CIRCULAR 400 NOVEMBER 1950

THE PRINCIPLES OF ORCHARD HEATING

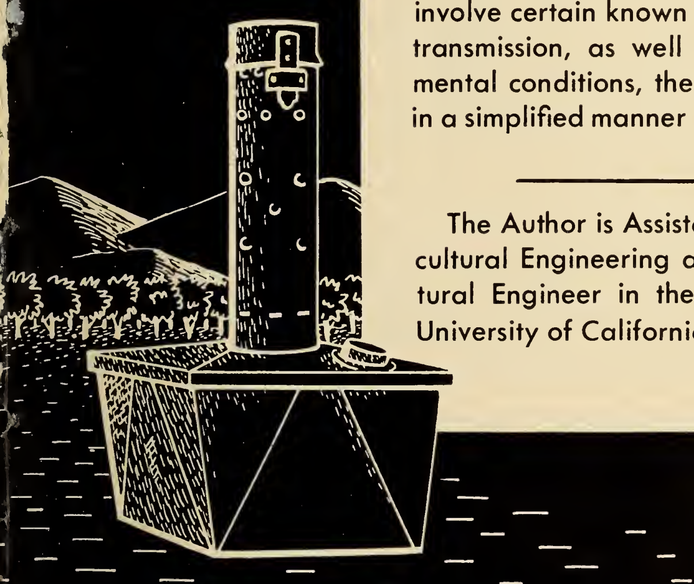
ROBERT A. KEPNER

This circular gives the highlights of findings made during orchard heating tests that were conducted in citrus orchards in southern California during 5 winters, from 1937 to 1942. The tests were made by the Division of Agricultural Engineering.

As a result of the tests and the findings, recommendations are made as to types of orchard heaters, their placement in the orchard, and their burning rates. Specific recommendations are made for border heating.

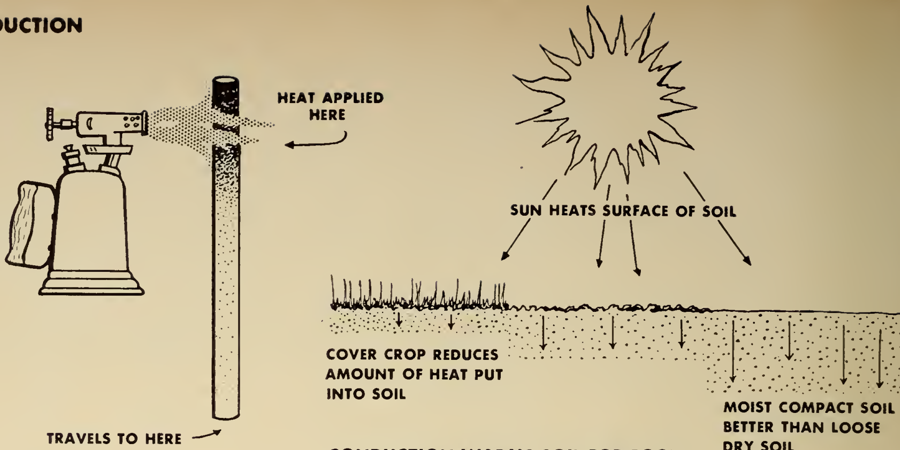
Since these studies and recommendations involve certain known physical laws of heat transmission, as well as orchard environmental conditions, these too are explained in a simplified manner in the first few pages.

The Author is Assistant Professor of Agricultural Engineering and Assistant Agricultural Engineer in the Experiment Station, University of California, at Davis



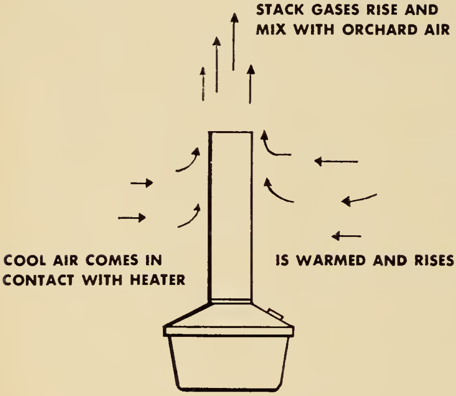
CALIFORNIA AGRICULTURAL EXPERIMENT STATION • THE COLLEGE OF AGRICULTURE • UNIVERSITY OF CALIFORNIA • BERKELEY

CONDUCTION

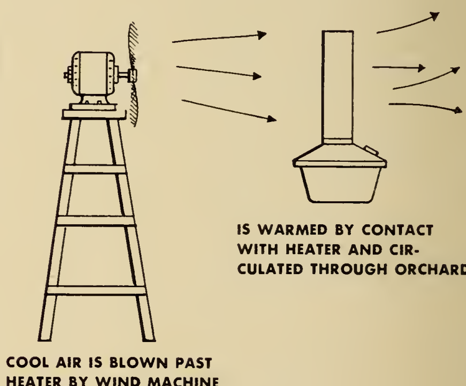


CONDUCTION WARMS SOIL FOR FOOT OR SO BENEATH SURFACE, STORING HEAT FOR USE AT NIGHT.

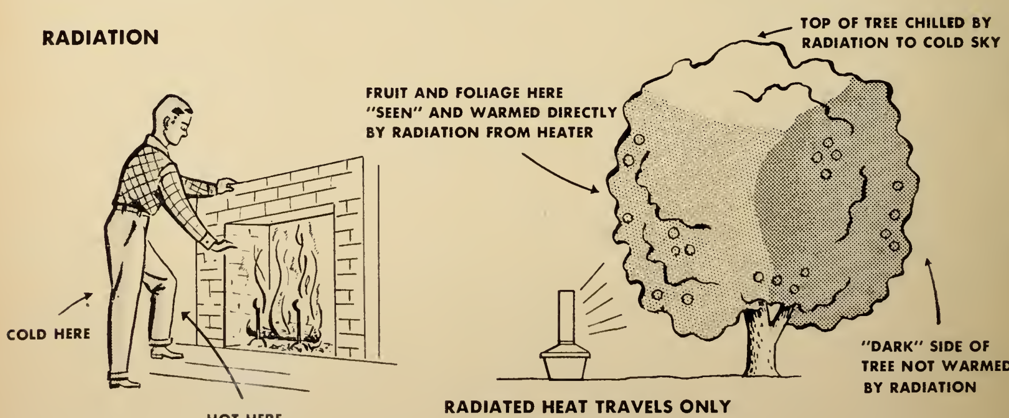
CONVECTION (NATURAL)



CONVECTION (FORCED)



RADIATION



RADIATED HEAT TRAVELS ONLY IN STRAIGHT LINES TO OBJECTS WHICH CAN "SEE" THE SOURCE.

For intelligent use of orchard heaters, it is well to know some fundamentals

BEFORE CONSIDERING the technical aspects of how orchard heaters function, how effective the various types may be, and how they should be used, it will be helpful to briefly review the ways in which heat may be transferred and the environmental conditions under which orchard heaters are used.

Heat transfer is accomplished in one or more of three different ways: by conduction, by convection, or by radiation.

Conduction is the transfer of heat from one part of a solid body to another part, or from one body to another that is in physical contact with it.

Thus if one end of a rod is heated, the other end will be warmed through conduction along the rod. Movement of heat beneath the surface of the soil is by conduction. When the sun heats the surface of the soil, heat is conducted downward into the top foot or so below the surface and stored until used at night.

Convection is the transfer of heat from one point to another within a gas (such as air) or a liquid, by motion or mixing.

In ***natural convection*** the motion is entirely the result of differences in density between the cooler and warmer portions. Warm air is less dense than cooler air (i.e., one cubic foot of it weighs less). Hence it tends to rise as the cooler air settles to take its place. This principle is used in a floor furnace in a home.

Forced convection means that the motion is primarily from an external source, such as a fan. Wind or a wind machine produces forced convection by circulating and mixing air in an orchard.

Radiation is the direct transfer of heat through space from a hotter body to a colder body. Radiation is transmitted without loss through empty space and with very little loss through dry air. Other gases, such as carbon dioxide and water vapor, absorb at least part of the radiant energy.

A typical example of radiant heat transfer is from a fireplace in a cold room. A person standing near the fire will be warmed on one side by radiation from the flame and hot bricks, but will remain cool on the side away from the fire.

Because radiant heat travels through space only in straight lines, an object must "see" the heat source in order to receive radiation from it directly. A shield or other object placed between the heat source and the cool body will reflect or stop part or all of the radiant heat transfer.

In an orchard, leaves and fruit which are exposed to a heater will be warmed by direct radiation from the heater and may be a degree or two warmer than the surrounding air. The opposite side of the tree, however, will remain cool unless "seen" by another heater.

Orchard heating requirements are influenced by a number of factors

Atmospheric radiation. Except for the rather infrequent invasion of citrus districts by cold air at low levels from the polar regions (the so-called freezes), most orchard heating is needed because of the loss of heat from the orchard by radiation to the cold sky. The air in an orchard becomes chilled mainly by contact with the exposed surfaces of the tree foliage or the cold ground, which are losing heat by radiation to the sky.

When the moisture content of the air is

high, the net rate of radiation loss from the soil and foliage to the sky is reduced and orchard conditions tend to be steady with a slow drop in temperature. On nights when the air is unusually dry (low dew point), the radiation loss is large and orchard temperatures may be expected to drop rapidly.

Temperature inversion. During the daytime the sun warms the ground and other exposed surfaces, which in turn warm the air that comes in contact with them. Thus the air near the ground is warmer than the overhead air during the daytime, and tends to rise.

During the night, the air near the ground is cooled (as discussed in the preceding section) instead of being warmed. Since this cooled air is more dense than the warmer air overhead, it remains close to the ground, becoming colder as the surface temperature of the earth continues to fall. Since this is just the reverse of daytime conditions, it is known as a temperature inversion.

A large inversion (overhead air considerably warmer than orchard air) is favored by a warm preceding day and strong atmospheric radiation during the night. A condition of large inversion is often referred to as a "low ceiling" because the heated air and stack gases from the heaters rise only a relatively short distance before encountering warm enough natural air to restrict their rising.

With a small inversion or "high ceiling," the heated air must rise higher before encountering warm overhead air. Under these conditions much of the convective heat from the heaters is wasted above the tree tops, and heating is more difficult than with a large inversion.

The graph on page 6 shows the amounts of temperature rise obtained at various heights during actual tests with a fairly small inversion and with a moderately large inversion. This chart shows that with a small inversion there is more heating above the tree tops and less within the tree zone, than for a large inversion. Typical air temperatures at various heights are also listed.

Cold air drift. Air chilled by contact with the ground or foliage, being heavier than warmer air, will slowly flow downhill and underrun the warmer air. The filling of ground depressions by cold air from neighboring slopes in this manner increases the frost hazard in the low spots. Conversely, there is less danger of frost on the higher slopes.

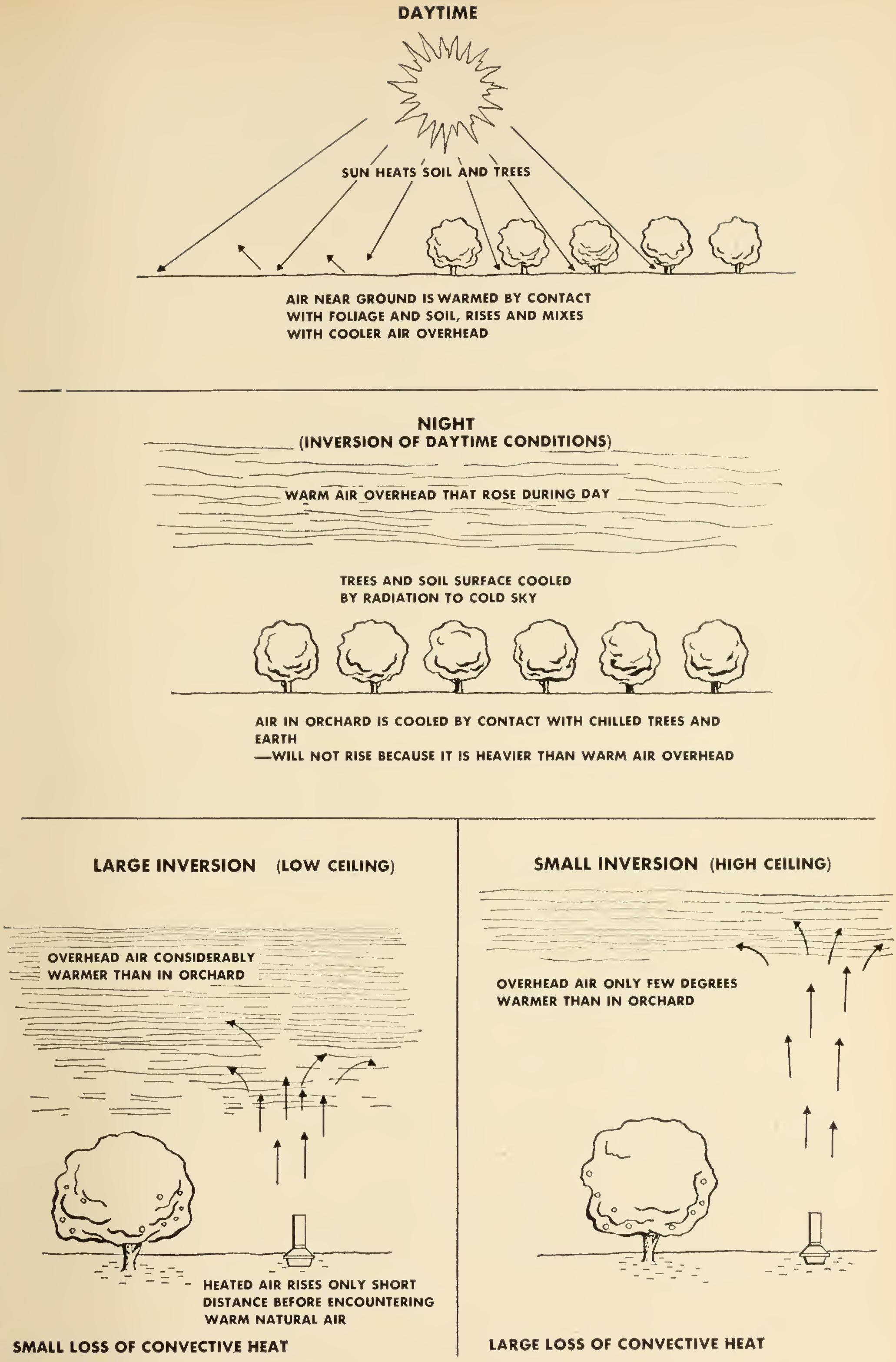
Even on nearly flat terrain and with a relatively quiet night, the air drift across an orchard may have a velocity of 1 to 2 miles per hour at the 20-foot elevation, with velocities within the tree zone being perhaps one-third as great. This incoming air must be heated if the orchard is to be adequately protected. The importance of border heaters in this regard will be discussed later.

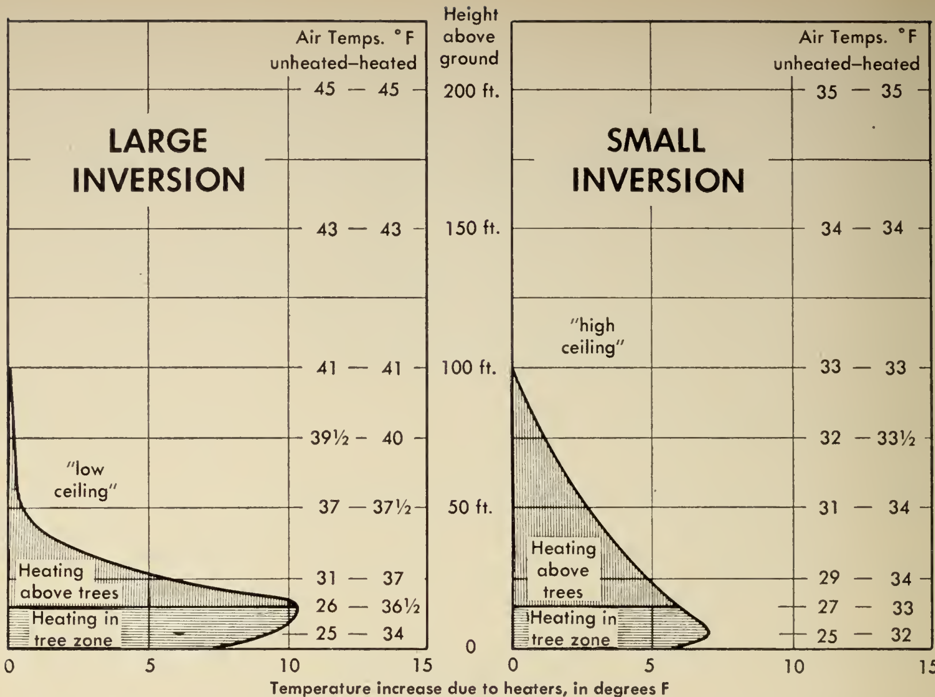
Thus air drift or air drainage is one of the major factors affecting the response from orchard heaters, particularly in isolated orchards. In the so-called "mass heating" of large areas, the air-drift effect diminishes except for border orchards.

Wind. When the wind velocity becomes great enough, the lower layers of air are warmed by mixing with the warmer air above. Such a wind (perhaps only 3 or 4 miles per hour) may greatly reduce the temperature inversion and boost orchard temperatures above the danger point within a period of a few minutes. If, however, there is little or no inversion, wind will increase heating requirements by bringing more cold air into the orchard.

Heat from the soil. In an unheated area, the ground is the main source of the heat lost by radiation to the cold sky during the night. Heat from the sun, which was stored in the top foot or so of soil during the daytime, is conducted up to the cooled ground surface during the night to replace the heat lost to the sky.

Any practice, therefore, which increases the soil thermal conductivity will


DAYTIME
SUN HEATS SOIL AND TREES
AIR NEAR GROUND IS WARMED BY CONTACT WITH FOLIAGE AND SOIL, RISES AND MIXES WITH COOLER AIR OVERHEAD
NIGHT
(INVERSION OF DAYTIME CONDITIONS)
WARM AIR OVERHEAD THAT ROSE DURING DAY
TREES AND SOIL SURFACE COOLED BY RADIATION TO COLD SKY
AIR IN ORCHARD IS COOLED BY CONTACT WITH CHILLED TREES AND EARTH
—WILL NOT RISE BECAUSE IT IS HEAVIER THAN WARM AIR OVERHEAD
LARGE INVERSION (LOW CEILING)
OVERHEAD AIR CONSIDERABLY WARMER THAN IN ORCHARD
HEATED AIR RISES ONLY SHORT DISTANCE BEFORE ENCOUNTERING WARM NATURAL AIR
SMALL LOSS OF CONVECTIVE HEAT
SMALL INVERSION (HIGH CEILING)
OVERHEAD AIR ONLY FEW DEGREES WARMER THAN IN ORCHARD
LARGE LOSS OF CONVECTIVE HEAT



Heating effects and temperatures at various heights, based on tests in a 15-acre orchard; average fuel consumption 33 gals. per acre per hour. The indicated temperatures for various heights are based on an assumed value of 25° F for the 5-foot elevation at the unheated station.

improve the availability of the soil heat, as well as increasing the flow of heat into the soil during the daytime. Covering or loosening the soil surface is detrimental to heat transfer, while a high moisture content is beneficial. However, if a frost occurs within a few days after an irrigation, evaporative cooling from the wet soil may more than offset the advantage of the increased thermal conductivity.

Some heaters were found more effective than others in small inversions

Heater characteristics. As already mentioned, the output from heaters in an orchard is available partly as convective heat (stack gases and air warmed by contact with the heaters) and partly as heat that is radiated from the flame or from hot metal surfaces.

When the inversion is large, both the radiant heat and the convective heat are useful. With a small inversion, however, most of the convective heat rises above the tree tops and is wasted, which means that radiant heat must then be the principal means of protection.

The proportion of heater output which is in the form of radiant energy is different for the various kinds of heaters. For example, the hot-stack type of heaters used in these tests (Jumbo Cone, Kittle, Return-Stack, and 7-inch Exchange Stack) had 25 to 30 per cent of their output available as radiant heat at normal burning rates. The lazy-flame heaters tested (Hy-Lo 230A and Riverside Junior Louvre) had about 20 to 22 per cent radiant energy, while the generating-type (Fugit) had only 18 per cent.

Performance in an orchard. The tests showed that when the inversion was large, there was little choice between the various types of heaters; i.e., the temperature response for a given fuel rate was about the same regardless of the kind of heater. When the inversion was small, however, those heaters which had the highest radiant output (hot-stack type) were the most effective. The generating-type heaters were the least effective at small inversions, and lazy-flame heaters were in between these other two types (see drawing below).

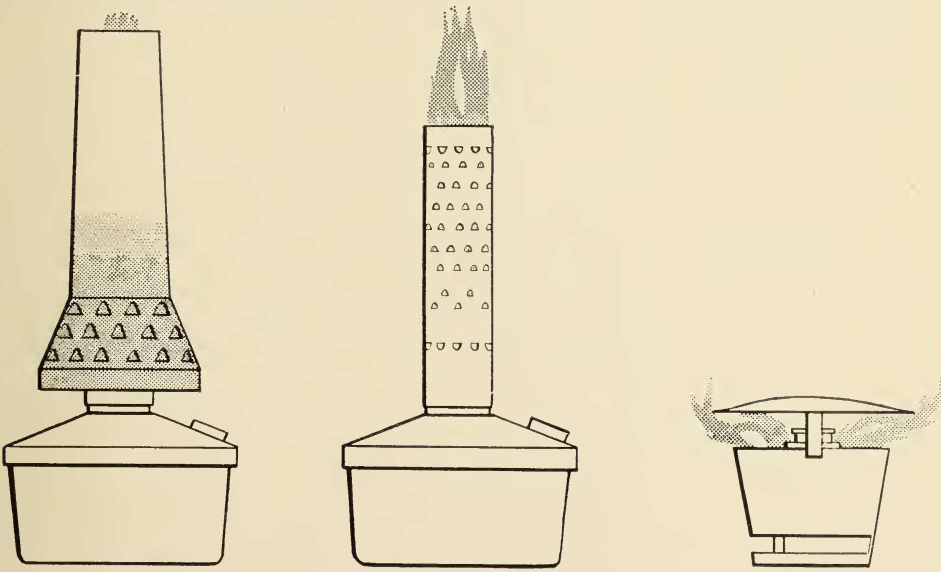
Regardless of the type of heater used, the amount of fuel required to obtain a given temperature rise is greater for small inversions than for large ones. For example the tests indicated that when the temperature 60 feet above the ground was only 4°F. warmer than at 5 feet (small inversion), the amount of fuel required for a given response in the center portion of a 15-acre orchard would be 50 per cent greater than with an inversion of 10°F. (moderate inversion). Fuel requirements near the edges of an isolated orchard are greater than in the center portion (as discussed in a following section).

Heater placement. In general, only about one-third to one-half of the energy radiated from a heater strikes the trees; the remainder goes to the sky or to the ground. Part of the heat radiated to the ground is useful in heating air that comes in contact with the warmed soil, but that which goes to the sky is practically wasted.

The location of heaters with respect to the trees has considerable influence upon the total amount of radiant heat received by the trees and upon the uniformity of distribution to the trees. Heater placement, then, is a factor to be considered, particularly under severe heating conditions (small inversion) where radiant heating is of prime importance.

In general, the use of a large number of small fires gives better distribution of heat (either radiant or convective) than a fewer number of heaters at higher burning rates. Assuming a maximum of one heater per 2 trees, the most uniform distribution of radiant heat is obtained when the heaters are placed at the centers of spaces between trees, in a stag-

Types of heaters tested. Left: hot-stack, or combustion-chamber type; center: lazy-flame type; right: generator type. The hot-stack heaters produce the most radiant heat and are the most effective under severe heating conditions.



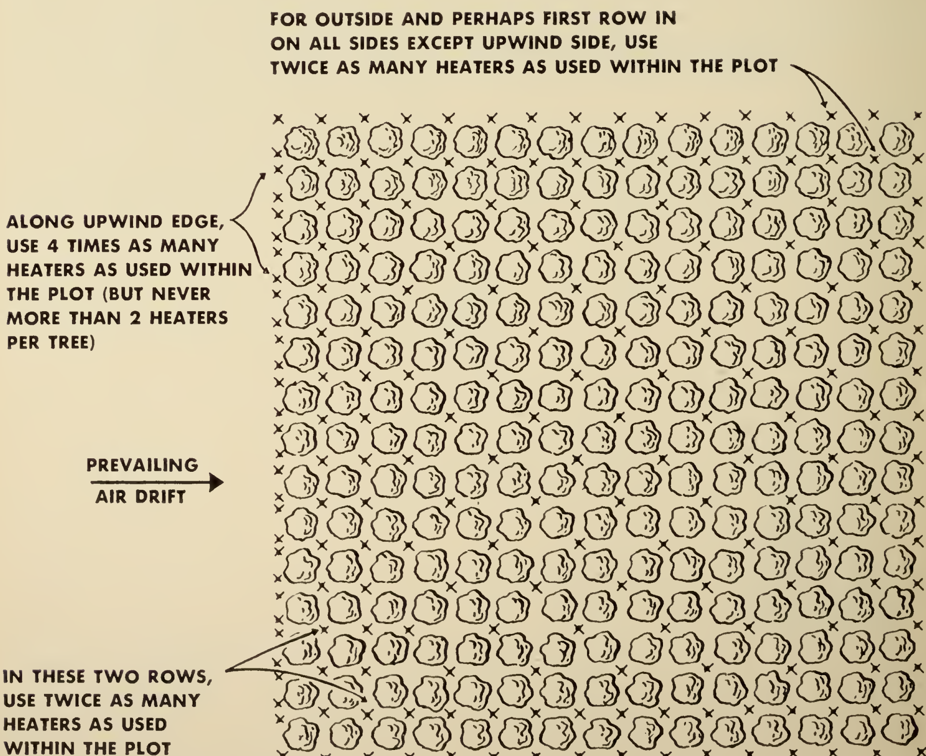
gered pattern. Each tree then receives equal amounts of radiation from two opposite sides. Placing the heaters in the tree rows reduces the loss of radiant heat to the sky (more of it strikes the trees), but the distribution is not so uniform because the heaters are close to one side of the trees.

With the above arrangements, if only every other row of heaters is needed (one heater per 4 trees), the pattern with heaters in tree spaces will still result in equal amounts of radiant heat to all trees; with the heaters in the tree rows, the other rows will receive only about one-third as much as the heated rows.

When the heating requirements are small and only every fourth row of heaters is used, the coldest rows receive very little radiant heat with either pattern, and therefore must be heated almost entirely by convection.

Border heating requires special attention— and on all sides of the orchard

Extra heaters on all sides. Tests in a 15-acre heated orchard indicate that the rising stack gases and heated air over an orchard create an updraft which draws in cold air from all sides of the plot, even on the downwind side directly against the prevailing air drift. For example, in two runs with a uniform distribution of heaters over the entire 15-acre area (no extras on borders), the temperature rise in the trees at the upwind edge was only about 40 per cent as great as in the center part of the orchard. On the *downwind* edge the response was



Typical example of border heater spacing when using one heater per 2 trees within the orchard.

somewhat greater than at the upwind edge, but still only 60 per cent as great as at the center. The response gradually increased for about 10 to 15 rows in from the edges, and was about constant over the remaining center portion of the orchard.

From these results, it is evident that extra border heaters are needed on all sides of an isolated orchard. The importance of border heating, even in fairly large orchards, becomes more apparent when one considers that with 90 trees per acre, a strip only 5 trees wide around a 15-acre area or 7 trees wide around 30 acres represents half of the entire orchard. Thus since the reduced response due to the inflow of cold air along the borders extends in ten rows or more from the edge on all sides, more than half of a 30-acre orchard would be affected by border conditions.

During the runs just mentioned, the rate of fuel consumption was about 33 gallons per hour per acre. In other tests with considerably lower fuel inputs (less heaters per acre and lower burning rates), there was proportionately less difference between the heating effects near the borders and in the center of the orchard, presumably because less cold air was drawn into the orchard by the reduced updraft.

The following general considerations should be kept in mind in regard to border heaters:

High radiant output is especially desirable from border heaters because the outside trees may then be heated directly by radiation without the need for warming all of the inflowing cold air before it enters the orchard. If a grower has more than one kind of heater, those giving the highest percentage of radiant heat (hot-stack or combustion-chamber type) should be used for border heating.

Burning rates. Do not operate border heaters at excessive burning rates; use larger numbers of heaters at normal burning rates. In the center portion of the orchard, burning rates should be kept as low as possible to minimize the amount of cold air drawn in by the updraft over the orchard.

Distribution of heaters. Border heaters should not be concentrated on the outside of the orchard, but should be distributed over the first 2 or 3 rows in from the edge. Extra border heaters are usually needed on all sides of an isolated orchard, but with greatest numbers on the upwind side.

The tests did not include enough large-plot runs to actually check the best arrangement of border heaters. However, for the usual conditions with reasonably flat terrain and low wind velocity, the following spacings are recommended for isolated orchards (see drawing on page 8).

On the outside of the orchard along the upwind border, use 4 times as many heaters per tree as are used within the orchard. For the first 2 rows in from the edge, use twice as many as are used within the orchard. However, never use more than 2 heaters per tree on the outside nor less than one heater per 2 trees on the outside and the first row in.

Along all other borders, use twice as many heaters per tree on the outside and perhaps for the first row in, as are used within the orchard. Never use less than one heater per 2 trees on the outside.

Large-scale heating. In the so-called "mass heating" of large areas, the border effects are confined mainly to the orchards on the outer fringes of the heated district. If an orchard well within a heated district does not have other heated areas reasonably close, it will probably need some extra border heaters.

Wind machines, when used in combination with uniformly distributed heaters, help to give a response greater than the sum of the normal responses when either heaters or wind machines are used alone. Within the zone of disturbance, the air mixing caused by the wind machines tends to make the convective heat from the heaters more useful than when heaters alone are used. However, beyond the zone of influence (such as in the corners of a square orchard) the heaters must do the entire job and high radiant output is fully as important as for border heaters in an orchard where wind machines are not used.

SUGGESTED READING

The following is a partial list of reading material which covers some of the aspects of orchard heating in more detail.

Schoonover, Warren R., F. A. Brooks, and H. B. Walker. Protection of Orchards against Frost. California Agric. Ext. Cir. 111: 1–70. 1939.

Discusses the need for heating and economic considerations (but based on 1937 costs). Includes a general discussion of methods of adding heat to an orchard, general orchard heating practices, and heating equipment.

Kepner, Robert A. Operation of Orchard Heaters. California Agric. Exp. Sta. Bul. 643: 1–32. 1940.

Presents observations, test results and recommendations regarding the field operation of various kinds of heaters without regard to their relative effectiveness in the orchard.

Brooks, F. A. Action of Wind Machines in Frost Protection. American Fruit Grower, March 1947.

Describes typical wind-machine installations and discusses conditions under which they may be expected to provide some protection from frost. (Note typographical error: brake horsepower should read 70 instead of 90.)

Brooks, F. A., D. G. Yerg and R. A. Kepner. Wind Machines Tested. Citrus Leaves, Vol. 28, No. 12, December 1948.

Presents results of tests and observations of wind machines used without heaters, during the winter of 1947–48. (See also California Agriculture, Vol. 2, No. 12, December 1948.)

Leonard, A. S., and Robert A. Kepner. Return-Stack Orchard Heater. California Agriculture, Vol. 4, No. 6, June 1950.

Discusses design principles which make the Return-Stack heater virtually smokeless, and presents results of general field experience with this heater during a 10-year period.

Brooks, F. A., D. G. Rhoades, and H. B. Schultz. Frost Protection for Citrus. California Agriculture, Vol. 4, No. 9, September 1950.

Reports preliminary tests to determine the response from a combination of wind machines and distributed heaters.

Kepner, Robert A. Orchard Heater Smoke Lessened. California Agriculture, Vol. 4, No. 10, October 1950.

Gives recommendations for proper operating and maintenance procedures to minimize the smokiness of the better types of orchard heaters.

In order that the information in our publications may be more intelligible it is sometimes necessary to use trade names of products or equipment rather than complicated descriptive or chemical identifications. In so doing it is unavoidable in some cases that similar products which are on the market under other trade names may not be cited. No endorsement of named products is intended nor is criticism implied of similar products which are not mentioned.

20m-11,'50(2930)WP

California

AGRICULTURE

. . . Contains brief, easy-to-read progress reports of agricultural research, and is published monthly by the University of California College of Agriculture, Agricultural Experiment Station.

FIELD CROPS

ORCHARDS

TRUCK CROPS

LIVESTOCK

CALIFORNIA AGRICULTURE offers information useful to the farmer and food processor, together with announcements of other publications dealing with farm subjects as they are issued by the College of Agriculture.

Upon your request, your name will be added to the mailing list to receive CALIFORNIA AGRICULTURE without cost. Send your name and address to:

California Agriculture, Publications Office, College of Agriculture, University of California, Berkeley 4, California