Measurement of the Frost Protection Capability of a Sprinkler Irrigation System In an Orchard

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EXECUTIVE SUMMARY

A series of frost control measurements was made in a pear orchard near Medford during March 1969. The orchard was protected by an over-tree solid set sprinkler irrigation system. Sprinklers on a 50 x 50 foot triangular spacing were each fitted with a single 1/8-inch nozzle and operated at about 80 pounds per square inch pressure. Temperatures were obtained from shielded and unshielded thermistors mounted on masts within the orchard. A variation in application rate was imposed by turning off one sprinkler in the center of the measured area. The objectives were to find the minimum application rate that would maintain bud temperatures at 31° F during a 24° F frost, and to determine how this required rate was affected by environmental conditions.

The results suggest that, for the range of conditions encountered during the tests, an application rate of 0.15 inch per hour would be required to maintain a bud at 31° F during a 24° F frost. Apparently this rate would have to be increased about 0.007 or 0.008 inch per hour for each mile per hour increment of wind velocity above two or three miles per hour. The seven-degree rise in temperature at 0.15 inch per hour suggests an average rise of nearly one degree for each 0.02 inch per hour increase in application rate. Another aspect of the results confuses this concept, however, because apparently a rate of 0.14 inch per hour would be required to raise a bud from 27° F to 31° F.

It seems to be slightly more difficult to maintain a satisfactory temperature in a bud, and to heat the air surrounding it, if it is located at the outer edge of a tree rather than near the trunk. There can also be differences with respect to height above ground, depending primarily on the natural vertical temperature gradient within the tree canopy at the time.

While bud temperature is being raised from 24° F to 31° F at 0.15 inch

per hour, the surrounding air will be raised only to about 27° F, according to this study. Therefore, one might conclude that although a bud receiving insufficient water would obtain some benefit from the surrounding air, its temperature might still be too low. Furthermore, the results indicate that another bud just a few feet away in a zone of lower application rate would be surrounded by air colder than 27° F, and would thus get even less help from its surroundings. The solution seems to be a sprinkler system with an excellent uniformity of water distribution. The system used in this study had a coefficient of uniformity of about 83 percent, which is quite good considering the three-dimensional nature of an orchard.

Intermittent operation of the sprinkler system failed to produce any desirable results during these tests.

Shielded mercury thermometers lying on a shelf under a horizontal board agreed in general with the shielded thermistors. Error in reading the thermometers was reduced somewhat by placement so they could be read with the greatest ease and at the greatest possible distance, thus reducing heat transfer from the person to the thermometer. Probably at least three thermometers placed four or five hundred feet apart in an orchard would be required to give adequate surveillance for turning on a system.

Unshielded mercury thermometers lying on top of a flat board with the bulb projecting over the edge gave readings that did not correlate well with the unshielded thermistors used in this study. Unshielded thermometers not receiving water from the sprinklers appeared to read too low during the coldest part of the night. Thermometers exposed to adequate sprinkler water rose almost immediately to about 31.5° F and remained there. Unshielded thermistors receiving the same rate of application responded more slowly, fluctuated more, and usually did not read much above 31.0° F.

There was no serious reduction in temperature caused by deficit sprinkling observed during these tests. Apparently the high humidity and low wind velocity (below three miles per hour) were responsible for this fortunate situation.

MEASUREMENT OF THE FROST PROTECTION CAPABILITY OF A SPRINKLER IRRIGATION SYSTEM IN AN ORCHARD

By

J. W. Wolfe, R. H. Brooks, P. B. Lombard

Pear growers near Medford, Oregon have been experimenting with sprinkler irrigation as a method of frost control. They are seeking a satisfactory alternative for the expensive, polluting method of heating their orchards with fuel. Several sprinkler systems have been quite successful, but improvements are still needed.

One disadvantage of using sprinklers is the excess soil moisture at a time when heavy spray equipment must travel through the orchard. Also, water used for frost control subtracts from the already limited amount available for irrigation. Although the State Engineer has declared frost control a beneficial use of water, it is considered separate from irrigation and a new water right must be obtained. Because the system capacity required for frost control is about ten times that required for irrigation, the capacity of present canal distribution systems would be inadequate to supply sufficient water to all orchards at once. Under present practice, the irrigation canals near Medford are normally not yet in full operation when the damaging spring frosts occur. Capital outlay for a frost control system is quite large and increases with increasing total system capacity. For these reasons, growers are anxious to find the minimum application rate that will give adequate frost protection.

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REVIEW OF LITERATURE

A detailed review of literature on this subject was made and reported by Wolfe (1969). Since this publication three additional pertinent reports have been reviewed and are summarized here because of their direct correlation with the work of this project.

Research by Hewett and Hawkins (1968) in apricot orchards in New Zealand was apparently conducted under climatic conditions very similar to those at Medford, Oregon. On November 3, 1966, temperature reached 24° F* and was below freezing for 9-3/4 hours. Apricot green fruit was about one inch in diameter. Frosted fruit in Toxburgh Red Variety plots was zero percent at 0.15 inch per hour, 10 percent at 0.12 inch per hour, and 80 to 100 percent in the check plots.

This result was supported by thermometer readings September 12, 1967, when ambient air temperature reached as low as 21°. An application rate of 0.15 inch per hour held the exposed sprinkled thermometer to at least 31° until about 0500 when the covered check thermometer reached about 23°. The exposed sprinkled thermometer started down at that time, and continued falling slightly faster than the covered check thermometer. It dipped to a low of 27° at 0745 while the covered check thermometer was leveling off at about $21\text{-}1/2^{\circ}$, so the difference between the two ranged from about 8° to $6\text{-}1/2^{\circ}$. The trees were in full bloom and some damage occurred.

These authors plotted the minimum temperature on the exposed, sprinkled thermometer against the corresponding minimum temperature on a covered, unsprinkled thermometer for all data points obtained at 0.15 inch per hour application rate. A second order polynomial was fitted to the points, with a standard error of estimate of the sprinkled temperature of 0.6°. Reading

*All degrees indicated are in Fahrenheit unless otherwise stated.

from the calculated curve, this application rate would maintain 31^{o} if the outside temperature did not go below 25^{o}. At 24^{o} outside temperature, 30.5^{o} could be maintained in a bud or blossom. Much of the curvature of the calculated best-fit line appeared to be caused by the natural upper boundary of 32^{o} for the sprinkled thermometers. These results of Hewett and Hawkins agree very closely with the results presented in this paper.

One apricot variety, Moorpark, set so many blossoms that the trees had to be thinned in 1967 even though nearly 90 percent of the buds or blossoms had been damaged on the unsprinkled plots by the end of September. The yield was comparable to the sprinkled plots where the corresponding loss was only 55 percent.

The recommendations of Hewett and Hawkins were to turn on sprinklers when the temperature was still two to three degrees above that recommended for lighting heaters, and to turn them off at 32^{o} air temperature, assuming no wind.

Gubbels (1969) observed the effect of various application rates on leaf temperature and corresponding damage to bean, pea, and potato plants. When the outside temperature reached -7.2^{o} C (19.04^{o}), an application rate of 2.9 mm per hour (0.114 inch per hour) appeared adequate to avoid severe damage. Bean leaves suffered about 20 percent damage in one night under these conditions. During the following season, potatoes protected by 1.2 mm per hour showed 20 percent damage by September 26, and 90 percent by October 2. Apparently, low-growing vegetable crops can be protected with less water than is required for orchards.

Researchers at the Snake River Conservation Research Center, USDA, ARS (1970) have shown that ice nucleation originates internally when the cell-water freezing point is above the external dew point temperature. If the cell-water freezing point is below the external dew point temperature, the nucleation source appears to be external and freezing progresses rapidly, they report. Perhaps these results at least partially explain the increase in critical temperature observed by Von Pogrell and Kidder (1960) when a plant with a relatively dry exterior was sprinkled. Apparently the sprinkling caused nucleation externally, thus permitting rapid freezing. However, without sprinkling, the ARS results suggest that a low dew point might be less damaging than a higher one, when air temperature is below 32^{o}.

OBJECTIVES

As a result of requests for information made by Dr. C. B. Cordy, then County Agent for Jackson County, speaking on behalf of the Medford pear growers, the following objectives were established for this project:

1. To find the minimum application rate that will protect pear orchards during a 24^{o} radiation frost.
2. To find mathematical expressions for the degree of protection expressed as a function of application rate, air temperature, humidity, wind velocity, and location within the orchard.

EXPERIMENTAL DESIGN

The review of literature by Wolfe (1969) revealed many measurements made to discover the limitations of frost control by sprinkling and several attempts to develop theoretical expressions describing the process. In most cases the measurements were conducted under controlled laboratory conditions, and the theoretical expressions require input data that are not easily available. A decision was made on this project, therefore, to obtain sufficient measurements in the field to derive predictive equations by statistical analysis.

An orchard was selected that met the desirable minimum requirements for tree size, tree spacing, system capacity, uniformity of water distribution, and adequate water supply. It was situated less than a mile west of Medford, and was designated as the Green Orchard by its owner, Dunbar Carpenter. The trees were mature, had been planted on the 25 x 25 foot spacing and were about 20 feet high. They had received their annual pruning. The sprinkler system had a 50 x 50 foot staggered or triangular spacing with each 20-foot riser coming up through the center of a tree. The sprinklers were Rain Bird Model 14V, with a 1/8-inch nozzle. Observed rotation rates of the sprinklers ranged from 22 seconds per rotation to 45 seconds, and averaged about 30 seconds. The pump supplied water at 80 to 90 psi, measured on the riser 15 feet below the sprinkler.

Eleven instrumented masts constructed of one-inch pipe spaced 10 feet apart in an "L" arrangement shown in Figure 1 were used to mount instruments for measuring temperature and precipitation. The masts were lettered A through F. Mast A came up through the center of a tree that also contained a sprinkler riser. Mast B was just beyond the edge of the tree located at A. Masts C and D were about 5 feet on either side of the trunk of the next tree, whereas Mast E was on the edge of a third tree. Mast F was in the center of the third tree, 50 feet from tree A, and was almost touching another sprinkler riser pipe. Mast F was at the apex of the "L" so the remaining Masts, G through K, were in line perpendicular to the line of Masts A through F. Mast K was in the center of another tree and was 25 feet from each of the two closest sprinklers.

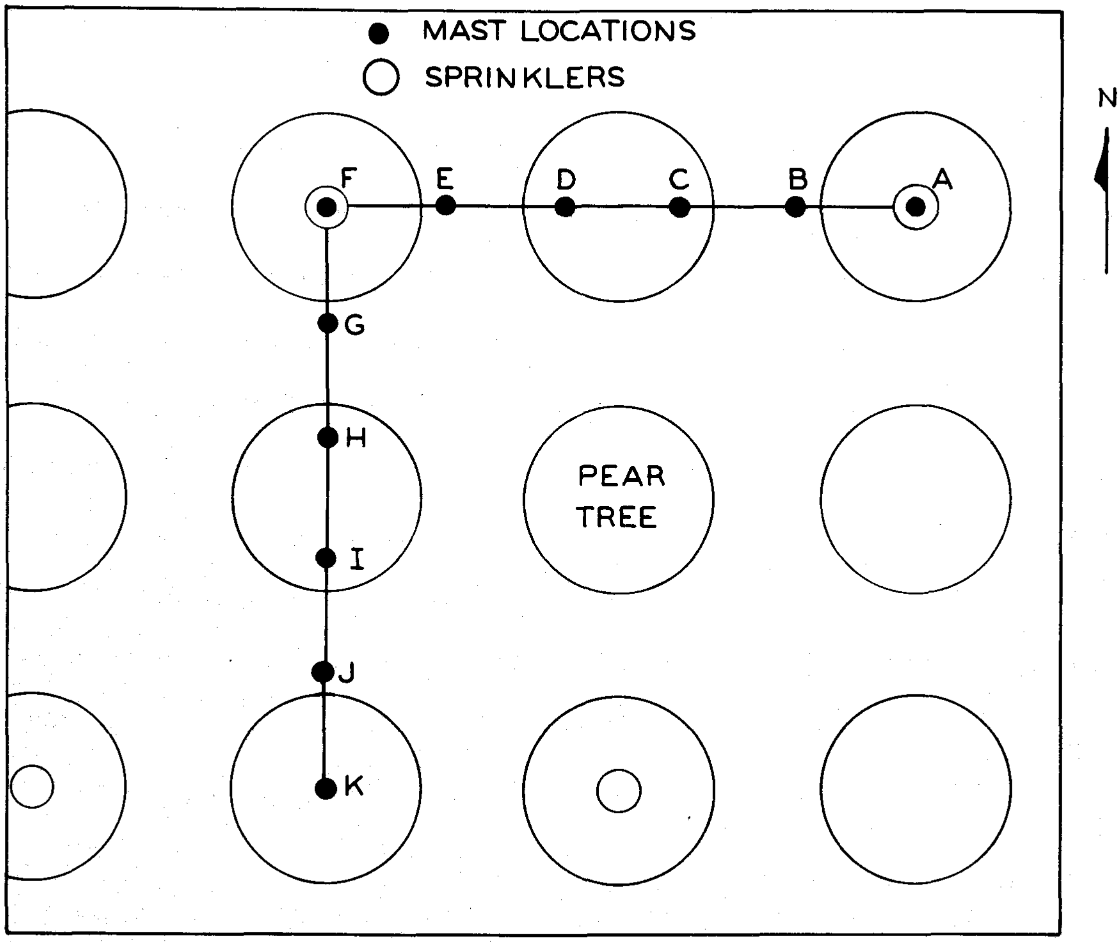


Figure 1. Plan view of center of test site, showing location of trees, masts, and sprinklers.

During the tests, the sprinkler at Mast F was turned off. This scheme provided a variable application along the line of masts, with the highest theoretical rates being at or near Masts A and K, and with progressively lower rates in the direction of Mast F. Water from only three sprinklers reached the cans on the masts, but at least two more rows of sprinklers on each side of the "L" were in operation during a test. Two remote masts, each located 500 feet from the "L" in opposite directions, contained similar sensors which were to monitor conditions outside of the test area. Instruments on each mast were mounted in four horizontal planes spaced 5 feet apart beginning 5 feet above the soil surface. Each plane on the mast held two thermistors and two catchment cans as shown in Figure 2.

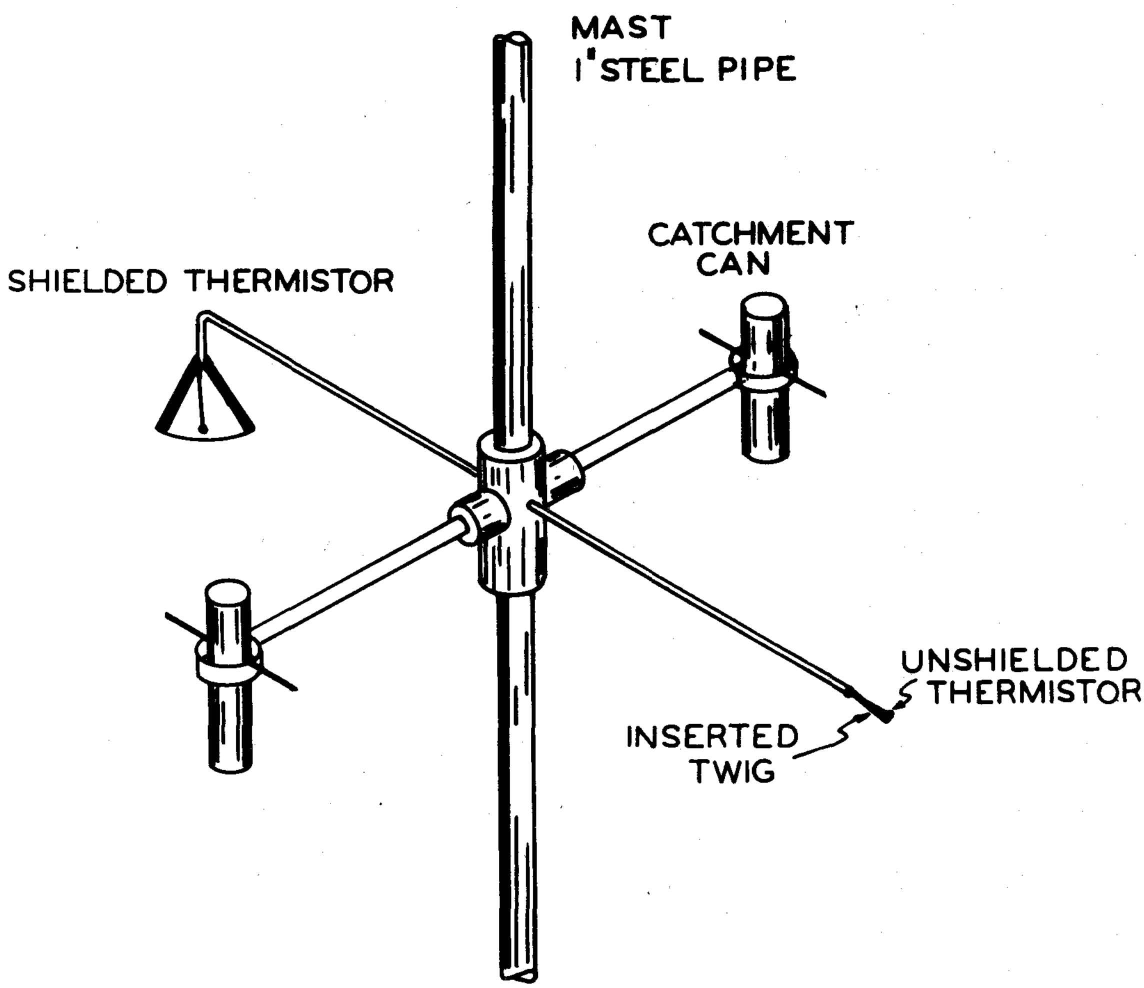


Figure 2. Arrangement of temperature sensors and cans for water catchment at one height on a mast.

INSTRUMENTATION

The sensing elements for measuring temperature were one percent tolerance thermistors manufactured by Yellow Springs Instruments. They were easily capable of 0.1^{o} accuracy. Connections to the thermistors were made through special gold-plated pin connectors. The lead wires and connecting wires were carefully insulated with plastic tubing and waterproofed at the joints with epoxy or silicon rubber. The thermistors themselves were encased in epoxy until they were about 5 mm or 0.2 inch in diameter and approximately spherical in shape. This size was chosen to simulate the size of a bud at the time frost damage is most likely to occur. Unshielded thermistors were placed adjacent to a small twig, thus the thermistor itself simulated a bud.

The shielded thermistors were placed inside an inverted 5-1/2 inch diameter plastic funnel. The thermistor dangled down inside the center of the funnel to a position about 1/8 inch above the circular rim. A 1/2-inch layer of urethane insulation covered with polished aluminum foil coated the inside of each funnel. This arrangement minimized the amount of heat the thermistor received from the warm ice on the outer surface of the funnel and it also protected it from losing heat by radiation to the cold open sky. Although it was not aspirated, the position of the thermistor barely above the rim of the funnel permitted the natural air current to minimize the error in sensing ambient temperature.

Wind velocity was measured at the remote mast located 500 feet upwind from the instrumented "L". An anemometer with a stalling speed of about 1/4 mile per hour, and a wind vane were mounted on top of a 20-foot mast. An event recorder collected continuous data on wind velocity and direction during each test.

The signals from all thermistors were brought in through multiwire cables to a 200-channel data acquisition system manufactured by Nonlinear Systems Inc. Data were recorded on an ARS-33 teletype. The system was housed in a small camping trailer at the edge of the test site. Except for making special readings, the data system was set to print out the resistance in each thermistor in ohms to four decimal places every ten minutes, and the same results were simultaneously punched on paper tape.

The thermistors were calibrated in a water bath prior to their installation on the masts. An equation for the best-fit straight line on a semi-log plot was then calculated on a computer for each thermistor. Several of the thermistors had to be recalibrated after the test because it was apparent from the results that their first calibrations were in error. In a few cases there was still excessive deviation from the best-fit line after the second calibration, and the data from those thermistors had to be discarded. It is possible that some additional inaccuracies were undetected. Drift, for example, was not evaluated.

Collection cans were constructed from 2-inch diameter irrigation pipe by cutting it into 8-inch lengths and welding a disc on the bottom of each piece. The top of each can was ground to a sharp edge.

Thermistors were located on the remote masts at the 5- and 20-foot levels only. A few glass thermometers were placed in the orchard during the tests and were read at irregular intervals. Some were placed in shielded, and some in unshielded positions. The shield consisted of a horizontal board fastened to the side of a 4 x 4 post, and a vertical board joining it on the lower side against the post. The shielded thermometer was placed on a small shelf under the top board, while the unshielded one rested on top of the top board with the mercury bulb projecting over the edge. Most of the thermometers were located in the sprinkled area. In a few instances a thermistor was placed adjacent to a thermometer.

PROCEDURE

The plan was to operate the system during radiation frosts early in March while the trees were still dormant. This procedure made more cold nights available and at the same time could not cause damage to the trees because of deficit sprinkling. Results were recorded automatically on paper tape so they could be fed into a computer for analysis.

The intended procedure on a night of test was to turn the irrigation system on just before the dry-bulb temperature reached 32^{o} and to turn it off after the wet-bulb temperature had risen to 32^{o}. For a variety of reasons it happened that during Runs 3, 5, and 7 the system was turned on too late and turned off too soon. On some occasions the sprinkler system was deliberately turned on and off at relatively short intervals at the beginning, to see if an intermittent operation would be adequate while the outside temperatures are still only slightly below freezing.

A thin film of diesel oil was applied to the interior surface of each collection can prior to measurement. The water in each can was measured volumetrically after the ice on the inside of the can had melted.

Test runs were made on the nights of March 8-9, 9-10, 10-11, 11-12, 18-19, 21-22, and 23-24. Each night was designated by a run number. The authors traveled to the experimental site on short notice by commercial airline.

EVALUATION, SORTING, AND SELECTION OF DATA

Basis for selecting Run 5

Visual inspection of the temperature data for the seven runs revealed that only three of them showed promise for yielding the kind of information needed to meet the objectives. Run 1 was a period of familiarization with the equipment. Portions of the system were not fully operational. In addition, the temperature was not low enough for a good test.

Run 2 should have been the best of all because it was on the coldest night. The shielded glass thermometer at remote station R-2 was read as low as 20.2°. Two corresponding shielded thermistor measurements were about 1.2° and 2.4° higher, respectively. The biggest discrepancy during Run 2, however, occurred after sunrise about 6:30 a.m., when the actual temperature rose but the thermistors indicated no rise. Although data obtained before sunrise might be very valid, it was decided not to make a detailed analysis of the data from this run.

Runs 4 and 6 were almost without value because the temperature did not get low enough to turn on the sprinklers. The data from Runs 3, 5, and 7 were the only ones subjected to statistical analysis.

Since there appeared to be differences among the groups of data from Runs 3, 5, and 7, an examination was made of their relative reliability. First, a visual inspection was made of the thermometer readings compared with the readings of the thermistors located closest to the thermometers. The results are listed in Appendix Table 4. The thermometer readings are generally below the thermistor readings during the colder portion of each night, and the unshielded thermometer readings are lower than the shielded. It is obvious, however, that the discrepancies were less during Run 5 than during the other two runs. The size of the discrepancies during Runs 3 and 7 are great enough to question the validity of these sets of measurements. Only part of the data from Run 3 could be used, due to a malfunctioning sprinkler at Mast A.

The R^2 values obtained from the step-wise multilinear regression, which indicate that portion of the variation explained by the regression, appear in Table 1. A comparison shows that with one exception the R^2 values are higher, and the standard deviations, s, are lower for Run 5 than for either of the other two runs. The one exception is the R^2 value for Run 3 for shielded thermistors. It will be shown later in Figures 15 and 16 that the results from the shielded thermistors during Runs 3 and 5 are very similar. The authors decided from these comparisons that Run 5 was by far the most reliable test and therefore the principal conclusions should be based on its results.

Table 1: Comparative values of variation explained by regression (R^2) and standard deviation (s) for regression analysis of Runs 3, 5, and 7.

Run Number	Shielded or unshielded	R^2	s
3	unshielded	0.619	1.208
5	unshielded	0.730	0.676
7	unshielded	0.540	0.804
3	shielded	0.838	0.424
5	shielded	0.747	0.336
7	shielded	0.625	0.428

Weather during Run 5

Run 5 was conducted during the night of March 18 and 19. It was clear and relatively calm, with winds gusting up to 3 miles per hour. The minimum air temperature recorded at the Medford Weather Bureau Station was 26^{o}, whereas the minimum dew point temperature recorded hourly on the hour was 27^{o}, (Appendix Table 3) suggesting that relative humidity must have been close to 100 percent during the coldest part of the night. The Weather Bureau records also showed a very weak temperature inversion of 4.5^{o} measured at a height of 1350 feet. Temperature differences of one or two degrees, or even more, commonly exist at the floor of this valley, sometimes within a distance of only a few hundred feet.

Comparison between shielded thermometers and shielded thermistors

The results of one attempt to calibrate a thermistor against a glass thermometer of a type commonly used by the pear growers is shown in Figure 3. The two sensors were lying side by side on the shielded shelf. The application rate was not measured at this location, but was relatively small since it was near the edge of the sprinkled area. Except for a little scatter, the agreement is reasonably good. There appears to be a tendency for the thermometer readings to be above the thermistor readings early in the night while the temperature is still fairly high, while the reverse seems to be true during the coldest part of the night. In either case, most of the differences are less than one degree.

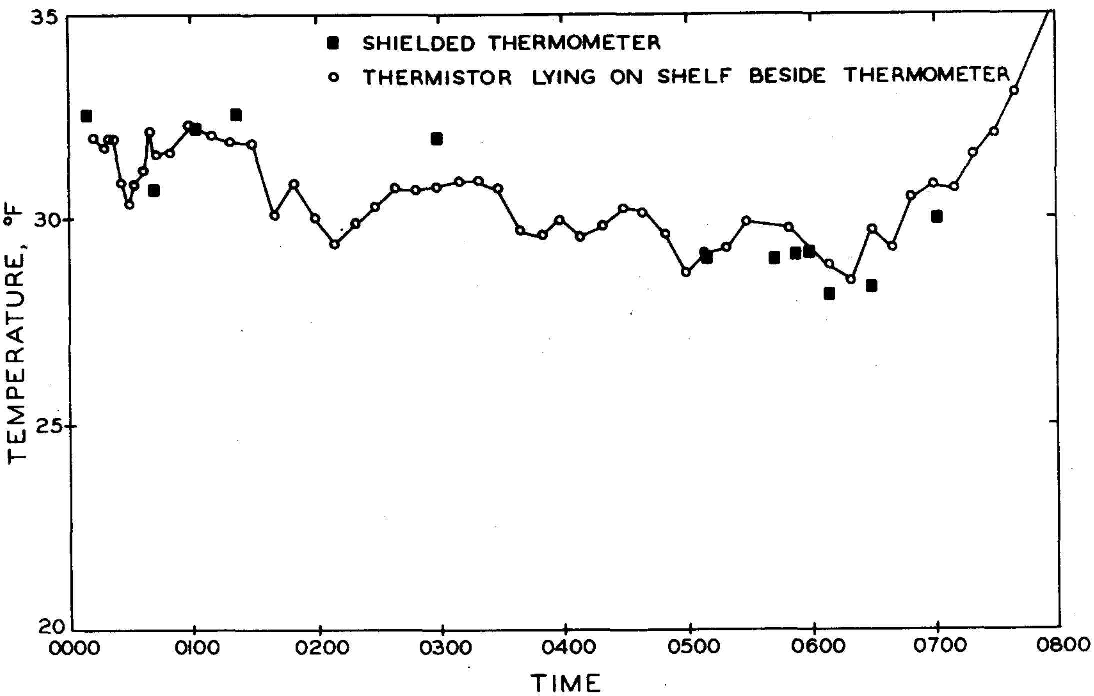


Figure 3. Temperature in shielded sensors just inside the sprinkled area near the instrument trailer during Run 5.

An interesting comparison between thermometer readings and thermistor readings can be observed in Figure 4. Readings taken at irregular intervals on the shielded thermometer at remote station R-2 at a height of 5 feet almost coincide with the mean temperature in all four thermistors on masts R-1 and R-2 for all readings taken prior to 0530. After 0530 the thermometer registered about one degree colder than the mean of the thermistors. This could easily have been a real difference, perhaps due to a low-moving mass of cooler air. The other two lines in Figure 4 are readings from two single thermistors at the 5-foot height at station R-2. One of the thermistors was mounted on the mast several feet away from the thermometer, and the other was lying on the shelf beside the thermometer. Note that their readings are

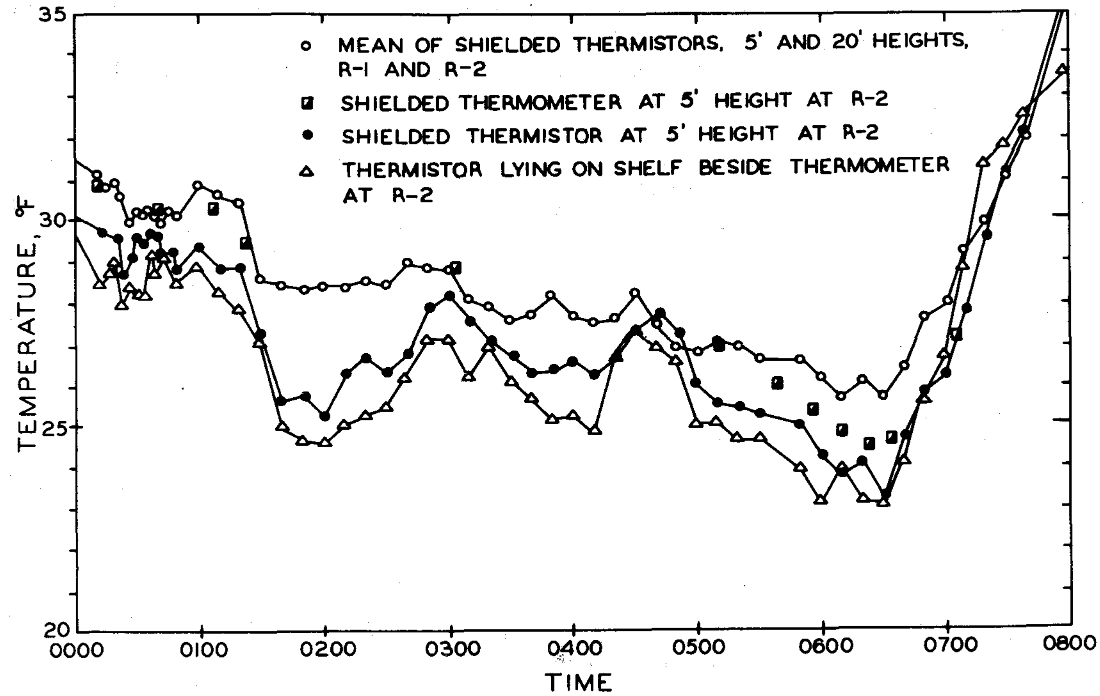


Figure 4. Temperatures in shielded sensors at remote masts R-1 and R-2 during Run 5.

both below the thermometer readings all the way, and that the one lying next to the thermometer appears colder than the other. The differences between the mean of the two thermistor readings and the thermometer readings appear to be quite constant up until sunrise about 0630, and ranged from about 1.0^{o} to 1.5^{o}, judging by the graphical plot. Likely these two thermistors were calibrated too low, but they tend to confirm that localized cooling did occur there after 0530.

Thus, the mean readings of the shielded thermistors on the remote masts, and the readings of the shielded thermometer at R-2 tend to validate each other's calibration, especially since the deviation after 0530 is explainable.

Another interesting observation from Figure 4 is that a localized 2^{o} drop in temperature occurred at 0140 and held for at least 20 minutes. Likewise there was a localized rise in temperature about 0435.

Comparison between unshielded thermometers and unshielded thermistors

By contrast to the shielded thermometer the unshielded glass thermometer does not seem to give meaningful temperature readings. An unshielded thermometer not exposed to sprinkling tends to give a lower reading than the unshielded thermistors, and considerably lower than shielded thermometers. In Figure 5 the two upper lines on the graph which rather closely parallel each other, represent the mean readings of unshielded thermistors on the remote masts and Mast F, respectively. The thermometer readings range from about 1^{o} to 4^{o} below these lines. An unshielded thermistor located only a few feet from the thermometer at R-2 follows the thermometer readings much more closely, but except for one thermometer reading still remains above them. It seems logical to assume from these data that the low thermometer readings just before sunrise are due partly to localized cooling and partly to the nature of this sensor. Apparently the physical characteristics of the unshielded thermometer bulb cause it to radiate proportionately more heat to the sky than a thermistor does.

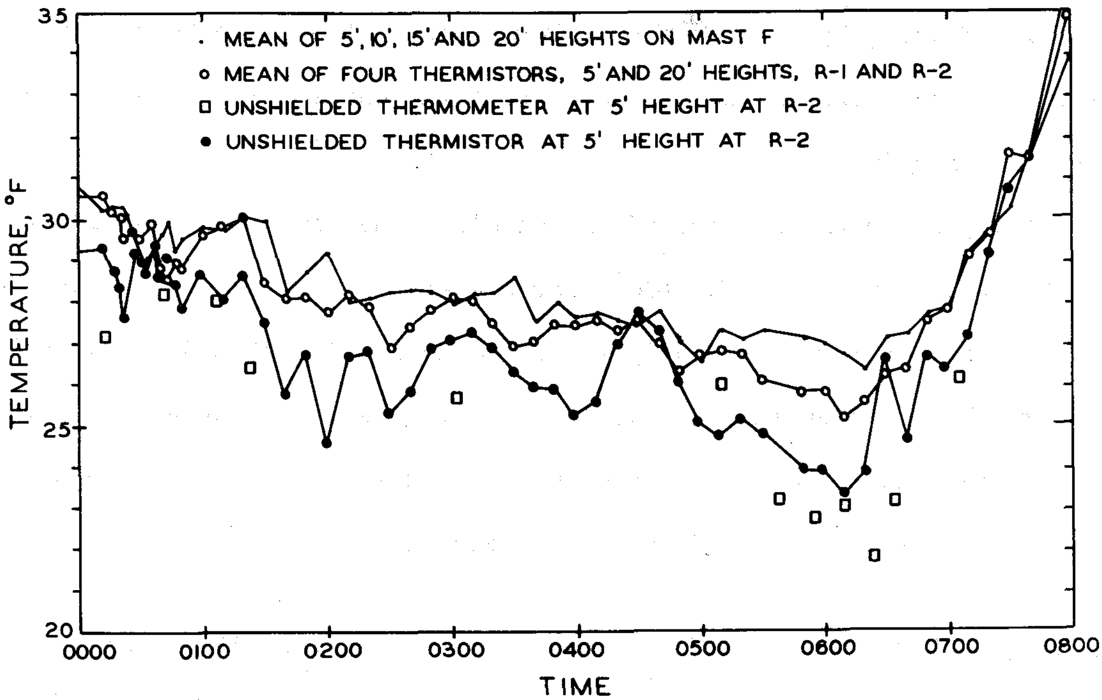


Figure 5. Temperatures in unshielded sensors at remote masts and Mast F during Run 5.

Comparing Figure 5 with Figure 4, it is interesting to note that all three thermistors at the 5-foot height show the localized drop in temperature at 0140 and the rise about 0430.

For some reason the unshielded thermistors seemed to respond more slowly to the application of water than the unshielded thermometers did. A typical lag is illustrated in Figure 6 by the plot of the temperature at 5 feet on Mast B, where the application rate was 0.175 inch per hour. It was nearly an hour after the sprinklers were turned on and left on at 0114 before the recorded temperature in the unshielded thermistor reached 31°. In general, this lag period varied from a few minutes to more than two hours. By contrast, the thermometer jumped from 29° to 31.5° after no more than 12 minutes of intermittent sprinkling.

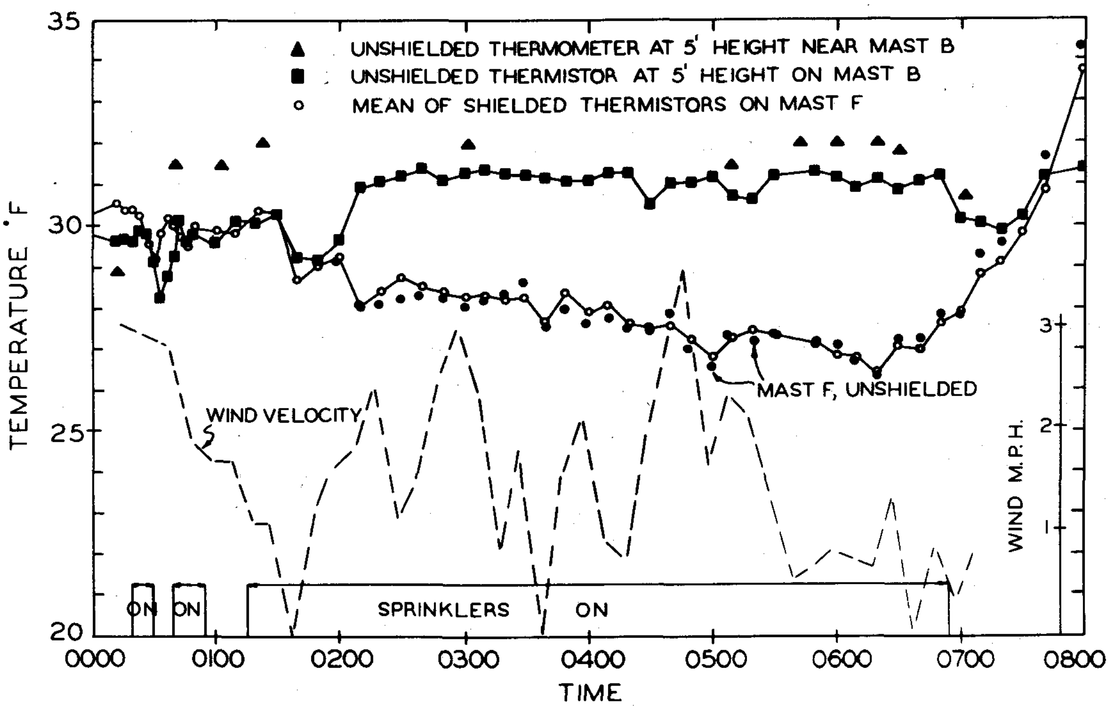


Figure 6. Comparison of selected temperatures on Mast B at 0.175 inch per hour and on Mast F at zero application during Run 5.

Failure of intermittent operation of sprinkler system

Thermistor number 34 plotted in Figure 7 responded more quickly than many of the others. Like the others, it shows almost no effect, however, of the sprinklers being turned on for 10 minutes, off for 10 minutes, on for 16 minutes and back off for 20 minutes before they were turned on to stay at 0114. By 0120, however, the temperature had risen above 31° and remained there for the remainder of the sprinkled period. If the sprinkler system had been turned on at 32° as we had planned, it is likely that a thermistor receiving adequate water never would have dipped appreciably below 31°. It is quite apparent from these results that intermittent sprinkler operation is not satisfactory when the starting is delayed as it was on this run. Sprinkler freezing was another hazard with intermittent operation.

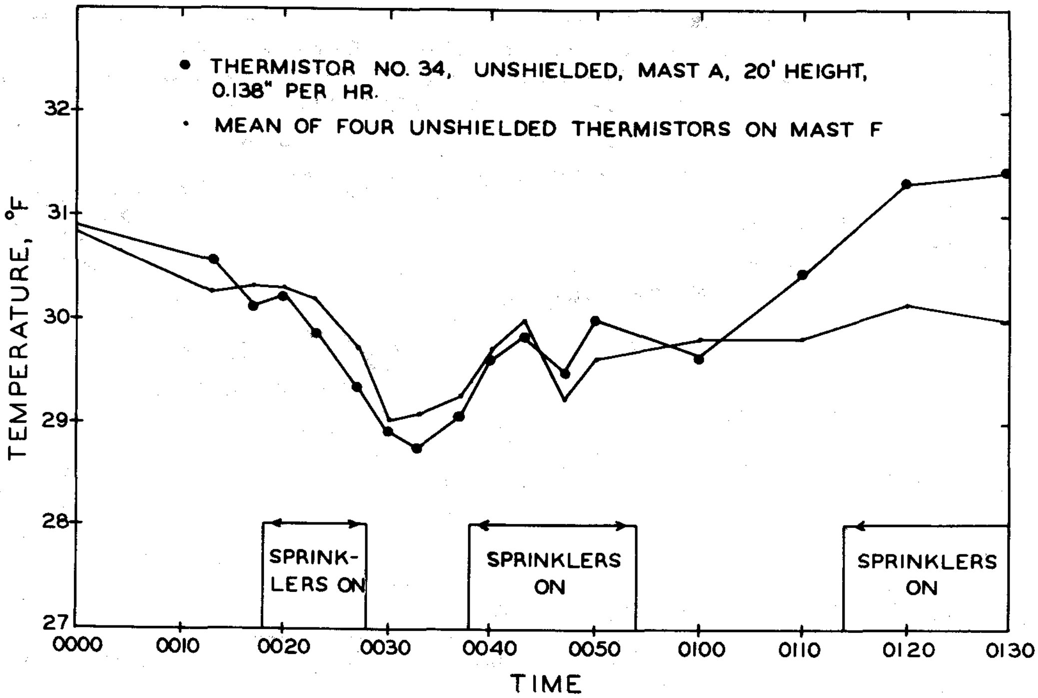


Figure 7. Effect of intermittent sprinkler operation on an unshielded thermistor during Run 5.

Comparison between shielded and unshielded thermistors

Figure 6 also compares the shielded and unshielded thermistors on Mast F where no precipitation occurred. Each data point is the mean of four thermistor readings. Only very small differences appear between the two sets of readings. Perhaps you could say the unshielded thermistors tend to be a bit colder during the dark portion of the night. As daybreak approaches they become very nearly equal, and after the sun comes up the unshielded thermistors have higher temperatures as one might expect. These differences are in the same direction as the differences in glass thermometer readings, but their magnitude is much smaller.

Thermistor response at different application rates

Figure 8 gives some concept of what happens to the temperature in an unshielded thermistor at different application rates. At the left edge of this graph, only the mean temperature on Mast F is shown because the others would coincide almost exactly. Each of the three lines start as soon as its temperature begins to deviate from the mean temperature at Mast F.

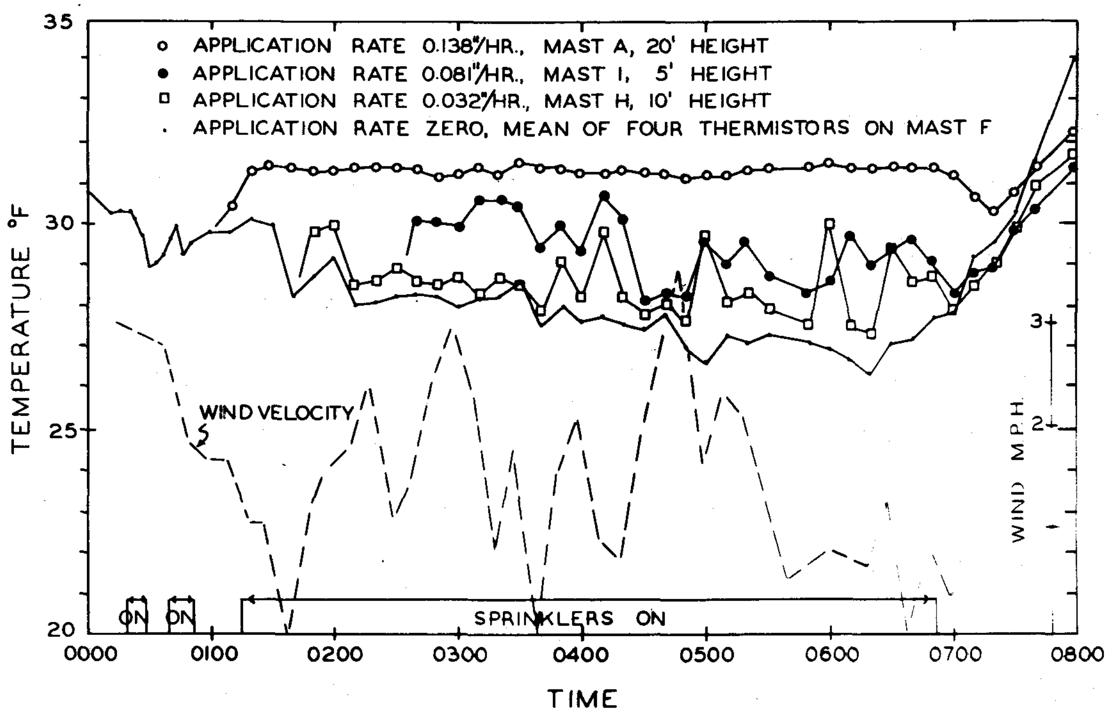


Figure 8. The effect of various application rates on the temperatures of selected unshielded thermistors.

The top line represents an application rate of 0.138 inch per hour. This thermistor responded more quickly to the water and held its temperature above 31^{o} more consistently than most of the others at this application rate. It dips as the others do as soon as the sprinklers are turned off at 0654, and very quickly approaches the mean temperature on Mast F.

The second line from the top represents an application rate of 0.081 inch per hour. The temperature in this thermistor follows the mean temperature on Mast F almost identically until 0240 when it jumps abruptly to a level between 30 and 31°. This level is sustained until 0340 when it dips for the next 20 minutes, somewhat paralleling the temperatures on Mast F. At 0410 it rises again nearly to 31°, perhaps aided by a localized warming trend or a direct hit by one or more drops of water. The thermistor on Mast I would receive relatively large drops because both sprinklers supplying it were at least 30 feet away. After 0430 the outside temperature had dropped low enough to prevent this thermistor from again rising above 30°.

The third line from the top in Figure 8 represents the temperature in a thermistor which received water at the rate of 0.032 inch per hour. This thermistor is nearly 40 feet from the sprinklers. It shows the first deviation from the mean temperature on Mast F at 0150 when it rises nearly to 30°. It drops back to within a half degree of the Mast F temperature is 0210, however, and keeps about this relationship with the mean Mast F through most of the remainder of the night. There are a few brief periods when it reaches up toward 30°, each of which probably represents receiving more drops of water than normal, coupled with a localized warming trend.

The wind velocity does have some influence on the degree of warming accomplished by the water, but its effect is somewhat obscure in Figure 8. One confounding factor is the six-minute travel time between the anemometer and the "L", for a one-mile per hour wind.

The temperatures in the shielded thermistors representing ambient air showed a bit less tendency for abrupt changes. Figure 9 illustrates that a rather low application rate causes a measurable increase in temperature, and that a rather high rate will not raise the air temperature more than about 3° under these conditions.

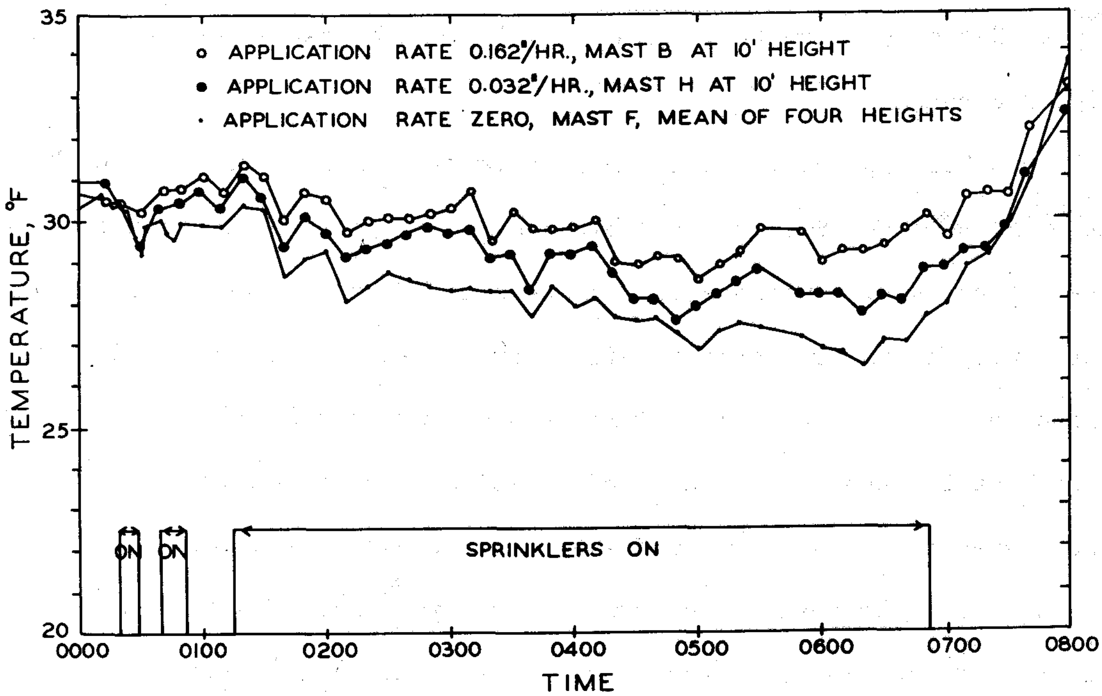


Figure 9. Temperatures in selected shielded thermistors subjected to various application rates during Run 5.

Uniformity of water distribution

The water application rate, as measured by the total amounts caught in cans on the 5 x 10 foot vertical grid, did not vary greatly with height during Runs 3, 5, and 7. The total can catchment figures suggest a very slight but consistent increase with height from 5 feet to 15 feet, but the catchment at the 20-foot level totalled only about the same as the 5-foot level (Appendix Table 1). Since the greatest difference in totals (12 percent) was between the 5-foot and the 15-foot levels, these measurements were compared as paired observation using the "t" test. Their differences did not show significance. If real differences do nevertheless exist as the totals suggest, the smaller catchment at the 20-foot level could be explained by the location of the sprinklers at the same level, since any horizontal or downward spray would not have a chance to reach the 20-foot cans. A gradual decrease below the 15-foot level could be explained by interception by higher branches.

In another approach, the can measurements from each of the four heights on Masts A, B, J and K only were compared. The measurements from Masts A and K were not changed, but those from Masts B and J were increased by adding the measurements for the respective heights from Mast E. Theoretically, if the distribution patterns of all sprinklers are symmetrical and identical, the cans on Mast E caught the amounts of additional water that would have accrued in the respective cans on Masts J and B, had the sprinkler at Mast F been operating. The catchments from Runs 1 and 2 were included in this analysis. The totals of the five runs showed the same relationship with respect to height as the first approach, except that the 5-foot height catchment was slightly less, and the 20-foot height slightly more than before. In fact, there was only 5 percent variation in total application among the 10, 15, and 20-foot heights. The 15-foot height caught 14 percent more water than the 5-foot height, and this difference was significant according to a "t" test on paired observations. An analysis of variance on the mean catchment at each respective height, using data from only Runs 5 and 7, did not show any real difference among the four heights.

The uniformity coefficient in the vertical section represented by Masts A, B, J, and K, was 83.0, 82.9, 83.1, and 83.8 percent, respectively, for Runs 1, 2, 5, and 7. These figures are relatively good considering the three-dimensional nature of the section. The calculations could be a bit too high because each observation used in the computation is the mean catchment in two cans on a mast, instead of just one. The catchments on Mast A, which was directly under one sprinkler and out of reach of all other sprinklers, appeared to be at least 27 percent less than on any of the other three masts in this group. An analysis of variance using the mean catchments from Runs 5 and 7 for each respective mast location failed to show any significant difference, however. See Appendix Table 2.

REGRESSION ANALYSIS

Selection of variables

A stepwise multilinear regression analysis was made on the data from Runs 3, 5, and 7, for both the shielded and the unshielded thermistors. Temperature increase, ΔT, was selected as the dependent variable. This increase was calculated by subtracting the mean temperature of four thermistors on Mast F from the temperature of the thermistor in question. For each computation, all thermistors were either shielded or unshielded. Because of the 32^{o} natural upper bound in the presence of ice, the data points for the regression analysis were selected to exclude those ΔT's that were limited by this barrier. The selection was made visually after first plotting the temperature of each thermistor throughout each run.

The independent variables selected for this analysis included precipitation rate in inches per hour, P, distance from the nearest tree trunk in feet, D, height of measurement above ground in feet, H, wind velocity in miles per hour, W, the mean temperature on Mast F, T, plus the following additional second order terms: D^2, PW, PD, PT, P^2, HD, and PH. Wind direction and certain other possible second order terms were discarded because they failed to show significance.

The mean temperature on Mast F was selected as the base for calculating ΔT instead of the temperature on the remote masts because it more closely paralleled the temperatures on other masts, thus reducing variability in the data. Being farther away, the remote masts were not in the same set of local conditions at any one time. Also, since the data from Run 3 was studied first, there was no evidence then of any important difference between Mast F and the remote masts. Later a comparison was made by treating the calculated means on Mast F and the corresponding calculated means on the remote masts as paired observations. The results are presented in Table 2, and indicate that for Run 5 at least, the air temperature was raised about $1/3^{o}$, and the unshielded simulated buds were warmed about $2/3^{o}$ due to the sprinkling which surrounded but did not touch Mast F.

Table 2: Mean shielded or unshielded temperatures on Mast F minus the respective mean shielded or unshielded temperatures on the two remote masts during Runs 3, 5, and 7.

Run Number	Mean difference of shielded temperatures, ^{o}F.	Mean difference of unshielded temperatures, ^{o}F.
3	+ 0.0205	- 0.2476*
5	+ 0.3235**	+ 0.6832**
7	+ 0.2822	+ 0.6200*

*Significant at 5percent level
**Significant at 1 percent level

Regression equations

Four of the regression equations having the highest percent of variation explained by regression (R^2), and the lowest standard deviation of ΔT(s) are listed below. Equations 1, 2, and 3 are from Run 5, while equation 4 is from Run 3. In each equation the terms are presented in the order selected by the computer for their relative influence on ΔT. Except for equation 2, each equation contains all the independent variables tested which had significant coefficients. Equation 1 is for unshielded thermistors during Run 5. A visual concept of the variability of the data used to develop this equation may be obtained from Figure 10. Equation 2 is also for unshielded thermistors during Run 5, but includes only the six first selected independent variables, thus making it linear with respect to P. Equation 3 is for shielded thermistors during Run 5, while equation 4 is for shielded thermistors during Run 3.

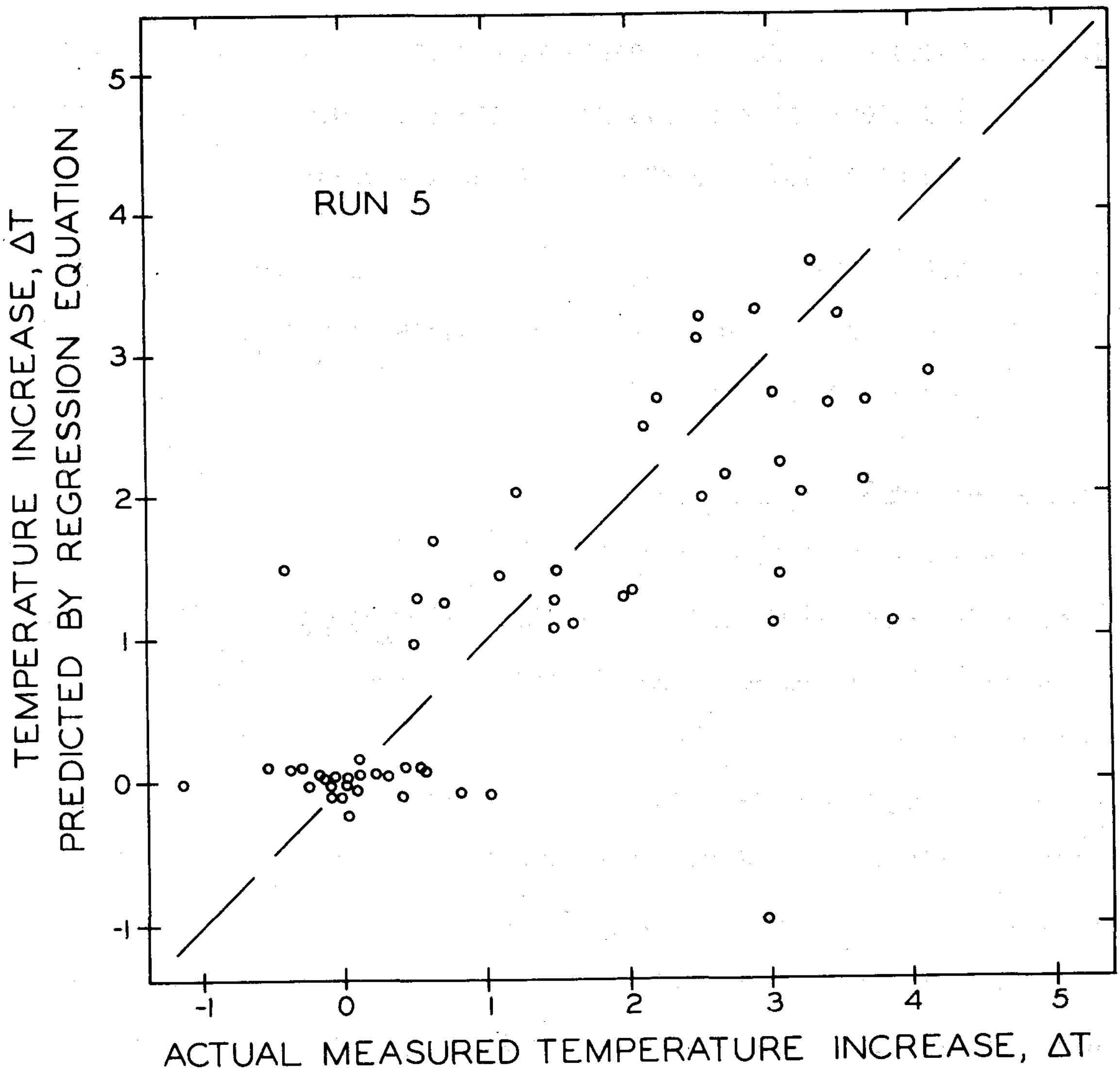


Figure 10. Randomly selected temperature increases during Run 5 vs. increases predicted by Equation 1.

1. $\Delta T = 1.290 + 171.485\ P - 0.027689\ D^2 - 5.81608\ PT - 2.0644\ PW + 0.21586\ D$
$- 0.7288\ PD + 36.999\ P^2 + 0.001599\ HD - 0.013518\ T + 0.61525\ PH$
$- 0.049366\ H$, with $R^2 = 0.730$ and $s = 0.676$

2. $\Delta T = - 0.0724 + 198.990\ P - 0.026559\ D^2 - 6.27857\ PT - 2.1196\ PW$
$+ 0.26927\ D - 0.9237\ PD$, with $R^2 = 0.720$ and $s = 0.686$

3. $\Delta T = 2.203 + 60.420\ P - 1.94666\ PT - 25.184\ P^2 - 1.0989\ PW - 0.026903\ H$
$+ 0.000255\ D^2 + 0.7579\ PD - 0.11505\ D - 0.08177\ W - 0.007291\ T$
$+ 0.06837\ PH$, with $R^2 = 0.747$ and $s = 0.336$

4. $\Delta T = 0.970 + 33.163\ P - 76.945\ P^2 - 1.7289\ PW - 0.002427\ D^2 + 0.3707\ PD$
$- 0.27029\ PT - 0.05514\ W - 0.001711\ HD + 0.010227\ H$, with $R^2 = 0.838$
and $s = 0.424$

Deviation from linearity

For any given temperature below 32° outside of a protected orchard, the rise in bud temperature, ΔT, due to sprinkling tends to increase nearly linearly with increasing application rate. For Run 5, increasing the number of independent variables in the prediction equation from six to eleven, including a second-order precipitation term, P^2, lowered the standard deviation, s, very slightly from 0.686 to 0.676, and increased R^2 from 0.720 to 0.730. Although the added terms are significant, these improvements may not be worth the extra effort of computation. However, in the range from 0.10 to 0.15 inch per hour, the predicted ΔT's from the long equation range as much as 0.4° below those of the shorter equation. Hence, the assumption of linearity with respect to precipitation rate is acceptable for Run 5 providing a user of the linear equation realizes it is a bit too optimistic. A visual comparison can be obtained from Figures 11 and 12.

For some reason the curvature of the lines in Figure 11 is opposite to that obtained in the laboratory studies of Von Pogrell and Kidder (1959).

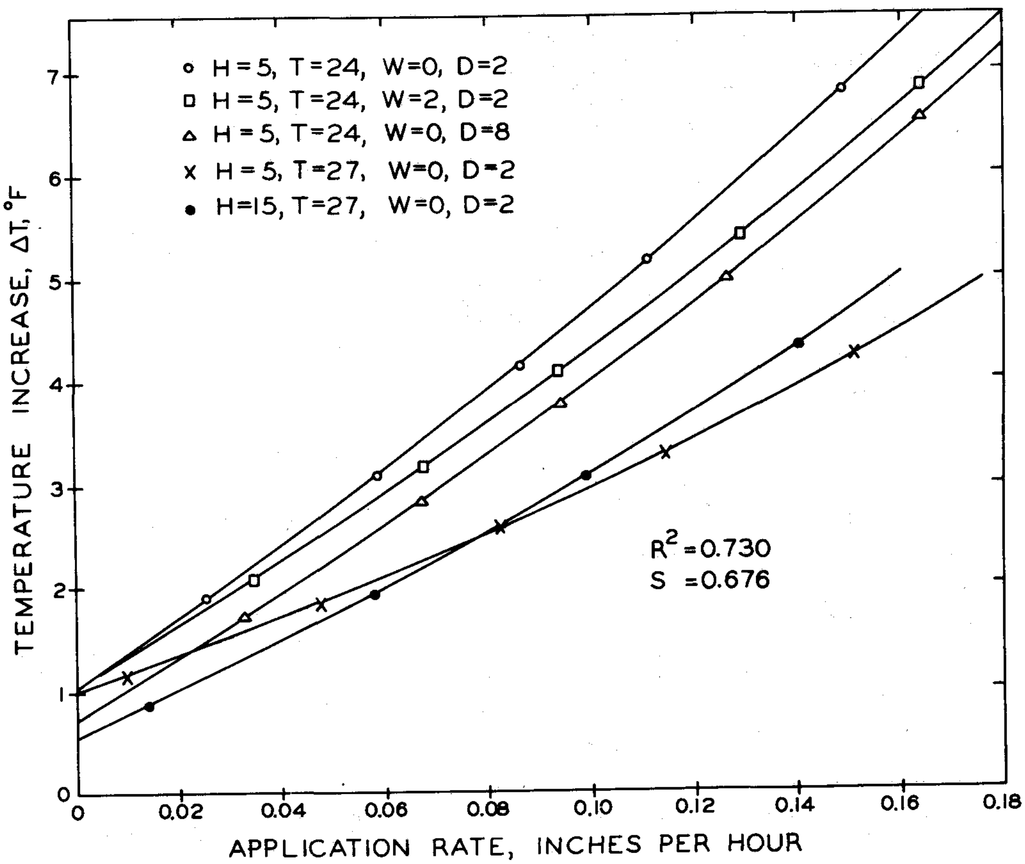


Figure 11. Temperature increases in unshielded thermistors during Run 5, as calculated by Equation 1.

For Run 7 there was no significant deviation from linearity in the readings from the unshielded thermistors. For Run 3 the function was definitely non-linear, but experimental errors are suspected as the cause. Since signals from the unshielded thermistors were all brought to the data acquisition system through adjacent channels 1 through 44, it is possible that part or all of these were temporarily malfunctioning while other banks of channels were operating properly.

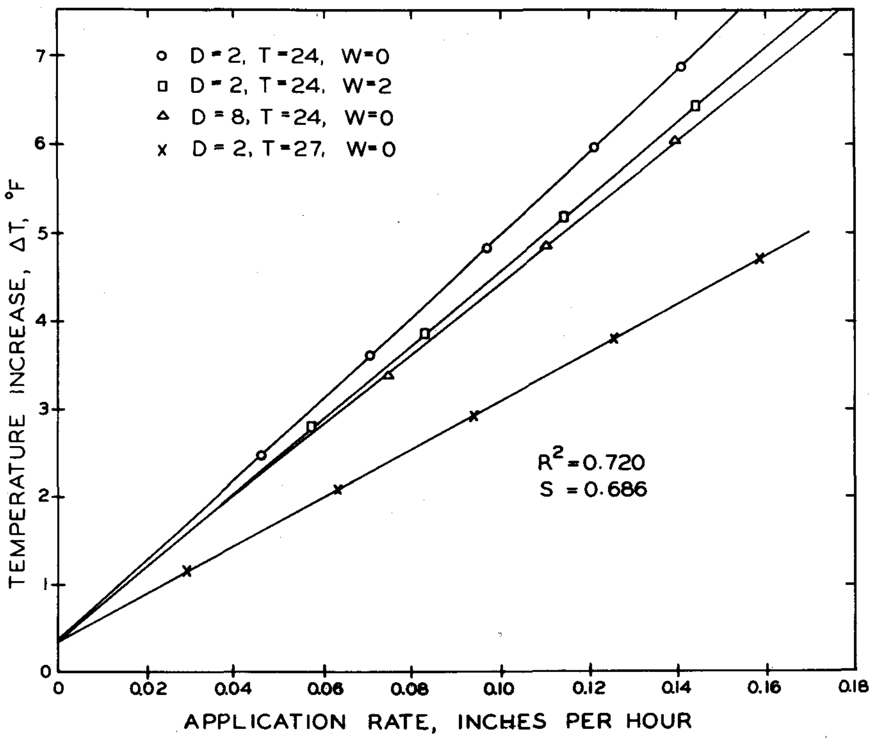


Figure 12. Temperature increases in unshielded thermistors during Run 5, as calculated by Equation 2.

RESULTS AND CONCLUSIONS

Application Rate

Prediction equation No. 1 obtained from the unshielded temperature measurements indicates that an application rate of about 0.15 inch per hour would be required to raise bud temperatures from 24 to 31° (Figure 11). To obtain this much protection, the buds would have to be located within 2 feet of the tree trunk, and the wind velocity zero. Buds located 8 feet from the trunk might be nearly 1° colder than those at 2 feet and thus require a rate of about 0.17 inch per hour. An increase in wind velocity from zero to two miles per hour would lower the temperature of all ice-covered buds receiving water at 0.15 inch per hour about 0.6^{o}, according to this prediction equation. The equation also suggests that an application rate of about 0.14 inch would be required if the outside temperature were 27^{o}. According to Table 2, the plotted curves in Figure 11 could possibly each be raised a maximum of $2/3^{o}$. Hopefully, this gain, plus the possibility of a bit more at other heights as will be discussed later, will be enough to compensate for increasing D to include the entire tree, and increasing W to one or two miles per hour without having to increase P above 0.15 inch per hour. The slopes of these curves suggest an approximate rise of one degree for each 0.02 inch per hour increase in application rate. The measurements by Hewett and Hawkins (1968) generally agree with these from Run 5.

Run 7 showed considerably smaller temperature increases due to sprinkling (Figure 13). However, the regression accounts for only 54 percent of variation during this run, so something else, such as instrumentation difficulty or convection caused by the strong temperature inversion that night was apparently adversely affecting the results. For both Runs 5 and 7 the calculated curves have been extrapolated for temperatures below 26^{o} and 27^{o} respectively. Since the Mast F temperatures did not go below those values perhaps this extrapolation was not justified.

Run 3 shows smaller ΔT's than Run 5 (Figure 14) and although the ambient temperature did go below 24^{o} on the night of measurement, observed irregularities suggest errors in data acquisition.

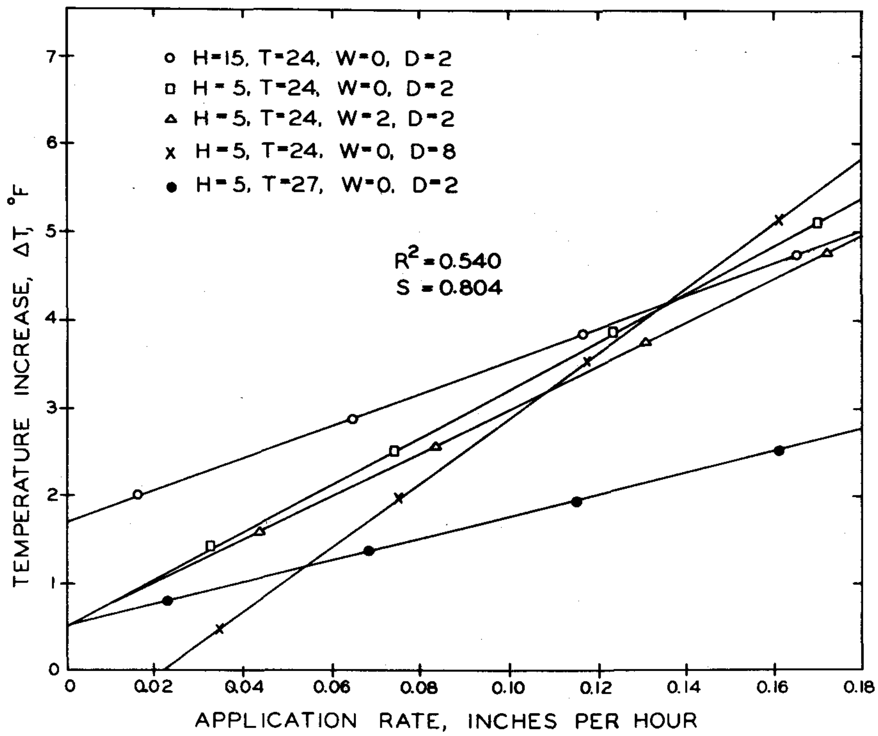


Figure 13. Calculated temperature increases in unshielded thermistors during Run 7.

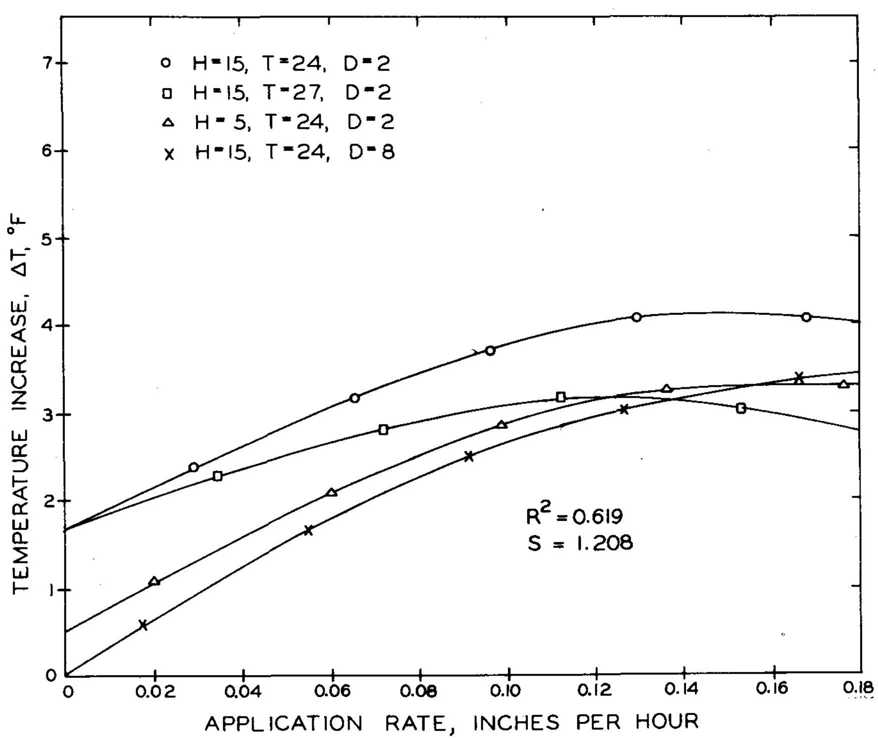


Figure 14. Calculated temperature increases in unshielded thermistors during Run 3.

Effect on air temperature

The rise in air temperature surrounding the protected buds and branches increased with increasing application rate, but more slowly and not linearly. The warming is noticeable at rather low application rates, but there appears to be little tendency for more than three or four degrees total rise regardless of further increase in application rate (Figures 15, 16, and 17). According to Table 2, the plotted curves for the shielded thermistors for Runs 5 and 7 could apparently all be raised about 1/3°.

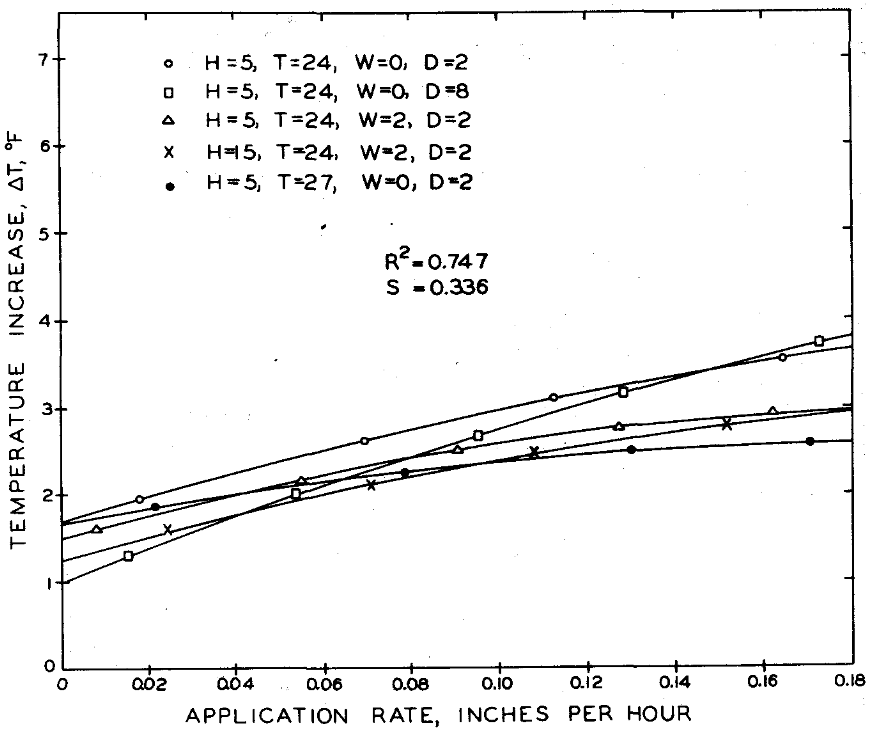


Figure 15. Temperature increases in shielded thermistors during Run 5, as calculated by Equation 3.

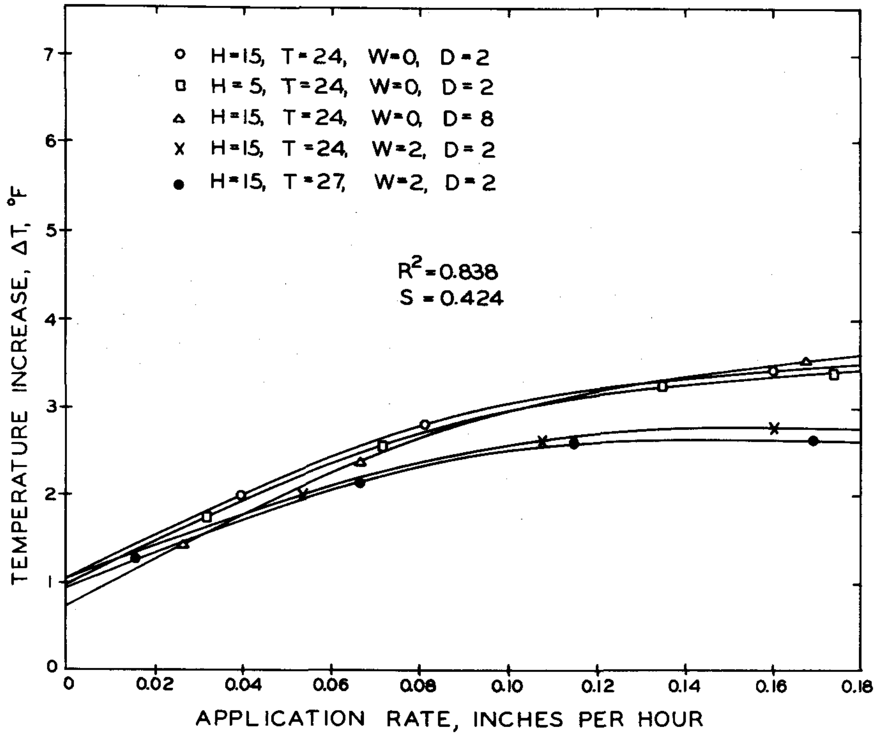


Figure 16. Temperature increases in shielded thermistors during Run 3, as calculated by Equation 4.

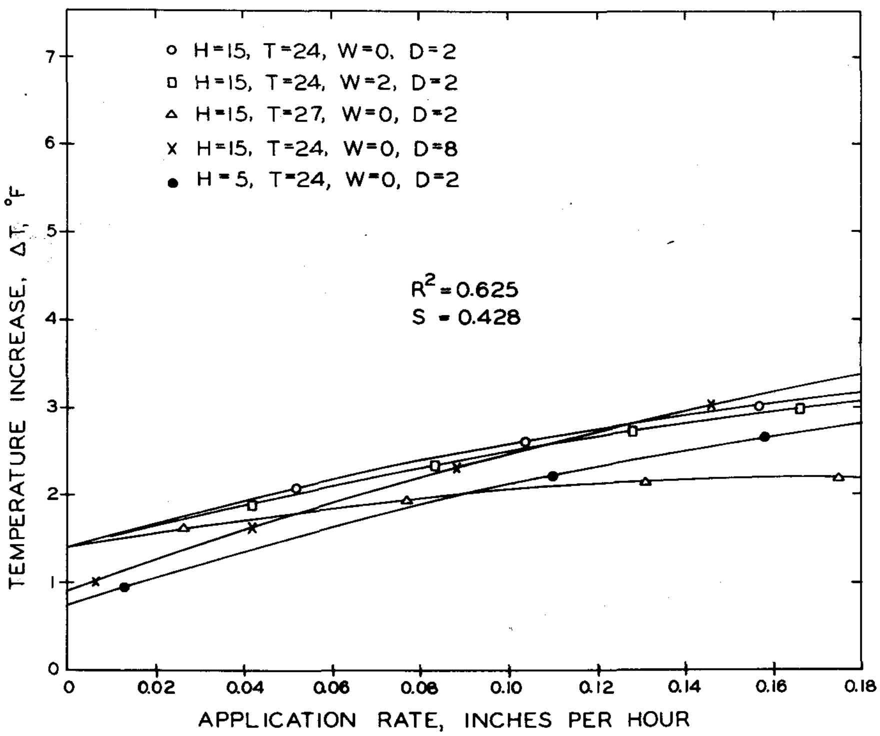


Figure 17. Calculated temperature increases in shielded thermistors during Run 7.

Effect of wind

When the wind increased from 0 to 2 or 3 miles per hour, it caused a significant decrease in the ΔT observed in both air temperature and bud temperature. The one exception was no significant effect on the unshielded temperatures during Run 3. Estimating from Figures 11 and 13 for an application rate of 0.15 inch per hour on the unshielded buds, the decrease in ΔT caused by increasing wind from 0 to 2 miles per hour was about 0.6^{o} and 0.3^{o} for Runs 5 and 7, respectively. For the shielded measurements the corresponding decreases were 0.6, 0.5, and 0.1^{o} for Runs 3, 5, and 7, respectively. Apparently for Runs 5 and 7 an increase in evaporation at the higher wind velocities reduced the temperature of the ice-coated thermistors toward wet bulb temperature, while the air surrounding them was reduced a slightly lesser amount.

Effect of distance from tree trunk

Exposed buds located close to the trunk of a tree tended to be warmed more than those at a greater horizontal distance from the trunk. Apparently each one was warmed somewhat by radiation from the relatively warm, ice-coated buds and branches near it, and those near the center of a tree were close to more radiating surface. For Run 5 this tendency increased with increasing application rate, whereas for Runs 3 and 7 it decreased. In fact, for Run 7 the D = 8 line crosses the corresponding D = 2 line at slightly less than 0.14 inch per hour, suggesting that some deviation from the general conclusion may exist at higher application rates.

For the shielded measurements of air temperature, the curves for D = 8 were lower during all three runs than those for D = 2 when the application rate is below 0.12 to 0.15 inch per hour. Above this range of rates, the trend reverses or is obscured. Apparently air temperature is influenced by its proximity to the relatively warmer ice-covered wood near the tree trunk when application rates are low, whereas other factors become more influential when rates reach or exceed the 0.12 to 0.15 inch per hour range.

Effect of height

The effect of the height of a particular bud above ground level on ΔT was not consistent among the three nights of measurement. For Run 5, where the effect of height was significant at the 10 percent level, ΔT was slightly greater at 15 feet, with differences ranging from 0^{o} at about 0.07 inch per hour to nearly 0.4^{o} at 0.14 inch per hour. Below about 0.07 inch per hour the effect of height is reversed. For Run 7 the effect of H was highly significant, but at 0.10 inch per hour the ΔT's were about 0.3^{o} larger at 15 feet than at 5 feet, whereas at 0.16 inch per hour they were about 0.4^{o} greater at the 5 foot level. Thus, the effect of height on ΔT followed opposite trends during Runs 5 and 7. The vertical air temperature gradient within the orchard offers an explanation. During Run 7 a temperature inversion of about 1^{o} existed between the 5 foot and the 20 foot levels according to a regression run on the readings from all the shielded thermistors. This was no doubt caused by the very strong 20^{o} inversion measured 550 feet above the valley floor at Medford. (Appendix Table 3). The higher air temperatures at the higher levels must have caused larger apparent ΔT's in the bud temperatures at those levels, at least for the lower application rates. Apparently, at higher application rates there was enough heat from the water to overcome the effect of the temperature gradient. During Run 5 the vertical air temperature gradient within the orchard was in the opposite direction, with the 20 foot level about $1/4^{o}$ colder than the 5 foot level (Figure 18). The corresponding Weather Bureau measurement showed only + 4.5° at 1350 feet above the valley floor -- a very weak inversion. As a consequence, the 5 foot level had larger ΔT's at low application rates than the 15 foot level did. The smaller differences in the ΔT's due to height during Run 5, correspond to the smaller air temperature gradient during that run.

A regression of (shielded) air temperature on height was made for Run 3, also, but no vertical temperature gradient was detected.

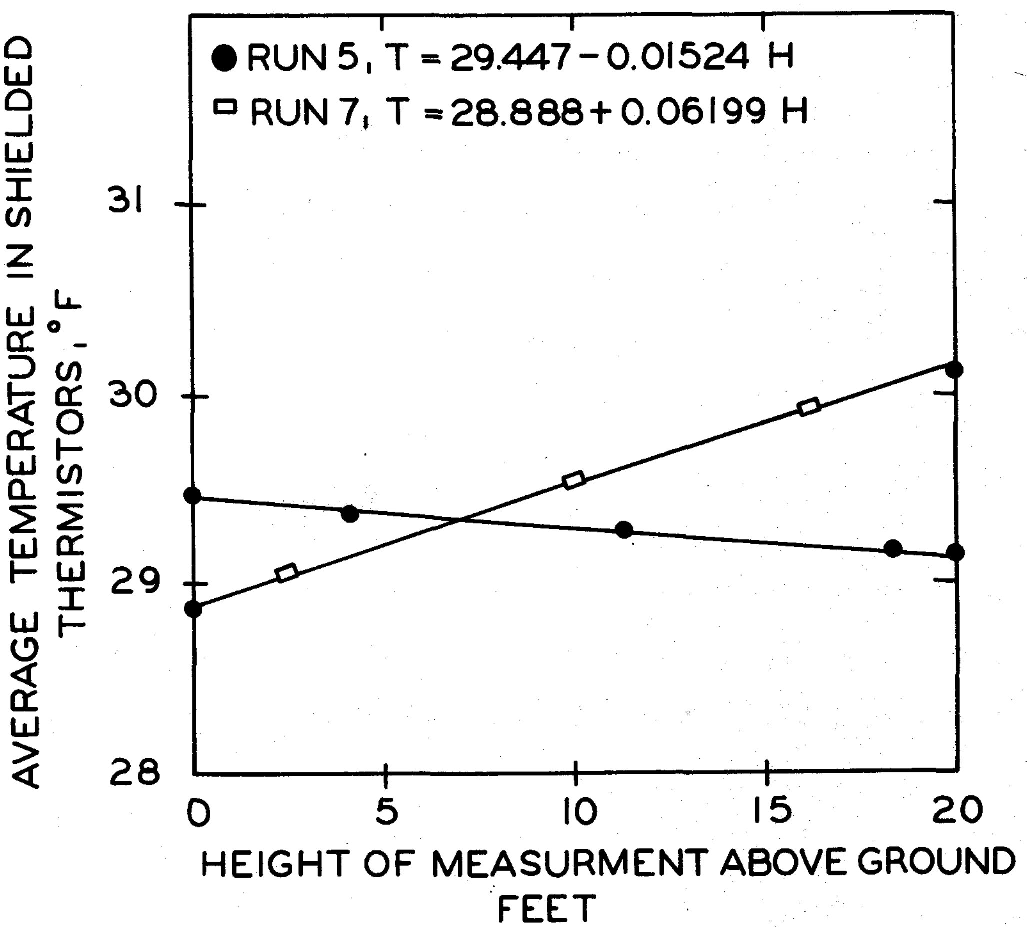


Figure 18. Calculated vertical gradients of ambient air temperature during Runs 5 and 7.

Effect of outside air temperature

The interaction between outside temperature and precipitation rate had a very significant effect during these tests on observed ΔT, both for shielded and unshielded temperatures. For the unshielded, ice-coated thermistors, Figure 11 suggests that while 0.15 inch per hour is adequate to raise temperatures from 24 to 31^{o} (H = 5, W = 0, D = 2), a rate of 0.14 inch per hour is required to raise from 27 to 31^{o}. The latter rate is higher than one would estimate if he assumed it is as easy to raise temperauure from 27 to 31^{o} as from 24 to 28^{o}. Perhaps the difference occurs when the ice-covered thermistors approach or reach the 32^{o} upper limit, even though an attempt was made to exclude data points from this analysis that were affected by this limit. The T x P effect is also quite apparent in the shielded thermistor data for Runs 5 and 7. In fact, in all prediction equations except the one for the shielded temperatures from Run 3, the mean temperature on Mast F was, next to application rate the factor having the greatest influence on ΔT at high application rates.

The curve in Appendix Figure 1 illustrates the effect of this interaction in a little different way. The curve was calculated from Equation 1 by requiring that $\Delta T = 31^{o} - T$, then solving for P. The figure appears to show the application rate necessary to raise a bud temperature to 31^{o} when the outside temperature, T, ranges from 26^{o} ($\Delta T = 5$) to 30^{o} ($\Delta T = 1$), with extrapolation to 24^{o}. However, most of the data points from which Equation 1 was calculated did not reach 31^{o}, so this procedure may not be valid. Constant values of H = 10 feet, D = 4 feet, and W = 1 mile per hour were chosen for this curve.

Effect of uniformity of water distribution

A uniform distribution of water is required to maintain protection to all parts of a tree when the application rate is barely adequate. Evidence of this is seen in the graphical illustrations of all the predictive equations, since ΔT approaches zero at zero application rate. The shielded thermistor equations show only about one degree rise in air temperature at a point within the sprinkled area receiving zero application, and the unshielded thermistors show even less, even though they may be only 5 or 10 feet from a point receiving significant water. Apparently the heat transfer by radiation and convection from a sprinkled area to an unsprinkled area just a few feet away is rather small. Further evidence can be found in Table 2, which suggests that Mast F, which received no water but which was itself in the center of the sprinkled area, was only about 1/3 or 2/3° warmer than the remote masts for the shielded and unshielded thermistors, respectively. Even though these two sets of temperature increments are probably additive, their totals wouldn't give much comfort to a bud receiving inadequate water in a 24° frost.

Effect of deficit sprinkling

Contrary to several experiences reported in the literature, there were no serious temperature depressions caused by deficit sprinkling observed during these tests. There was a fraction of a degree reduction in temperature caused by the wind during Run 5, but the regression equation does not suggest that this reduction increases at lower application rates. Only Run 7 shows any tendency for negative ΔT's, and then only near the outer edge of the tree, as the precipitation approaches zero.

Apparently the high relative humidity and the low wind velocity during these tests prevented any large temperature reductions due to evaporation.

The effect of these conditions was also observed when the sprinklers were shut off prematurely at the end of Runs 3, 5, and 7. No recorded temperatures dipped more than a fraction of a degree below the corresponding mean temperature on Mast F at that time.

Comparison of these results with other observations at Medford

As reported by Wolfe (1969), observations by C. B. Cordy at Medford indicated that pear orchards were protected by a 0.12 inch per hour application rate during a season in which the outside temperature reached 24^{o} one night when the critical temperature was 31^{o}. This compares with the 0.15 inch per hour minimum rate suggested in this paper. One possible explanation for this difference is the tendency of fruit trees to set more blossoms than needed. In one of the orchards observed by Cordy, the owner estimated his crop at 90 percent of full crop. Perhaps some damage occurred during the 24^{o} frost, but the remaining blossom set was nearly adequate for a full crop. Water application is never absolutely uniform, so many buds will receive adequate protection in average rates lower than 0.15 inch per hour. If this situation is similar to that described by Hewett and Hawkins (1968), any successive nights when the temperature reached 24^{o} would each have caused a further reduction in yield in orchards protected by only 0.12 inch per hour.

Comparisons among orchard sprinkler systems with the same nominal application rate can be difficult if there are any variations in sprinkler spacing or operating pressure that have not been accounted for in the design. Even the nozzle size will vary with usage and with the precision of manufacturing. On a very cold night the operator will raise the pressure if he can and thus increase the application rate. Thus, some systems rated at 0.12 inch per hour may discharge more or less than that amount. In the test orchard the average can catchment of four runs listed in Appendix Table 2 was 0.15 inch per hour. The theoretical rate, if the spacing were exactly 50 x 50, was 0.16 inch per hour at 80 pounds per square inch pressure. This is very close agreement, considering the difficulty of making an accurate water catchment among the branches. Also, the catchment cans were located in a vertical plane, whereas the theoretical rate was calculated for a horizontal plane.

SUMMARY

The capability of an overhead, solid set sprinkler system for protecting a mature pear orchard against frost damage was evaluated near Medford, Oregon during March, 1969. Temperature was recorded automatically from shielded and unshielded sensors mounted on closely spaced masts in the orchard. Water application was varied by turning off one sprinkler, and was measured in cans mounted on the masts. Data were plotted and also analyzed statistically to obtain prediction equations.

Results indicate that a rate of about 0.15 inch per hour will raise bud temperature from 24° to 31°, which is an average of nearly 1° rise in temperature for each 0.02 inch per hour increase in application rate. Increasing the wind from zero to two miles per hour lowered the temperature of an ice-coated bud about 0.6° at 0.15 inch per hour application rate. Buds close to the tree trunk were warmed very slightly more than those at the outer edge of a tree. The product of application rate and the average temperature on the mast receiving no water was, next to application rate, the most important measured factor affecting temperature increase.

There was very little tendency for low application rates to depress bud temperatures, probably because of high relative humidity and low wind velocity. However, there was little help gained from the surrounding branches when one

location received insufficient water. The increase in temperature of the air surrounding the heavily sprinkled branches did not usually exceed 3^{o} when the outside temperature was between 24^{o} and 27^{o}.

Observed irregularities in the measurements required that all data be evaluated and sorted, and that only the best of it be selected for analysis. Further testing to confirm or further clarify these results would be desirable.

REFERENCES

Christiansen, J. E., Irrigation by Sprinkling, Agr. Exp. Sta. Bul. 670, Univ. of Calif., Berkeley, 1942.

Gubbels, G. H., Frost Protection of Crops by Sprinkler Irrigation, Can. J. Plant Science, Vol. 49, 715-718, 1969.

Hewett, E. W. and J. E. Hawkins, Sprinkler Irrigation to Protect Apricots from Frost, New Zealand Journal of Agricultural Research, Vol. 11, No. 4, November 1968.

USDA-ARS-SWCRD, Northwest Branch, Significant Findings--Northwest Branch, Year Ending March 31, 1970, Boise, Idaho, 1970.

Von Pogrell, H. and E. H. Kidder, The Effectiveness of Water Use in Sprinkler Irrigation for Frost Protection. Michigan Agricultural Experiment Station Quarterly, Bulletin 42:(2) 323-330, 1959.

Von Pogrell, H. and E. H. Kidder, Experimental Study of Critical Leaf Temperature in Regard to Frost Protection by Sprinkling. Michigan Agricultural Experiment Station Quarterly Bulletin, 42:(3) 615-621, 1960.

Wolfe, J. W., Sprinkling for Frost Protection, Agr. Exp. Sta. Special Report 280, Oregon State University, Oct. 1969.

APPENDIX TABLE 1

Water catchment (mean of two cans, at designated heights and mast locations during Runs 3, 5, and 7) in inches per hour.

Run No.	Mast location	Height of measurement, feet 5	10	15	20
3	F	.0000	.0000	.0000	.0000
3	G	.0004	.0000	.0000	.0000
3	H	.0330	.0260	.0190	.0002
3	I	.0740	.0890	.0860	.0780
3	J	.1370	.1630	.1680	.1600
3	K	.1540	.1550	.1630	.2020
5	A	.0970	.1224	.1099	.1377
5	B	.1753	.1616	.1624	.1398
5	C	.0635	.0755	.0843	.1088
5	D	.0396	.0461	.0483	.0491
5	E	.0041	.0045	.0196	.0154
5	F	.0000	.0000	.0000	.0000
5	G	.0020	.0010	.0000	.0000
5	H	.0389	.0324	.0236	.0056
5	I	.0808	.1197	.0706	.0851
5	J	.1676	.1903	.2784	.1563
5	K	.1640	.1902	.1663	.1862
7	A	.0843	.0961	.1089	.1331
7	B	.1163	.1173	.1482	.1440
7	C	.0688	.0749	.0882	.0290
7	D	.0245	.0379	.0396	.0389
7	E	.0041	.0046	.0014	.0000
7	F	.0000	.0000	.0000	.0000
7	G	.0036	.0014	.0000	.0000
7	H	.0266	.0269	.0000	.0058
7	I	.1291	.0593	.0765	.0632
7	J	.1437	.1594	.1973	.1336
7	K	.1502	.1706	.1496	.1717

APPENDIX TABLE 2

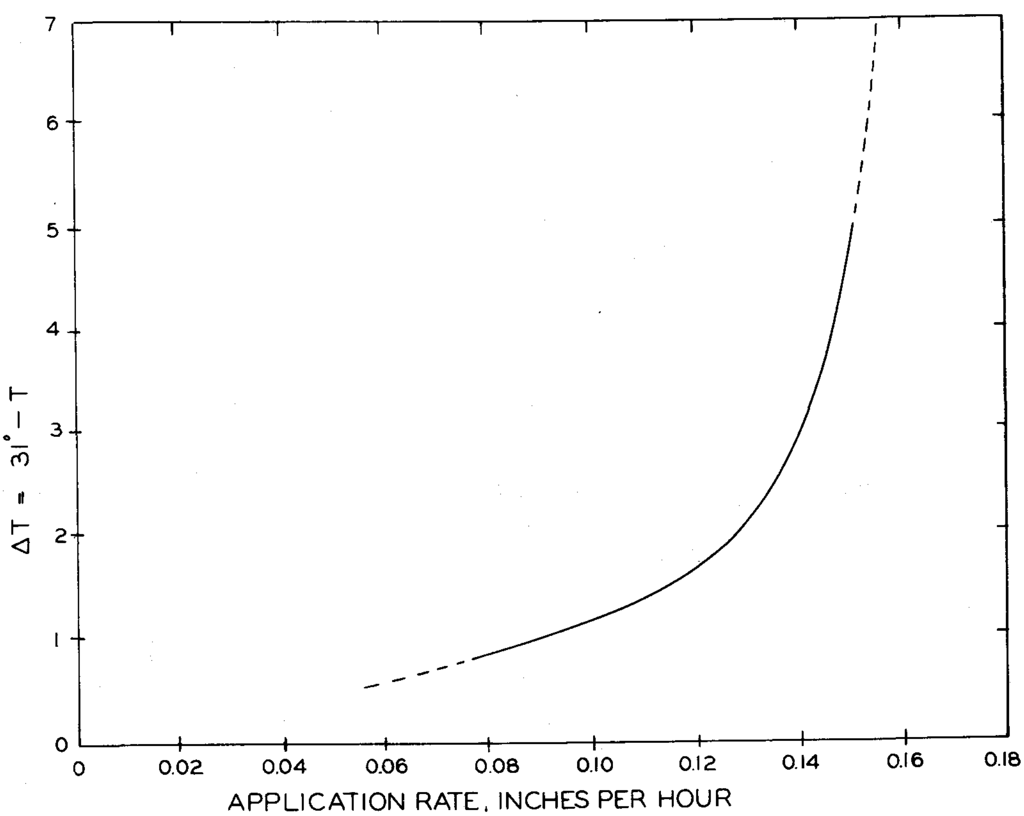
Water catchment (mean of two cans, at designated heights and mast locations, with Masts B and J each augmented with Mast E catchments for respective heights, for Runs 1, 2, 3, 5, and 7) in inches per hour.

Run No.	Mast location	Height of measurement, feet			
		5	10	15	20
1	A	.0889	.1222	.0963	.1148
1	B	.1445	.1534	.1260	.1460
1	J	.1489	.1912	.1749	.1497
1	K	.1690	.1831	.1727	.1964
2	A	.1030	.0900	.1010	.0940
2	B	.1554	.1251	.1611	.1270
2	J	.1404	.1501	.1701	.1460
2	K	.1430	.1640	.1570	.1850
3	A				
3	B				
3	J	.1411	.1676	.1785	.1677
3	K	.1540	.1550	.1630	.2020
5	A	.0970	.1224	.1099	.1377
5	B	.1794	.1661	.1820	.1552
5	J	.1717	.1948	.2980	.1717
5	K	.1640	.1902	.1663	.1862
7	A	.0843	.0961	.1089	.1331
7	B	.1204	.1219	.1496	.1400
7	J	.1478	.1640	.1987	.1336
7	K	.1502	.1706	.1496	.1717

APPENDIX TABLE 3

Climatic Data from the Weather Bureau Station at Medford

Run No.	Days in March	Dew point temperatures, °F Time 2300	2400	0100	0200	0300	0400	0500	0600	0700	Min. air temp. °F	Temp. inversion Diff. °F	Ht. of meas. feet
1	8-9	27	27	27	28	27	28	28	28	28	29	3	900
2	9-10	22	20	21	21	21	21	19	20	20	22	8.5	850
3	10-11	22	22	22	22	21	21	20	20	21	23	4	400
4	11-12	27	29	30	30	30	30	31	32	30	34	0	
5	18-19	28	28	31	29	29	28	27	27	28	26	4.5	1350
6	21-22	31	31	32	31	30	31	29	29	30	33	8.0	300
7	23-24	28	27	27	25	25	25	24	25	25	29	20.0	550



Appendix Figure 1. Apparent application rates required according to Equation 1 when imposed restrictions include $\Delta T = 31^{o} - T$, H = 10 feet, D = 4 feet, and W = 1 mph.

APPENDIX TABLE 4

Thermometer readings at remote Mast R-2 and corresponding interpolated mean thermistor readings from R-1 and R-2, degrees Fahrenheit.

Run No.	Days in March	Time	Thermometer Shielded °F	Thermometer Unshielded °F	Mean of thermistors Shielded °F	Mean of thermistors Unshielded °F
2	9-10	0348	23.3	21.2	24.46	24.50
		0635	20.2	20.2	22.62	22.33
3	10-11	0035	25.1	21.8	26.32	26.27
		0240	23.2	21.9	25.67	25.63
		0355	21.9	19.8	24.58	24.29
		0423	21.7	21.3	24.93	25.17
		0430	21.2	20.5	24.98	25.03
		0540	21.5	20.8	23.10	22.94
5	18-19	0012	30.8	27.2	31.18	30.57
		0041	30.2	28.2	30.28	29.51
		0106	30.2	28.0	30.78	29.70
		0123	29.4	26.4	30.39	30.02
		0302	28.8	25.7	28.78	28.15
		0510	26.9	26.0	26.99	26.77
		0539	26.0	23.2	26.65	26.03
		0555	25.3	22.7	26.53	25.81
		0610	24.8	23.0	25.85	25.35
		0623	24.5	21.8	26.05	25.55
		0633	24.7	23.1	25.69	26.22
		0705	27.1	26.1	28.25	28.06
6	21-22	0423	31.5	29.8	32.84	32.06
7	23-24	0250	28.2	26.5	29.64	28.50
		0400	26.3	24.8	27.60	26.75
		0510	25.0	22.3	27.68	26.37
		0553	25.9	24.2	29.29	28.06
		0653	31.8	30.0	32.53	31.84