few minutes of operation. Also, water in the stand-pipes may freeze if you wait too long. Experience has shown that this clogs the nozzles, resulting in an erratic, uneven start for the night. Therefore, starting at 33°F. provides a margin of safety. This temperature should be taken in the coldest spot in the area to be sprinkled.

It is safe to end the sprinkling after sunup when the rising temperature reaches 33°F. outside the treated area and the ice is beginning to melt. If it is windy, it is wise to wait until the air temperature rises to 35°F. It is not necessary to wait until all the ice has melted.

Running the overtree sprinkling system from the time the temperature drops to 33°F. until it returns to 33°F. 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 the 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. Rigidly trained apple trees with a central leader and strong branches will support more ice than the older open-vase trees. However, it may be necessary to install ropes or some form of branch support

OTHER METHODS OF FROST PROTECTION

New techniques of preventing frost or freeze injury are being discussed and researched. These include humidification, chemical sprays, polarization, and covering the orchard with foam. Until successful demonstrations of these proposed methods have been made, no recommendations can be advanced.
to prevent limb breakage or warpage.

Growers contemplating the use of this principle should be aware of the potential of excessive application during the frost season. Experience in central Washington has shown that as much as 15 inches of water can be applied within 30 days. The orchard soil should have the ability to absorb or drain off the amount in excess of its water holding capacity.

Keeping the water free of sand, silt, and other debris is essential to prevent plugging of sprinkler nozzles. It is difficult enough to patrol sprinklers at night in freezing weather without adding the grievance of finding and correcting inactive sprinkler nozzles.

During the “wet” season it may become impossible to take heavy equipment into the orchard. The grower may find it necessary to fly on the sprays required at this time.

The grower should also pay careful attention to the nutritional needs of the trees and cover crop. The excessive applications of water during a long frost season may leach nitrogen, boron, and other elements out of the root zone.

### ARTIFICIAL FOGS

The absence of frost damage on cloudy or foggy nights is due to the ability of natural clouds and fog to act as blankets to outgoing radiation. In recent years there have been many attempts to find a successful artificial substitute. This principle is one of the oldest proposals of frost prevention.

Oil fog generators have been tried, but have failed—even when copious amounts of opaque fog were held over the test area. Because of its almost complete transmissivity to the low temperature radiation encountered between the ground and the sky, oil fog is valueless as a means for protecting against frost.

The success of an artificial fog will depend upon the water droplet size and the quantity of the product that can be held over the area to be protected.

In recent years, new generators have been developed to create fog with the water droplets stabilized with cetyl alcohol. The theory is still being tested, even though the trials have failed to produce a dependable, economically feasible technique.

It should also be pointed out that fog stabilized with cetyl alcohol is presently classified as a hydrocarbon pollutant and will exceed a No. 1 Ringelmann reading.

### 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 separates the temperature required to kill 10% of the buds from that required to kill 90% of them. Cold weather (below 28°F. to 30°F.) 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% of the buds and 90% of them may be as great as 20 degrees. 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% and 90% 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. Radiative cooling makes these flowers enough cooler than sheltered flowers that they almost always are the first to freeze.

In the small green fruit stage, the freezing point is 29°F. to 31°F. The fruit will not survive freezing. It has practically no ability to harden. There is no variability in hardiness. 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 Service 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., 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 hardness** 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 hardness. 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 hardness 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 hardness. 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 hardness of the tissues. Early 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 no harder than other varieties.

VARIETAL 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 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 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 designed to widen our view of critical temperatures. Several changes from the old standard temperatures in Extension Mimeo 1616 have been made.

The division of stages of development has been made more specific for each species. Critical temperatures from the WSU Extension Mimeo 1616, “Frost Protection,” by Rogers, Luce, and Snyder, have been adapted to the altered stages of development and appear unchanged.

An average date for the beginning of each stage has been added. These figures are for the orchards at the WSU Research Center at Prosser, which has an elevation of 1100 feet, and are an average of the years 1964-1970. They may serve as a guide to when buds become susceptible.

Average temperatures required to kill 10% and 90% of normal buds are shown. This data comes from freezing tests performed at Prosser over the same 1964-1970 period. These new values are not replacements for the old standard temperatures. Instead, they provide additional information. The most reliable data are on the cherries because the most work
has been done there. Much research remains to be done.

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% 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 10% 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.

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.

### 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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<tr>
<td>Old Standard Temp.</td>
<td>16</td>
<td>16</td>
<td>22</td>
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<td>28</td>
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<tr>
<td>Ave. Temp. for 10% Kill</td>
<td>15</td>
<td>18</td>
<td>23</td>
<td>27</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
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<tr>
<td>Ave. Temp. for 90% Kill</td>
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<td>10</td>
<td>15</td>
<td>21</td>
<td>24</td>
<td>25</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>
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<td>Old Standard Temp.</td>
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<td>19</td>
<td>22</td>
<td>23</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</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>
</tr>
</thead>
<tbody>
<tr>
<td>Old Standard Temp.</td>
<td>23</td>
<td>23</td>
<td>25</td>
<td>28</td>
<td>28</td>
<td>29</td>
<td>29</td>
<td>29</td>
<td>30</td>
</tr>
<tr>
<td>Ave. Temp. for 10% Kill</td>
<td>17</td>
<td>22</td>
<td>25</td>
<td>26</td>
<td>27</td>
<td>27</td>
<td>28</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Ave. Temp. for 90% Kill</td>
<td>5</td>
<td>9</td>
<td>14</td>
<td>17</td>
<td>21</td>
<td>24</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

* For Bing. Lambert and Rainier approximately 1 to 2 degrees hardier through First White.
### PRUNES*

<table>
<thead>
<tr>
<th>Bud Development Stage</th>
<th>First Swelling</th>
<th>Side White</th>
<th>Tip Green</th>
<th>Tight Cluster</th>
<th>First White</th>
<th>First Bloom</th>
<th>Full Bloom</th>
<th>Post Bloom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Standard Temp.</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>23</td>
<td>27</td>
<td>27</td>
<td>30</td>
</tr>
<tr>
<td>Ave. Temp. for 10% Kill</td>
<td>14</td>
<td>17</td>
<td>20</td>
<td>24</td>
<td>26</td>
<td>27</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Ave. Temp. for 90% Kill</td>
<td>0</td>
<td>3</td>
<td>7</td>
<td>16</td>
<td>22</td>
<td>23</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Average Date (Prosser)</td>
<td>3/13</td>
<td>3/20</td>
<td>3/27</td>
<td>4/3</td>
<td>4/8</td>
<td>4/12</td>
<td>4/16</td>
<td>4/23</td>
</tr>
</tbody>
</table>

* 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>
<th>Post Bloom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Standard Temp.</td>
<td>23</td>
<td>—</td>
<td>—</td>
<td>25</td>
<td>—</td>
<td>27</td>
<td>30</td>
</tr>
<tr>
<td>Ave. Temp. for 10% Kill</td>
<td>18</td>
<td>21</td>
<td>23</td>
<td>25</td>
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<td>28</td>
</tr>
<tr>
<td>Ave. Temp. for 90% Kill</td>
<td>1</td>
<td>5</td>
<td>9</td>
<td>15</td>
<td>21</td>
<td>24</td>
<td>25</td>
</tr>
<tr>
<td>Average Date (Prosser)</td>
<td>3/7</td>
<td>3/16</td>
<td>3/19</td>
<td>3/29</td>
<td>4/3</td>
<td>4/11</td>
<td>4/18</td>
</tr>
</tbody>
</table>

* For Elberta.

### APRICOTS

<table>
<thead>
<tr>
<th>Bud Development Stage</th>
<th>First Swelling</th>
<th>Tip Separates</th>
<th>Red Calyx</th>
<th>First White</th>
<th>First Bloom</th>
<th>Full Bloom</th>
<th>In the Shuck</th>
<th>Green Fruit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Standard Temp.</td>
<td>—</td>
<td>23</td>
<td>—</td>
<td>25</td>
<td>—</td>
<td>28</td>
<td>—</td>
<td>31</td>
</tr>
<tr>
<td>Ave. Temp. for 10% Kill</td>
<td>15</td>
<td>20</td>
<td>22</td>
<td>24</td>
<td>25</td>
<td>27</td>
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<td>28</td>
</tr>
<tr>
<td>Ave. Temp. for 90% Kill</td>
<td>—</td>
<td>0</td>
<td>9</td>
<td>14</td>
<td>19</td>
<td>22</td>
<td>24</td>
<td>25</td>
</tr>
<tr>
<td>Average Date (Prosser)</td>
<td>—</td>
<td>—</td>
<td>3/8</td>
<td>3/16</td>
<td>3/22</td>
<td>3/28</td>
<td>4/4</td>
<td>4/18</td>
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</tbody>
</table>

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