AN EXPERIMENTAL STUDY OF THE EFFECT OF WIND AND WATER APPLICATION FACTORS ON FROST PROTECTION BY SPRINKLING

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INTRODUCTION

The use of sprinkler irrigation equipment for frost protection has expanded rapidly in the past few years. In Michigan it is estimated that over 5,000 acres of strawberries, besides some other crops, are being protected from frost by sprinkling.

In the past this method has been used mainly for protection from radiation frosts, but even under so-called still conditions there is a certain amount of air movement by natural convection and air drainage. Any laboratory work which may be done in either a cooling chamber or simulated radiation chamber will also have these natural convection air currents as well as others that may result from the operation of the equipment.

Recent interest in the application of sprinkling for frost protection of fruit trees has increased the need for knowledge of the effects of wind movement on the protection received. It is probable that more air movement will be encountered in orchard frost protection studies than has been in the frost protection of low growing crops. There are several reasons for this: (1) Fruit trees bud earlier than most crops now protected by sprinkling. Therefore the starting date will be earlier, increasing the probability of wind-borne freezes. (2) Orchards are normally planted where good air drainage exists, thus more air movement through the area can be expected, even during radiation frosts. (3) The higher elevation of the trees above the ground and the greater depth of foliage will tend to increase the natural convective air currents. (4) This higher elevation of the trees places them in an area of more rapid air movement as compared to crops near the soil surface.

Wind removes heat from a wetted plant surface by convection and evaporation. It is possible that evaporation may cool the surface below the air temperature so that heat is actually added to the surface by convection until a state of equilibrium is reached. This is the case in the common wet bulb temperatures. Very often wet bulb temperatures below freezing are obtained even when the dry bulb temperatures are several degrees above 32° F. At these temperatures the wet bulb may be wet (super-cooled water) or ice covered. In the field, the author has observed sprinkled leaves to be ice covered under windy conditions when the temperature was above freezing. This raises the question as to whether a sprinkled leaf or bud under wind conditions may react in a manner similar to a wet bulb thermometer.

To answer this and other factors this study will be concerned only with the effect of wind on frost protection by sprinkling. If this can be determined in the laboratory, the additional amount of water needed to equal the heat lost by radiation can be added for field trials.

The objectives of the study were as follows:

1. To build a tunnel in which the plant may be placed and sprinkled where the various wind factors (velocity, dry bulb temperature, wet bulb temperature) may be measured if not controlled.
2. To obtain data on plant temperatures and freezing damage when the plant is sprinkled with different application rates (inches per hour) at different repeat frequencies (time between the starting of successive applications of water) for the various combinations with the wind factors.
3. To determine the effect of sprinkling on the temperature of the leaf when the temperature of the wind is near or above freezing.

REVIEW OF LITERATURE

Most of the research work in this country on frost protection by sprinkling has been for radiation frosts with little or very low wind speeds. In many cases the wind velocity has not been recorded. However, Beahm (1) working in a simulated radiation chamber, found the rate of air movement influenced the protection received. He calculated theoretical application rates to protect various size flat plates, cylinders, and spheres for different wind speeds and temperatures. His graph for flat plates one inch long, parallel to the wind, and including outgoing radiation of 28 B.T.U. per hour square foot is shown in Fig. 1. With wind speeds of 1.25 miles per hour parallel to the leaf he measured leaf edge temperatures of 26° F. when the leaf center temperatures were 31° F. He also reports that, with an ice coat, leaf center temperatures of 30.5° F. were reached before edge damage was noted and leaf center temperatures of 29.5° F. before center damage was noted.

In preliminary trials of frost protection of apple trees by sprinkling, Wheaton and Kidder (7) encountered wind speeds up to 5 miles per hour at temperatures of 25° F. and dew points of 21° F. They also observed considerable freezing damage to the leaf edges. Palmer (6) and

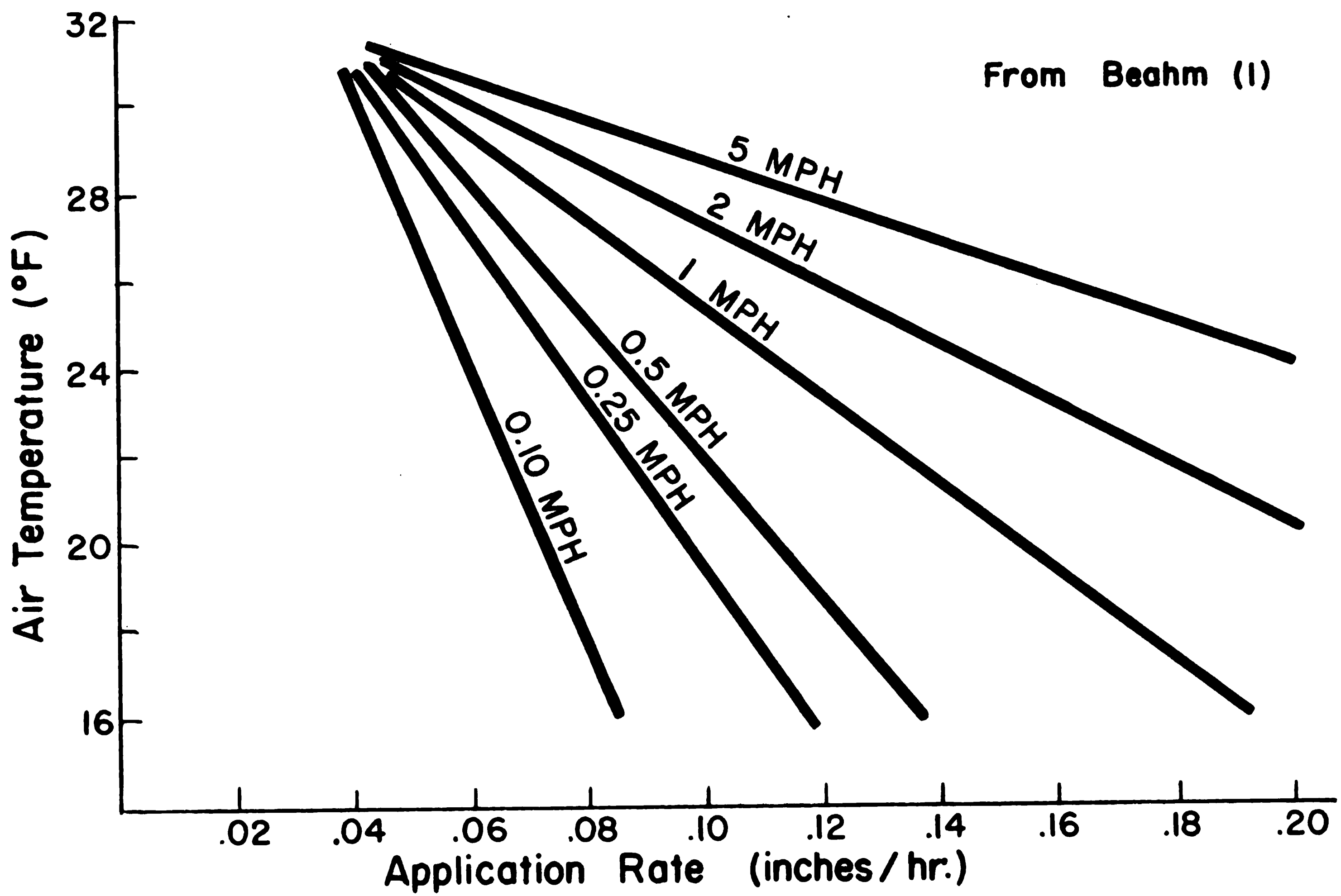

FIG. 1 THEORETICAL APPLICATION RATE FOR A FLAT PLATE OF LENGTH ONE INCH FOR VARIOUS AIR TEMPERATURES AND WIND SPEEDS PARALLEL TO THE PLATE.

Mandigo (4) reported similar wind speeds and temperatures in orchards which they were sprinkling for frost protection.

Witte and von Pogrell (8) investigated the effect of wind speed on the amount of precipitation required for the protection of plants. Their findings are shown in Table I.

TABLE I

MINIMUM AIR TEMPERATURE FOR FROST PROTECTION AT VARIOUS WIND SPEEDS

Air Temperatures ° F.	Wind Speed M.P.H.	Precipitation Required (in./hr.)
25.7-27.5	1.1	0.04-0.06
	3.1-5.6	0.06-0.10
22.9-23.5	1.1-	0.10-0.14
	3.1-5.6	0.14-0.18
16.2-19.0	1.1	0.14-0.18
	3.1-5.6	0.26

Carrier (2) states that the rate of evaporation from a wet surface is 3-1/2 times greater at a wind speed of 4000 feet per minute than at 1000 feet per minute, but for practical purposes the wet bulb depression is the same in both cases. In a later writing (3) he states that the rate of evaporation is almost proportional to the air velocity, other conditions being constant. He goes on to say that a wetted surface unaffected by internal or external heat (other than the air) tends to approach the wet bulb temperature.

Niemann (5) gives the following values for heat loss by evaporation from an ice surface at 32° F. (Values are Cal/meter^2 hour.)

Air Temp. ° F.	Wind Velocity (ft./min.)		
	39	195	780
28.4	5.97	11.97	22.88
23.0	11.35	28.7	57.4

The above values are for 100 per cent relative humidity. For 90 per cent R.H. he states the values are 25 per cent greater and for 80 per cent R.H. they are about 50 per cent greater.

In discussing the effect of ice thickness Niemann calculated the temperature drop in five minutes for various thicknesses. With a wind speed of 39 feet per minute and an air temperature of 14° F., a 1 mm. thick ice layer would drop from 32° to 18.5° while a 20 mm. layer would drop to only 30.5° F. Using the same air temperature but increasing the wind speed to 780 feet per minute the ice temperatures would fall to 14.4° and 26.1° F., respectively. During an experiment in which he had air at 25.7° F. and slow wind speeds, a delay (ice remaining at 32°) of about 4 minutes was recorded while at great wind speeds a delay of only 1-1/2 minutes was observed. These delay periods would correspond to the time between repeat applications of water by a slowly turning sprinkler, during which time the water would all freeze and the temperature of the ice start to drop before more water was added.

APPARATUS

Construction of Test Tunnel

A tunnel 8 feet long with inside dimensions of 12 by 14 inches was constructed of plywood (Figs. 2 and 3). Five feet of one end was lined with one inch of styrofoam to eliminate the radiation factor. This left an area 5 feet long with inside dimensions of 10 by 12 inches for the test area. An access door was provided in one side and a hole over the plant for the entrance of the water spray.

The other end of the tunnel was used for straightening tubes and for a plenum chamber. Two sets of straightening tubes were employed: one where the air entered the tunnel and a second set at the entrance to the test area. A cotton gauze filter was placed over the upper end of this second set of tubes to act as a pressure drop and further aid in obtaining a uniform air velocity in the cross section of the test area.

Air Temperature--Measurement and Control

The outdoor air was used as the source of cold air. This was brought in through an 8 inch conduit through a sliding gate valve to a mixing box into which warm indoor air could be admitted to obtain the desired temperature.

For control purposes air temperatures were measured by standard mercury thermometers. Air temperatures in the

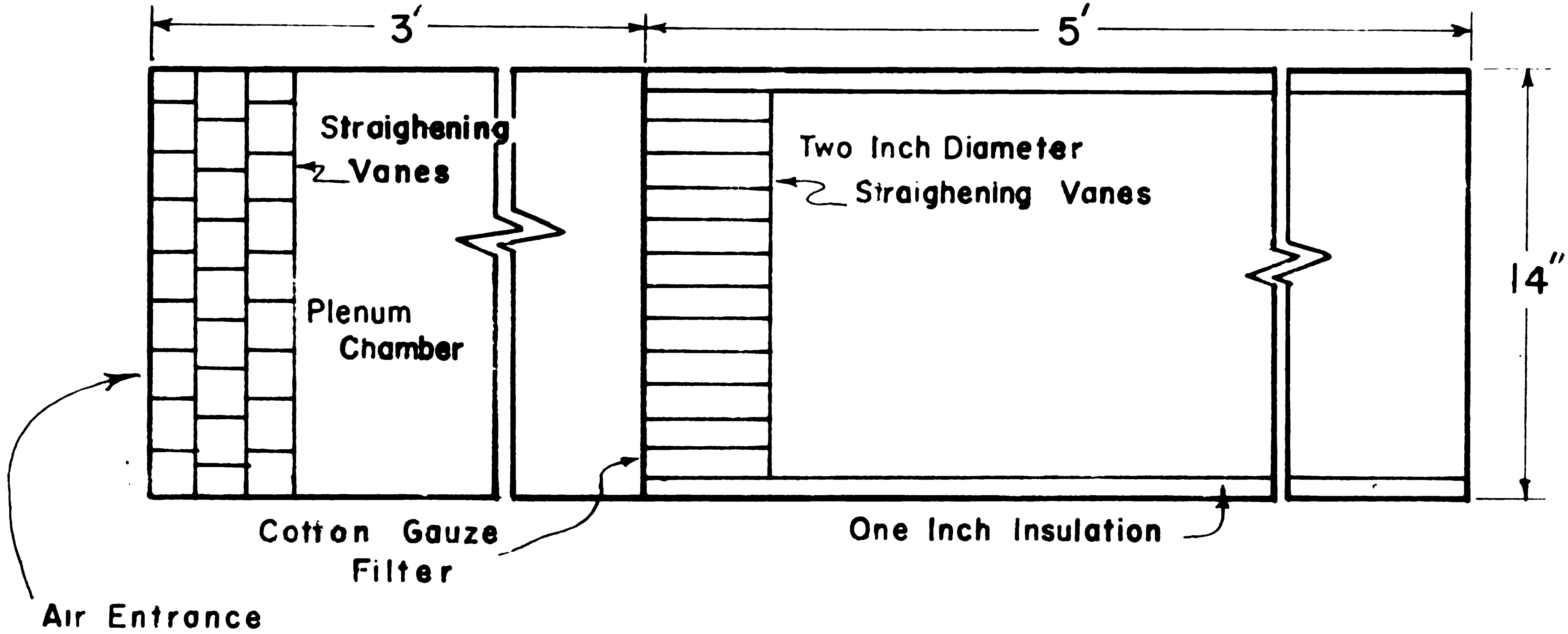

FIG. 2 SCHEMATIC OF TEST TUNNEL

testing tunnel were measured by two No. 24 s.w.g. calibrated thermocouples which were connected to a 16 point recording potentiometer. One thermocouple was placed in the center of the tunnel about 1 foot upwind from the plant. The other was placed about 2 feet downwind from the plant.

Wind Velocity Measurement and Control

A centrifugal fan driven by an electric motor was used to produce wind. It was connected to the air temperature mixing box by an insulated 10 inch diameter metal conduit. Connection from the fan to the testing tunnel was achieved by use of a tapered plywood conduit which was wrapped with a cotton packing pad for insulation (Fig. 4).

Wind speed was measured in the center of the test tunnel (the plant location) about 2 feet downwind from the plant. For velocities exceeding 200 feet per minute a calibrated vane anemometer was used. All speeds below 200 feet per minute were measured by a hot wire anemometer. Readings of the two anemometers were correlated for the ranges in which they overlapped.

Velocity control was made possible by a sliding door at the entrance to the test tunnel. Opening of the door allowed air from the fan to discharge directly into the room, reducing the velocity past the plant under test. This discharge of air allowed the adjustment of air to the air mixing box to remain constant, thereby simplifying control of the air temperature.

Wet and Dry Bulb Temperature Measurements

Wet and dry bulb temperature readings were taken by a standard sling psychrometer. The thermometers, which were graduated to 0.5° F., were calibrated before being used. Instead of being whirled, the thermometers were placed in the air stream about 2 feet from the fan where the velocity exceeded 1000 feet per minute.

Water Application

A full cone spray nozzle was placed about 2.5 feet above the plant leaf location in the test chamber. A styrofoam-insulated pyramid was constructed from the top of the test chamber to the nozzle. The size of the spray pattern in the test chamber was controlled by the diameter of the hole placed in an intercepting disk about 2 inches below the spray nozzle. Excess water was carried from this plate by a drain line. A magnetic solenoid valve actuated by a time clock was used to turn the water off and on. The waste line shown in Fig. 5 between the solenoid and the pressure gauge drained the line to prevent dripping of the nozzle, and rapidly reduced the pressure so the valve would snap shut. To control pressure and produce as large drops as possible a pressure regulator was installed in the water supply line and adjusted to produce about 2 pounds per square inch when the solenoid valve was open. This produced drops about 1/2 millimeter in size.

The industrial time clock used to control the frequency of water application could be rapidly adjusted to cycles of 20, 60, and 120 seconds by changing drive gears. The percentage of the dwell or on period was adjusted to control the application rate. By marking the cam with a scribe it was possible to reset the dwell time to obtain an application rate used in a previous test. Application rates of all tests were determined by the use of a small straight-sided can.

Leaf Temperature Measurement

A small wire frame with thread net was used to support the leaf during all tests. Two No. 40 s.w.g. calibrated thermocouples were connected to a recording potentiometer to record leaf temperatures. One thermocouple was attached to the leaf about 1/8 inch from the leading edge (the edge from which the wind was blowing) and the other was attached to the center of the leaf (Fig. 6).

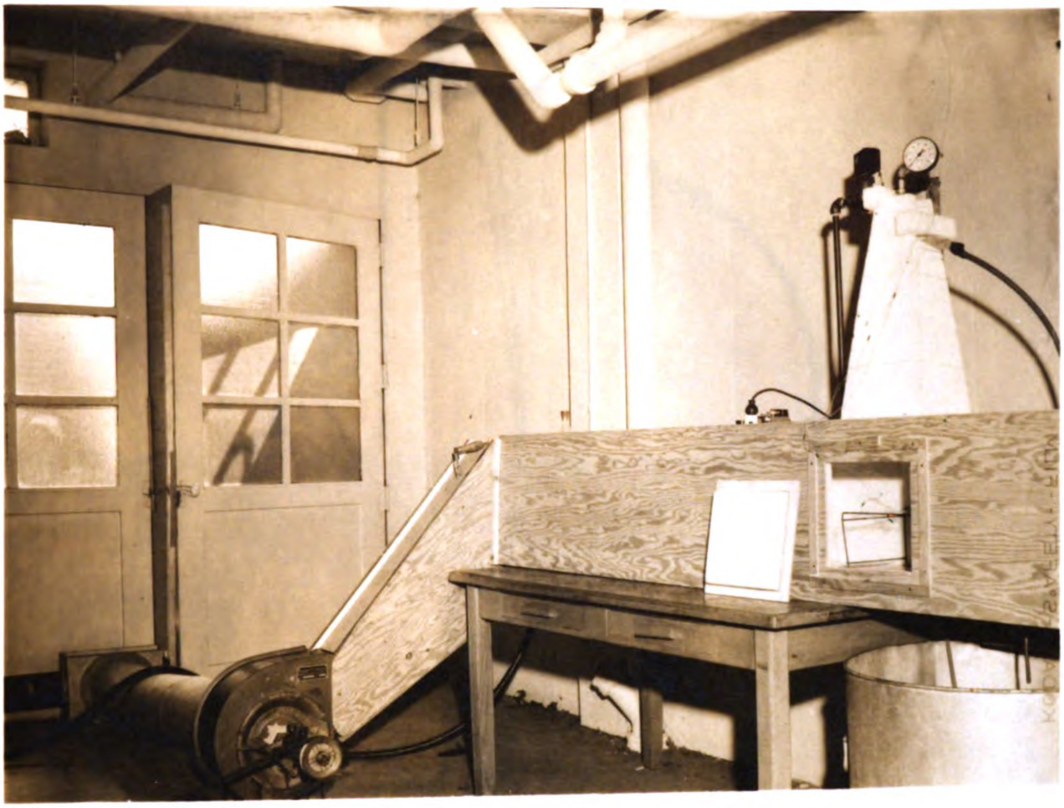

Fig. 3. Over-all view of test equipment.

Fig. 4. Close-up showing air temperature mixing box, fan, and conduit to test tunnel, insulation removed.

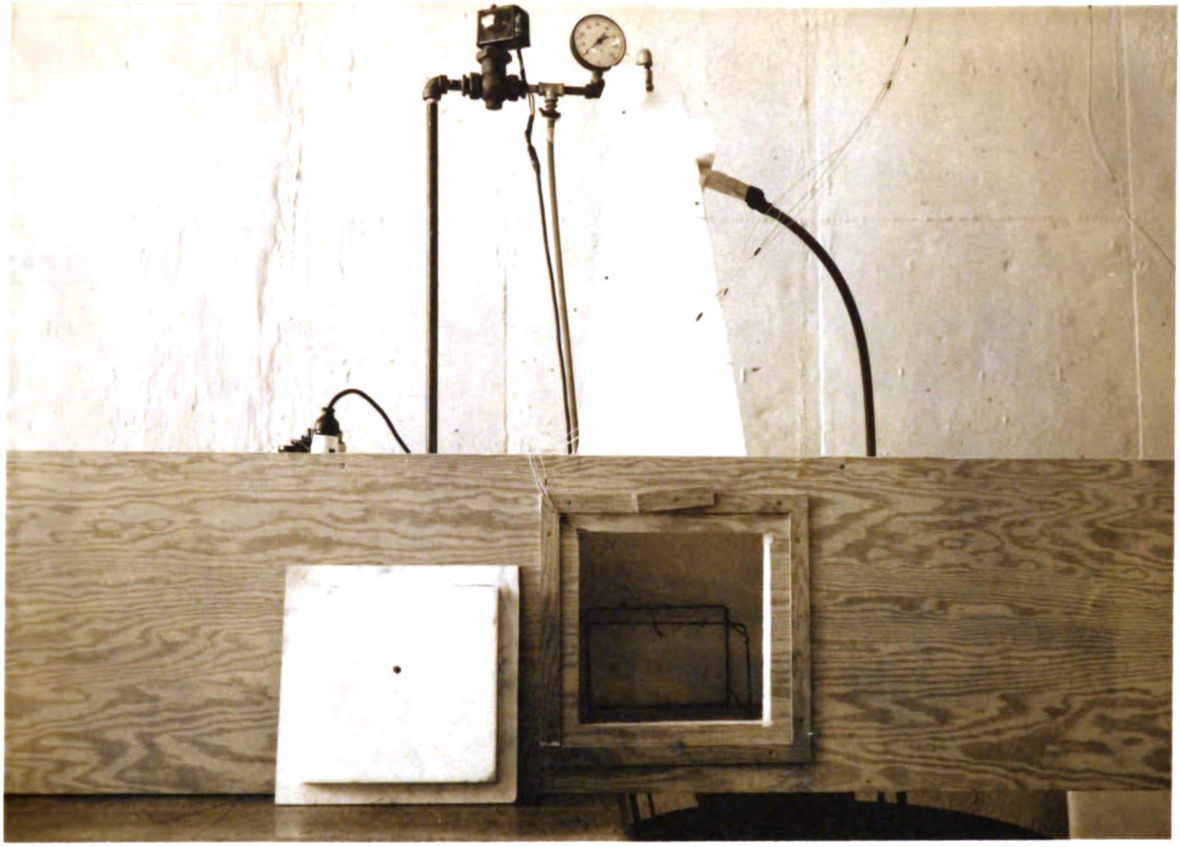

Fig. 5. Close-up showing leaf support, solenoid valve, waste line, pressure gage, spray nozzle, and insulated pyramid.

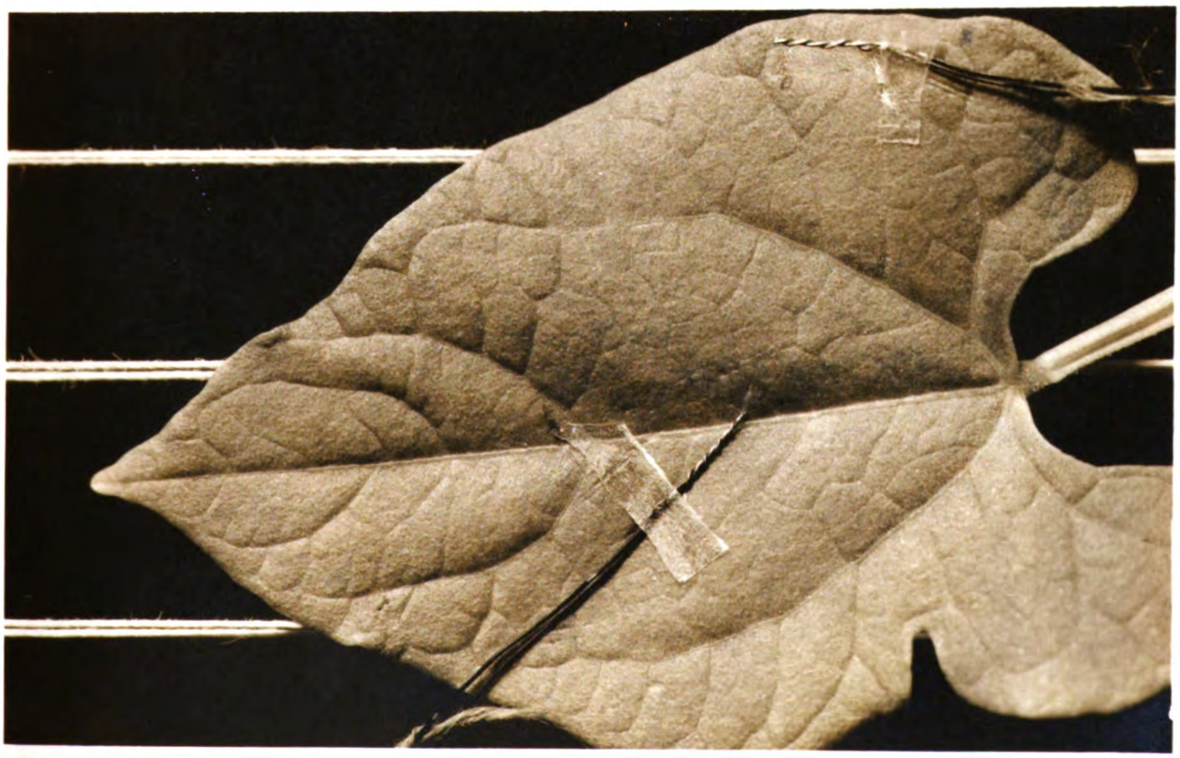

Fig. 6. Thermocouples attached to a leaf.

PROCEDURE

Calibration of Equipment

All of the measuring equipment used was calibrated either before or during use. The mercury thermometers were placed in ice water and checked for accuracy at 32° F. The thermocouples were connected to the recording potentiometer, placed in ice water, and the reading stamped by the potentiometer checked for accuracy. This recorder had been previously calibrated for temperatures from 10° F. to 50° F. The accuracy of the recorder and the thermocouples was very satisfactory, limited only by the accuracy to which the scale could be read--1/2 F°.

Wind speeds were measured in the center of the test tunnel at the outlet end, it having been previously determined that the velocity of the wind was the same here as at the location of the plant leaf. For velocities above 200 feet per minute a 3 inch diameter vane anemometer was used. This instrument had been calibrated in the factory and the calibration curve was available. Velocities below 200 feet per minute were measured by a hot wire anemometer. A correlation curve (Fig. 7) was made for the two anemometers covering the range in which they both operated. In general the curve shows the hot wire anemometer to read 10 to 15 feet per minute less than the vane anemometer.

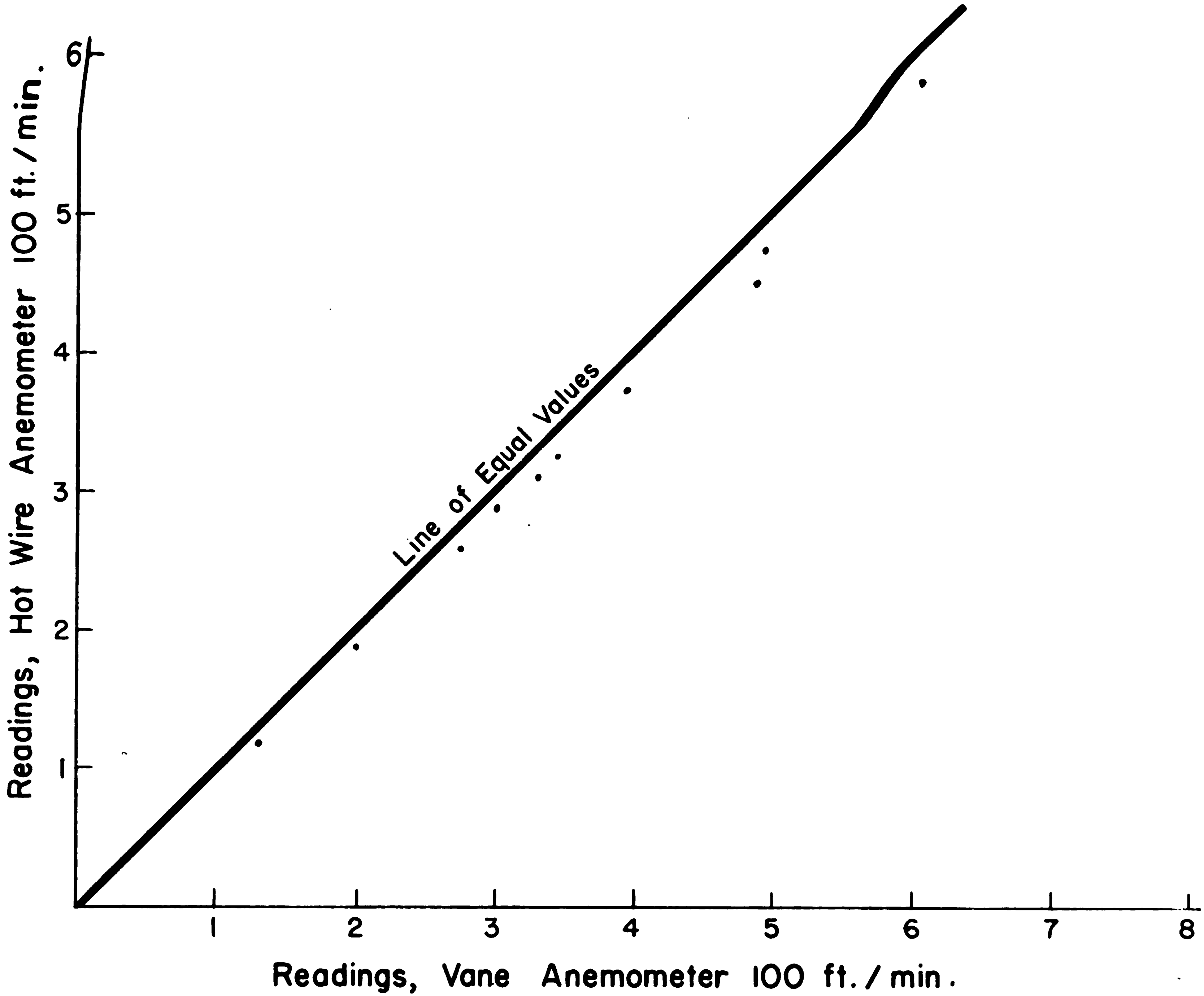

FIG 7 CORRELATION OF HOT WIRE AND VANE ANEMOMETERS

Water application rates were calibrated by placing the top of a one quart oil can in the same location and at the same height as the plant leaf would be during the tests. Tests were run for at least one hour, and in the case of the low application rate (0.04 inches per hour) they were continued for two hours. At the completion of the test run, the water from the oil can was poured into a graduated cylinder and the water measured in cubic centimeters. The conversion figure of one cubic centimeter equal to 0.005 inches of water was determined. Calibrations were made for each application rate at different wind speeds. It was found that the wind did not influence the amount of water received. Tests of the application rates were made each time that the cam on the time clock was adjusted, although it was found that by use of a scribe mark on the cam the clock could be reset to obtain the desired rate.

Leaf Selection, Placement, and Criteria for Protection

Greenhouse grown white pea bean leaves were used in all of the tests. Leaves of uniform size, about one and three-quarters inches long and one inch wide, were clipped off of the plant, placed on the supporting thread net, and thermocouples attached.

The leaves were supported horizontally in the center of the test tunnel with the long axis of the leaf perpendicular to the wind. A few trials were made with the leaf inclined 45° and 90° to the wind with the long axis still across the wind.

Beahm (1) reported that at 1.25 miles per hour leaf center temperatures of 30.5° F. could be reached before edge damage was noted. He suggested a temperature of 31° F. as a safe temperature for bean leaves. Preliminary trials with higher wind velocities indicated that no damage occurred if the leaf edge was kept at 31° F. or above; therefore, this temperature was selected as the critical temperature to which the leaf edge could be lowered without damage. Experience during the conducting of these tests indicates that this was a satisfactory temperature to prevent damage to the leaf edge.

To measure these temperatures a No. 40 s.w.g. thermocouple was attached about 1/8 inch from the edge of the leaf. A second thermocouple, of the same size, was attached to the center of the leaf. These thermocouples were secured to the leaf surface by a small piece of cellophane tape placed behind the junction of the wires. After taping, the wires of the thermocouple were bent slightly to insure contact between the leaf surface and the thermocouple junction. Each of these two thermocouples was connected to seven points in succession on the recording potentiometer. This technique permitted the recorder to print a temperature versus time curve, for each thermocouple, as it shifted through the seven successive points.

Conducting the Tests

The most difficult setting of the equipment was the adjustment of the time clock cam to control the application rate. Therefore an application rate was selected and held constant while all of the other factors in the test were varied. With the leaf in place and the spray nozzle operating, the air temperature was adjusted by regulating the amount of warm and cold air entering the mixing box.

Next the velocity of the air over the plant leaf was adjusted until the maximum wind speed was obtained at which protection was possible for the application rate, temperature, and frequency of water application being tested. It was very difficult to determine the maximum safe velocity if the test started at slow velocities and gradually increased; however, if the test started at higher wind speeds and slowly decreased it was much easier to determine the safe velocity. After equilibrium conditions had been reached additional readings of the wind speed and the wet and dry bulb temperatures were made and recorded on the recorder chart. To insure that the conditions recorded were the maximum at which protection could be obtained, the wind velocity was gradually increased and the temperatures observed.

When a series of tests had been completed for a particular application rate, temperature, and frequency of application, the drive gears on the time clock were changed and new trials started for the same application rate and temperature but for a new frequency of application.

After all three frequencies (20, 60, and 120 seconds) had been completed the temperature was adjusted and the above tests repeated. When the safe levels had been determined for the various combinations of temperature, wind speed, and frequency of application the test was stopped, the application rate checked, the cam on the time clock reset for a new application rate, and new tests started. Additional points for each application rate and frequency for the various temperatures and wind speeds were obtained by running similar tests on different dates.

Since it was impossible to control the moisture content of the air except to add moisture (and this influenced the temperature) it was felt best to measure the wet bulb temperature and make no attempt to control the amount of the moisture in the air.

The preceding discussion has been on tests conducted with the leaf horizontal. A few preliminary trials were made with the leaf supported at an angle of 45° and 90° to the wind. Also a few tests were made when the outside air was near 32° F. so that the effect of applying water to the leaf under wind conditions with a wet bulb temperature below freezing could be evaluated.

At the end of several of the tests the water was shut off to determine the minimum temperature to which an ice covered leaf would fall.

APPARATUS--RESULTS AND DISCUSSION

Air Temperature

Air temperatures obtained in the test tunnel ranged between 21° and 33° F. The majority of the tests were conducted in a temperature range of 25° to 30° F. A few preliminary trials were made with the temperature at or slightly above 32° F. Temperature control was satisfactory, except it was not always possible to obtain the desired minimum temperature as this was limited by the temperature of the outside air. As the air was the only cold sink used in this experiment it was necessary to maintain a minimum air velocity of 75 feet per minute through the tunnel to control the temperature therein. The use of mechanical refrigeration equipment would have greatly simplified the test procedures and would have facilitated replication of the tests.

Wet Bulb Temperature

Theoretically the dew point temperature is the easiest to use since at a particular atmospheric pressure it is influenced only by the moisture content of the air. In practice the dew point temperature is difficult to measure and requires more expensive equipment than the measurement of the wet bulb temperature. Therefore, the wet bulb temperature is the measurement most commonly made to determine the moisture content of the air even though it is influenced by both the amount of moisture and the temperature of the air. The wet bulb temperature lies between the dew point and the air temperature except at 100 per cent saturation (100 per cent relative humidity), at which point all three are equal. When the wet and dry bulb temperatures are known the dew point, specific humidity, relative humidity, and vapor pressure may be determined by the use of psychrometric charts, tables, calculators, or formulas.

To obtain accurate wet bulb readings they must be made where the wind velocity is approximately 900 feet per minute. The only place that velocities in this range always existed was in the conduit between the fan and the test tunnel. Since some warming of the air took place between this point and the plant leaf location the wet bulb temperatures for the air in the test tunnel were calculated. This was possible since only heat and no moisture was added to the air between these two locations; thus the dew point was the same for both areas.

During this experiment the wet bulb temperature ranged between 20° and 31° F. For the reasons discussed in the section on procedure, no attempt was made to control the moisture content of the air.

As predicted by Carrier (2,3) and discussed later in this report, it was found that under wind conditions a wetted surface tends to approach the wet bulb temperature.

Wind Velocity

With the equipment used it was possible to vary the wind speed continuously in the test tunnel between 75 and 600 feet per minute. Velocities in excess of 600 feet per minute could have been obtained. However, experience indicates that 500 to 600 feet per minute is a practical maximum velocity above which present sprinklers will not distribute water satisfactorily for frost protection. A minimum wind speed of 75 feet per minute was necessary to control the temperature in the test tunnel.

Precipitation Rates and Frequency of Application

Complete tests were made using application rates of 0.04, 0.11, and 0.20 inches per hour. A few trials were made with application rates of 0.17, 0.28, and 0.37 inches per hour. Calibrations of the application rates made at the end of each test indicated that (1) the rates could be reset with an accuracy of 0.005 inches per hour and (2) the application rate was affected very little by a variation in wind speed.

Three frequencies of application (20, 60, and 120 seconds) were used during the tests. The frequency was controlled by the selection of the gear driving the cam on the time clock. In this manner it was possible to rapidly adjust the frequency of spraying while holding the application rate and other factors constant.

Temperature Measurement and Recording

The use of the 16 point recording potentiometer and four thermocopules (two for air and two for the leaf) was very satisfactory. The printed temperature record could be read to 0.5° F. and estimated to 0.2° F. For more accuracy it would be desirable to have a recorder with a smaller range. The two No. 40 s.w.g. thermocouples used for leaf temperature measurement responded very rapidly to any temperature change. The thermocouple measuring the temperature near the leaf edge was connected to points 3 through 9 and the one measuring the leaf center temperature to point 10 through 16.

The recorder measured and printed a temperature every 14-1/2 to 15 seconds. Combining this speed of operation with the method of thermocouple connection provided a means of obtaining a leaf temperature curve (a point every 15 seconds) 102 to 105 seconds in length. The recorder could be advanced manually so that a curve of any time length could be obtained. For example, after points 3 through 9 had been printed the recorder could be advanced manually to point 3, which would then be printed about 15 seconds after point 9. This technique worked very well for the

60 and 120 second frequencies of application but was not quite as satisfactory for the 20 second frequency.

It was felt that the attachment of the two thermocouples to the leaf surface gave a satisfactory measurement of the temperature at the interface between the ice and the leaf. This method of attachment needs more study for periods when the leaf is wet but no ice has formed. During some of the tests temperatures below 30° F. were recorded before ice formation, yet no frost damage to the leaf was observed.

Air temperatures were measured by two thermocouples. One was placed about 1 foot upwind from the plant leaf and the other was about 2 feet downwind. These thermocouples were connected to points 1 and 2 on the recorder. When wind velocities exceeded 200 feet per minute these thermocouples recorded the same temperature, but for velocities below 100 feet per minute a temperature rise of several degrees, from the effects of the water spray, was in evidence.

Fig. 8. Slight freezing damage to the leading edge of the leaf.

Fig. 9. Severe freezing damage to the leaf edges.

DISCUSSION OF EXPERIMENTAL RESULTS

Critical Plant Temperature

As long as the temperature at the plant leaf surface remained at 31° F. or above no frost damage was observed. When the leaf was parallel to the wind the most critical area was the leading edge. Throughout most of the tests the temperature at the center of the leaf remained at 32° F. even if the leading edge temperature fell several degrees below freezing. This condition produced frost damage to the edges of the leaves (Figs. 8 and 9) similar to that observed by Wheaton and Kidder (7) while working in the field under wind conditions.

Often it was observed that when the air temperature was only a few degrees below freezing a rim of ice would form around the edges of the leaf and a small pool of water would be confined in the center (Fig. 10).

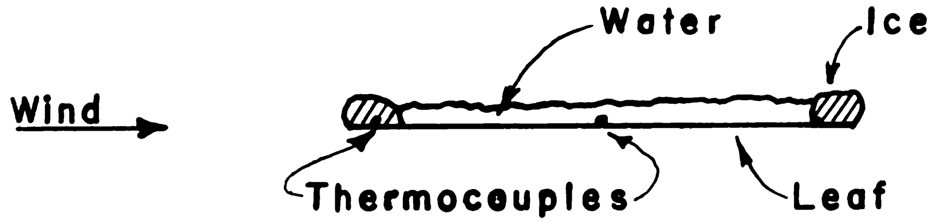

Fig. 10 Ice on Leaf Edges Only

In the following discussion, protection of the leaf from frost damage is assumed only when the thermocouple at the leading edge of the leaf measured temperatures of 31° F. or above. This assumption is consistent with observations of freezing damage to the leaf made during the tests.

The results obtained for application rates of 0.04, 0.11, and 0.20 inches per hour are shown in Tables 2 through 4, respectively.

TABLE 2

CRITICAL CONDITIONS WITH AN APPLICATION RATE OF 0.04 IN./HR.

Freq. Seconds	Wind Velocity Ft./Min.	Dry Bulb Temp. °F.	Wet Bulb Temp. °F.	Minimum Leaf Edge Temp. °F.
20	75	26.5	21.5	31.0
20	150	27.5	23.0	31.5
20	150	28.0	24.5	31.0
20	240	30.0	26.0	31.5
20	245	30.5	27.0	31.0
60	75	29.0	26.0	31.0
60	120	29.5	26.5	31.0
60	160	30.5	26.5	32.0
120	unable to maintain temp. on leaf edge above 31° F.			

TABLE 3

CRITICAL CONDITIONS WITH AN APPLICATION RATE OF 0.11 IN./HR.

Freq. Seconds	Wind Velocity Ft./Min.	Dry Bulb Temp. °F.	Wet Bulb Temp. °F.	Minimum Leaf Edge Temp. °F.
20	150	25.0	21.5	31.5
20	170	25.0	21.5	31.0
20	250	27.0	24.0	31.0
20	350	29.0	25.5	31.0
20	400	29.5	26.0	31.0
60	75	25.5	20.5	31.0
60	150	28.0	24.0	31.0
60	160	27.0	23.5	31.0
60	200	29.5	26.0	31.0
60	220	29.0	24.0	31.0
60	260	29.5	24.5	31.5
60	300	30.5	26.5	31.0
120	75	30.0	24.5	31.5
120	140	31.0	25.5	31.0

TABLE 4

CRITICAL CONDITIONS WITH AN APPLICATION RATE OF 0.20 IN./HR.

Freq. Seconds	Wind Velocity Ft./Min.	Dry Bulb Temp. °F.	Wet Bulb Temp. °F.	Minimum Leaf Edge Temp. °F.
20	190	21.0	----	31.0
20	250	25.0	22.0	31.0
20	330	26.5	22.5	31.0
20	360	27.5	22.5	31.0
20	370	28.0	25.0	31.0
20	445	29.0	24.0	31.0
20	450	28.5	25.0	31.0
20	480	29.5	25.0	31.0
20	530	30.0	26.0	31.0
60	75	26.0	23.0	31.0
60	215	27.0	25.0	31.5
60	310	28.5	25.5	31.0
60	300	28.0	26.5	31.5
60	340	28.0	23.5	31.0
60	420	30.0	26.0	31.0
120	75	29.5	27.0	31.0

The author does not propose that the values in the above tables are absolute, but rather they represent approximate minimum temperatures for which protection may be accomplished for a given set of conditions. The values are for wind-borne freezes only, as radiation was not included in the study. The data from this experiment show several effects and trends, each of which will now be discussed individually.

Effect of Application Rate

Figure 11 for a 20 second and Fig. 12 for a 60 second frequency of application show the relationships of 0.04, 0.11, and 0.20 inches per hour application rates for the various wind speeds and air temperatures. There is an increase in protection received with an increased application rate. At a frequency of 20 seconds and temperature of 26° F., the 0.04 inch/hour rate gave protection only to a wind speed of 75 feet/minute while a 0.11 inch rate gave protection to 200 feet/minute and 0.20 inch rate to a speed of 300 feet per minute. At a wind speed of 250 feet/minute the rate of 0.20 inches per hour gave protection to a temperature of 25° F., the 0.11 inch rate to 27° F., and the 0.04 inch rate to only 30° F. Similar data for other wind speeds and temperatures or for the 60 second frequency of application may be read from the two figures.

Beahm (1) reported what he called a decrease in efficiency with increased application rate. If all of the water applied remained and froze on the leaf the protection received (heat available to protect the leaf) would increase in direct proportion to the amount of water applied. In the

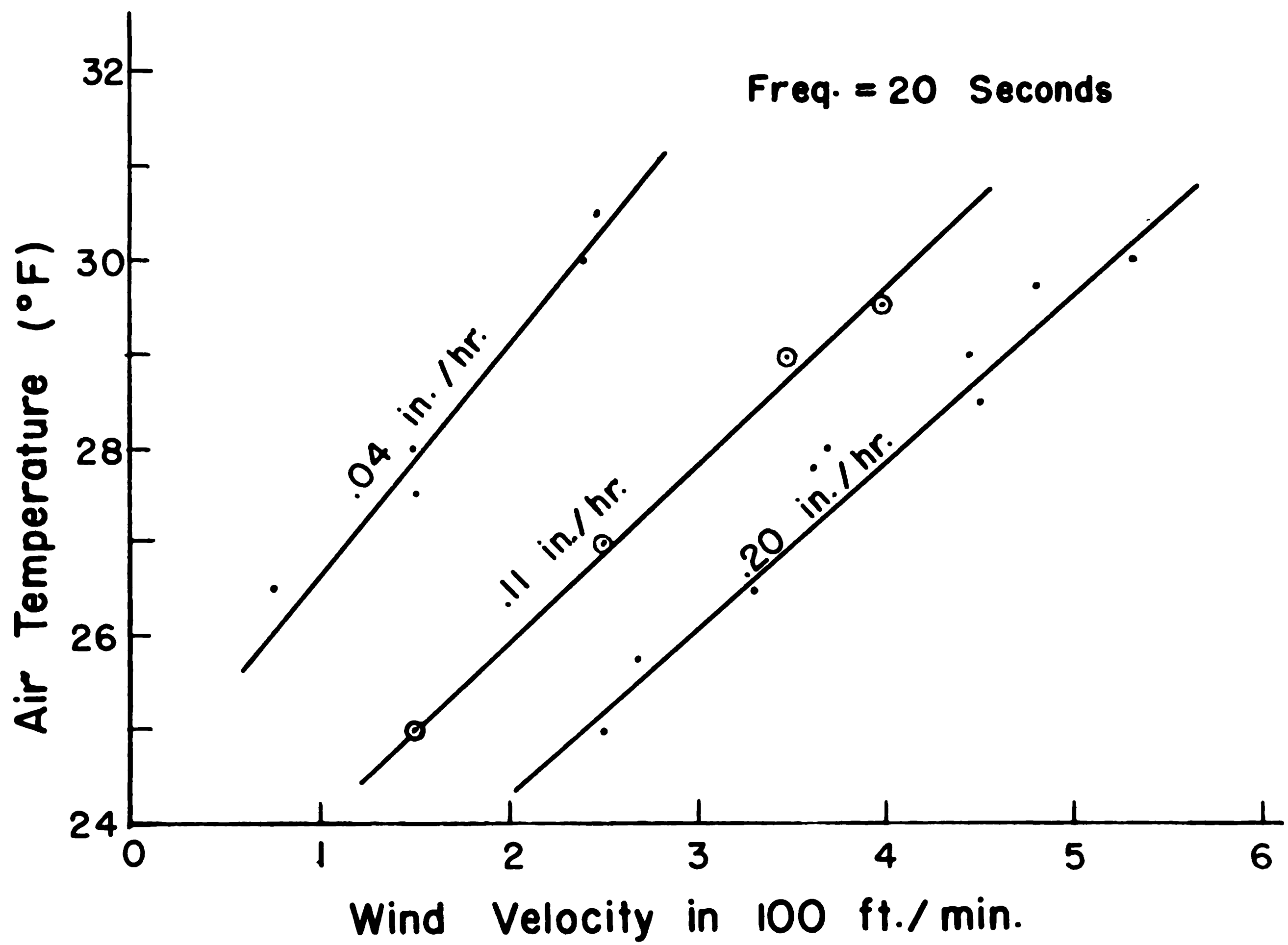

FIG. 11 EFFECT OF APPLICATION RATE

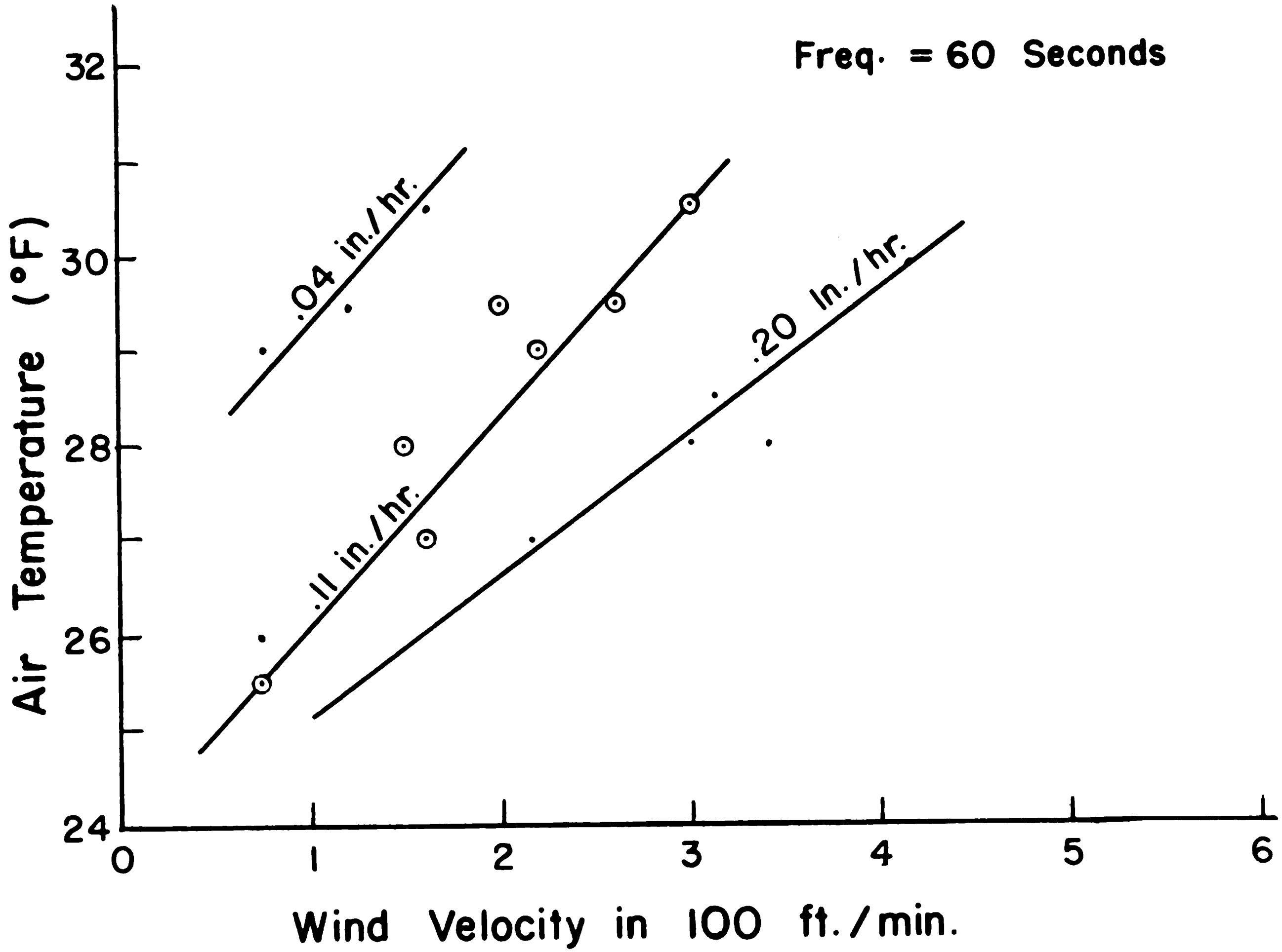

FIG. 12 EFFECT OF APPLICATION RATE

preceding two figures there is no direct evidence of this decrease in efficiency with increased application rate unless it is the flatter slope of the curve for the 0.20 inch per hour application rate at the 60 second frequency of application.

A large amount of runoff from the leaf was observed with the higher application rates. This was true even when the leaf temperature was below freezing and would seem to give weight to Beahm's theory of decrease of efficiency with increased application rate. Only small icicles about an inch long would build up after several hours time when the 0.04 inch per hour application rate was used, but with the 0.20 inch rate icicles 1/2 inch in diameter and 6 to 7 inches long would develop in one hour's time. Also with the higher application rates the ice thickness built up rapidly on the leaf surface and made it difficult to determine the exact point of protection. This is evidenced by the wider scattering of points on the curves for the higher rates.

Effect of Frequency of Application

Other workers (1, 8) have reported an increase in protection with an increase in the frequency of spraying. This is also shown in Figs. 13 through 17 and in Fig. 21. For a frequency of 20 seconds and an application rate of 0.04 inches per hour the leaf was protected down to 26° F. at a wind velocity of about 75 feet per minute, while

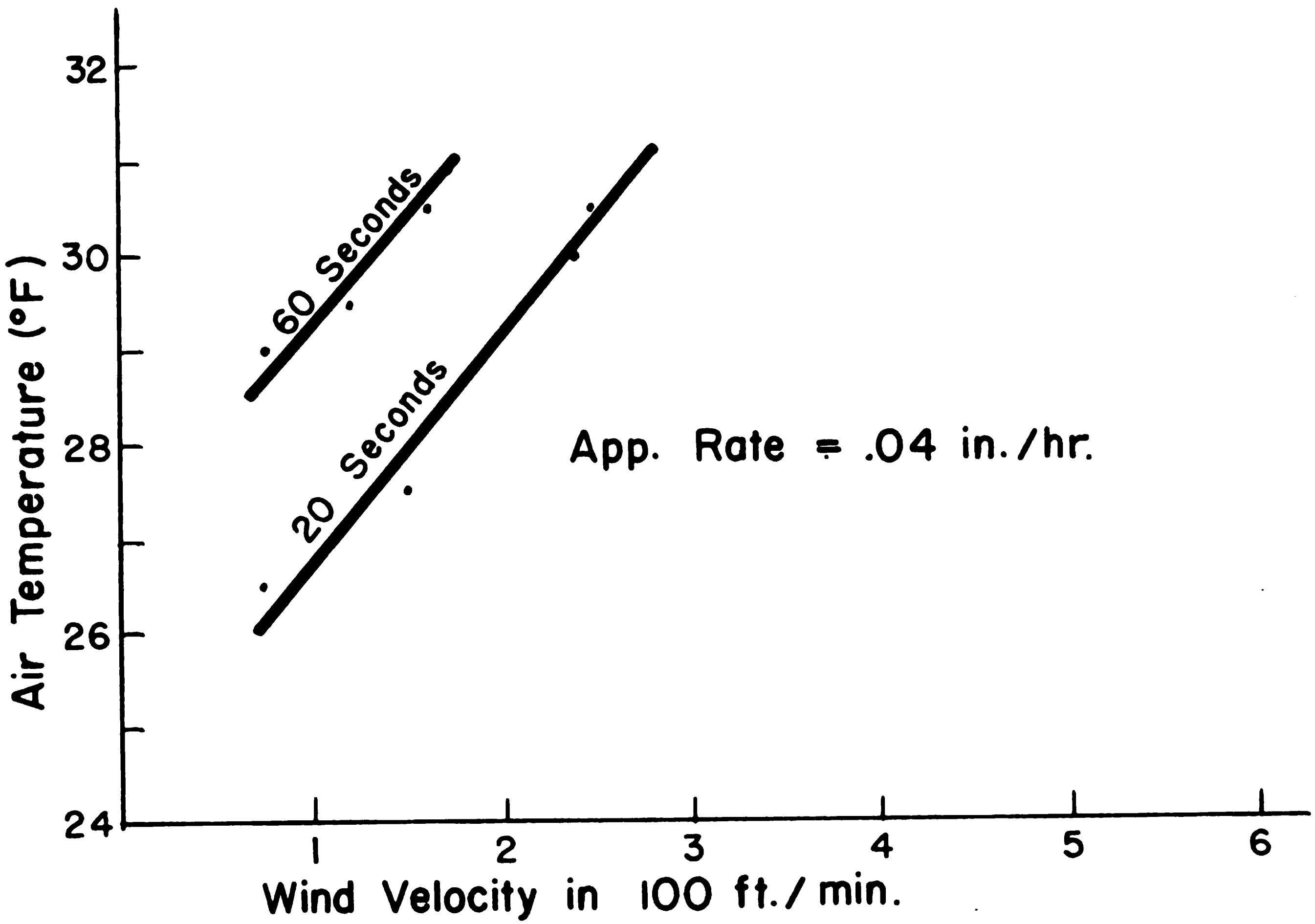

FIG.13 EFFECT OF FREQUENCY OF APPLICATION

protection was accomplished down to only 29° F. with a 60 second frequency and the same wind speed. At 30° F. the leaf was protected to a wind speed of only 130 feet per minute with the 60 second frequency, but with a 20 second frequency of application it was protected to a wind speed of 240 feet per minute using the same application rate of 0.04 inches per hour. No protection was received with a 120 second frequency, a wind speed of 75 feet per minute, and an application rate of 0.04 inches per hour.

Increased protection with the 0.11 inch per hour application rate is shown in Fig. 14. It also shows the same increase in protection with increased frequency of application as is shown in Fig. 13. For example, at 30° F. the 120 second frequency protected the leaf to a wind speed of only 75 feet per minute while the 60 and 20 second frequencies protected it in wind speeds up to 275 and 410 feet per minute, respectively.

Fig. 15 shows the effect of frequency for an application rate of 0.20 inches per hour. The same influence on protection is found with this rate as with the two previously discussed rates. Sufficient points were not found for the 120 second frequency to establish the location of the curve.

Niemann (5) proposed that three conditions could exist with different frequencies of application, (1) the sprinkler could revolve so fast that the plant is still wet at the

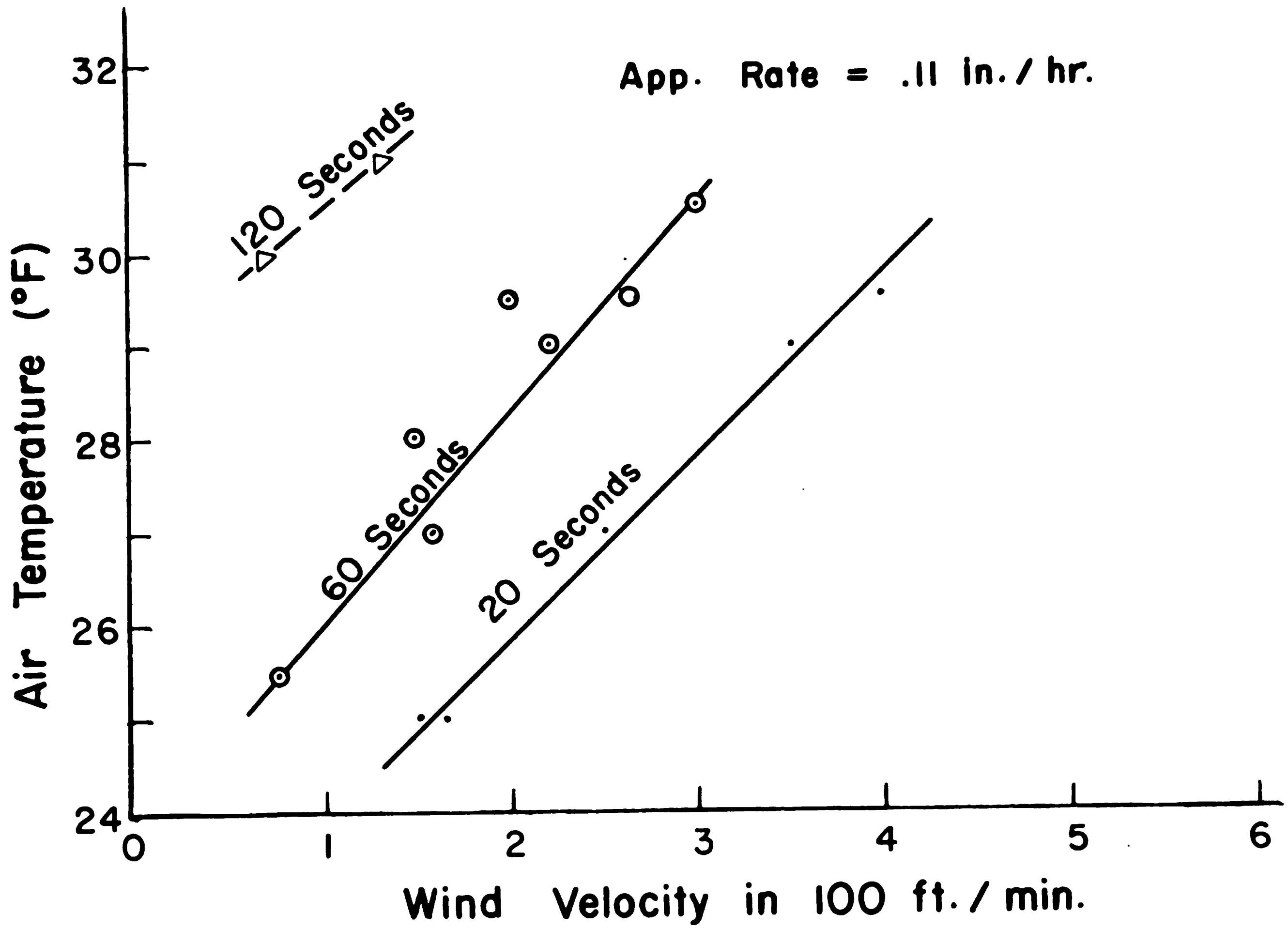

FIG. 14 EFFECT OF FREQUENCY OF APPLICATION

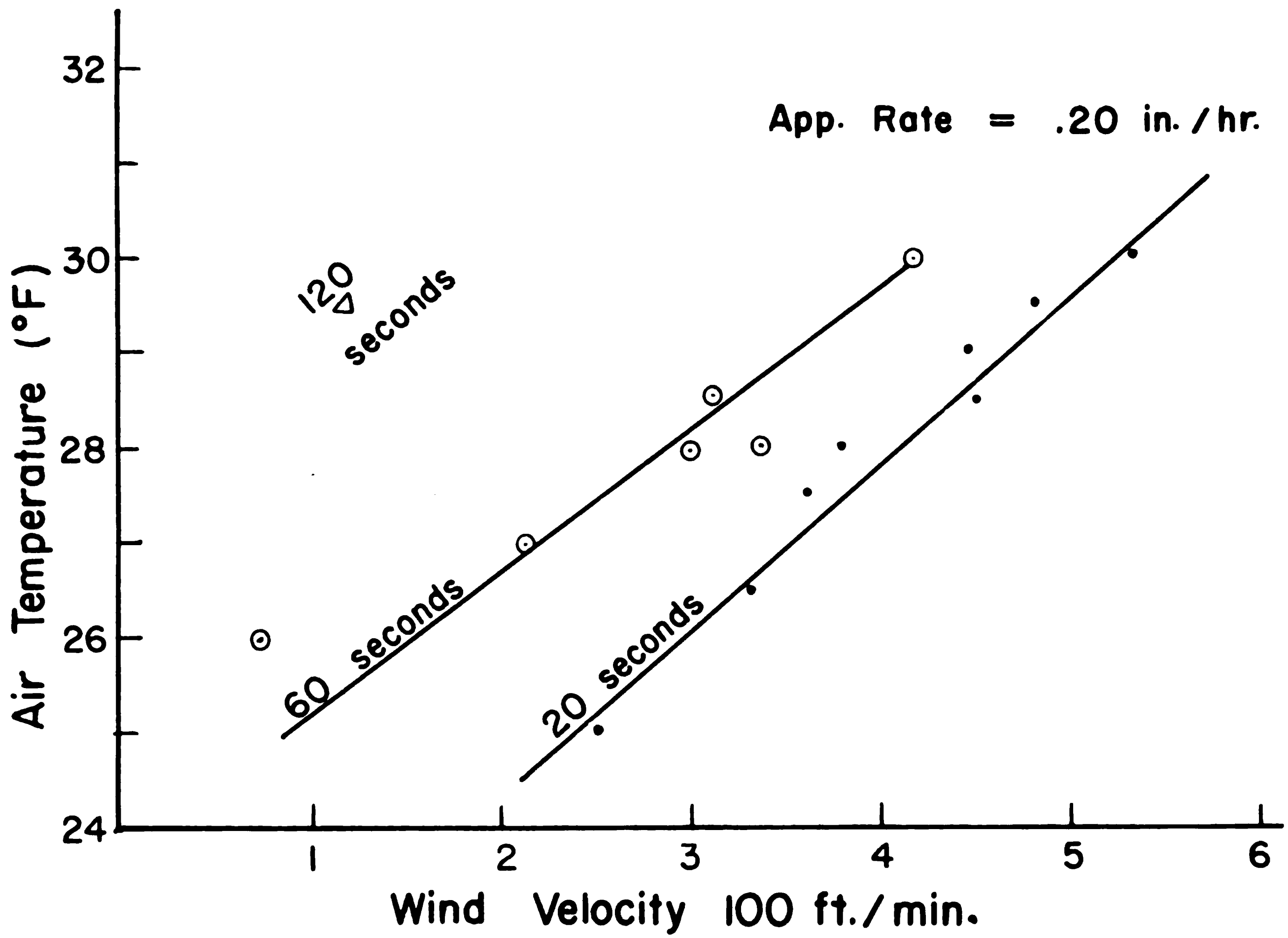

FIG. 15 EFFECT OF FREQUENCY OF APPLICATION

next pass of the sprinkler, (2) the speed of rotation may be such that all of the water has been turned to ice at the next rotation of the sprinkler, and (3) the rotation speed may be so slow that the water all freezes and the temperature of the ice falls below 32° F. before the next pass of the sprinkler. If, other factors being constant, the three conditions proposed by Niemann exist, there must be some runoff of water in at least two of them. Since there is still free water remaining in his condition No. (1) it could be argued that this is the most efficient. The ideal condition would be No. (2), in which the application rate was such that no runoff of water occurred. Theoretically Niemann's conditions Nos. (1) and (2) would be the same under these circumstances.

An example of excess water with one frequency of application but lack of protection with the same application rate but longer frequency of application is shown in Fig. 16. In this case the 20 second frequency kept the leading edge of the leaf at 32° F. or above while with the 60 second frequency the temperature varied between 30° and 32° F. The reason that the temperature peaks do not occur every 20 seconds for the 20 second frequency of application curve is that the recorder only printed a temperature every 14-1/2 to 15 seconds; thus, the exact peaks of temperature were not always recorded. However, observation of the temperature indicator showed that they did occur with

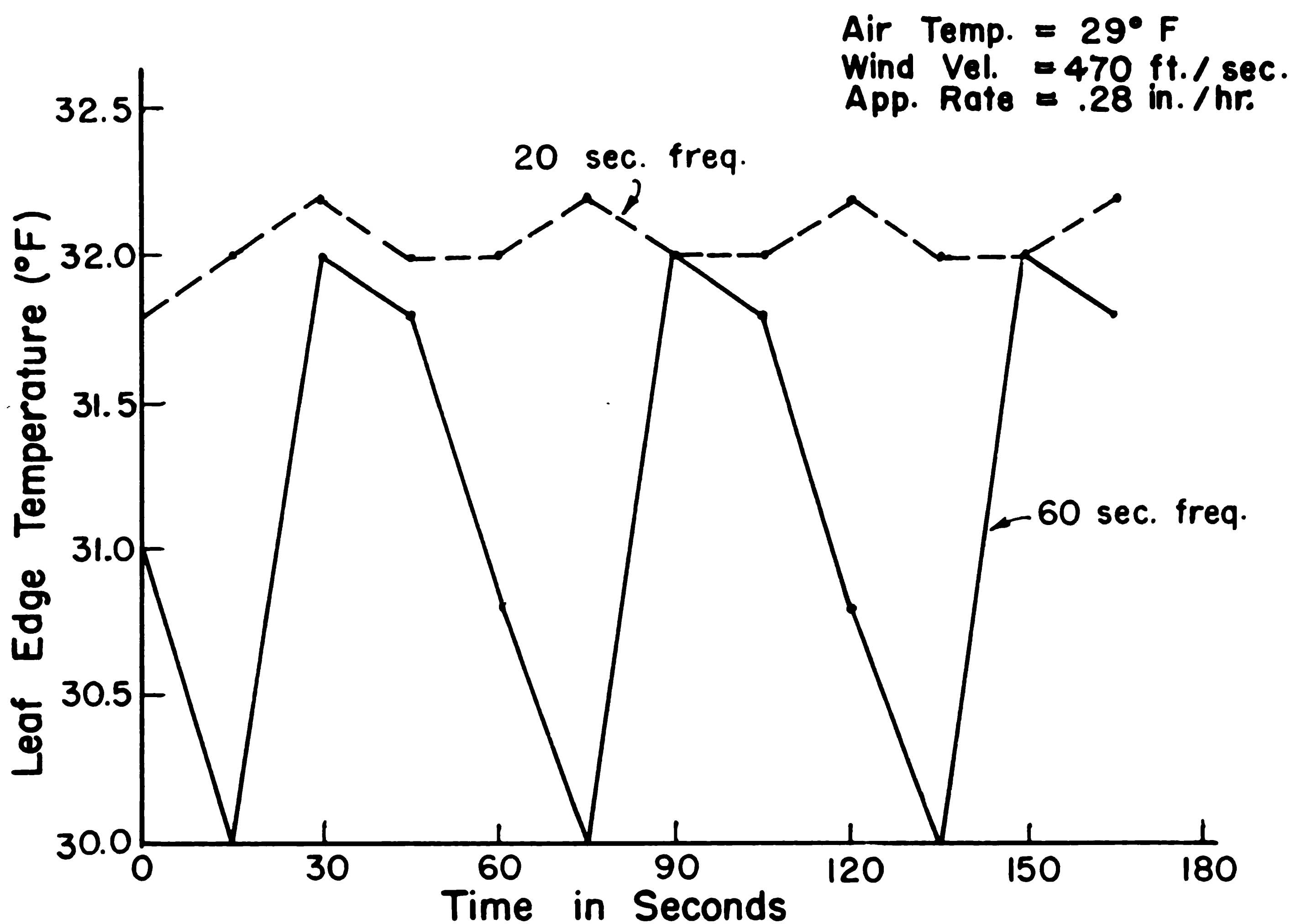

FIG. 16 EFFECT OF FREQUENCY OF APPLICATION ON LEAF EDGE TEMPERATURE.

each application of water and that the values recorded gave, over a longer period of time, a true indication of the variation of temperature. This problem did not develop with the 60 and 120 second frequencies of application.

In Fig. 17 the 60 second frequency kept the leaf edge temperature very near 32° F. while the 120 second frequency allowed it to vary between 31.8° and 30.5° F. Fig. 21 is an additional example of the effect of application frequency on the temperature of a leaf under wind-borne freeze conditions.

The instantaneous application rate of the equipment used in this experiment was the same at any frequency. This is approximately true for the sprinklers used for frost protection. However, the amount of water applied per application is inversely proportional to the frequency of application. Thus it is probable that for any one application rate, other conditions being constant, there is a maximum frequency (amount of water) that may be applied without runoff. Water that has left the plant surface will do little to keep the plant from freezing. This may explain why not only is the temperature fluctuation greater for the longer frequencies of applications but also the average temperature is often lower (Fig. 17).

Effect of Wind Speed and Air Temperature

The previous discussions on the effects of application rates and frequencies have covered the effect of wind speed

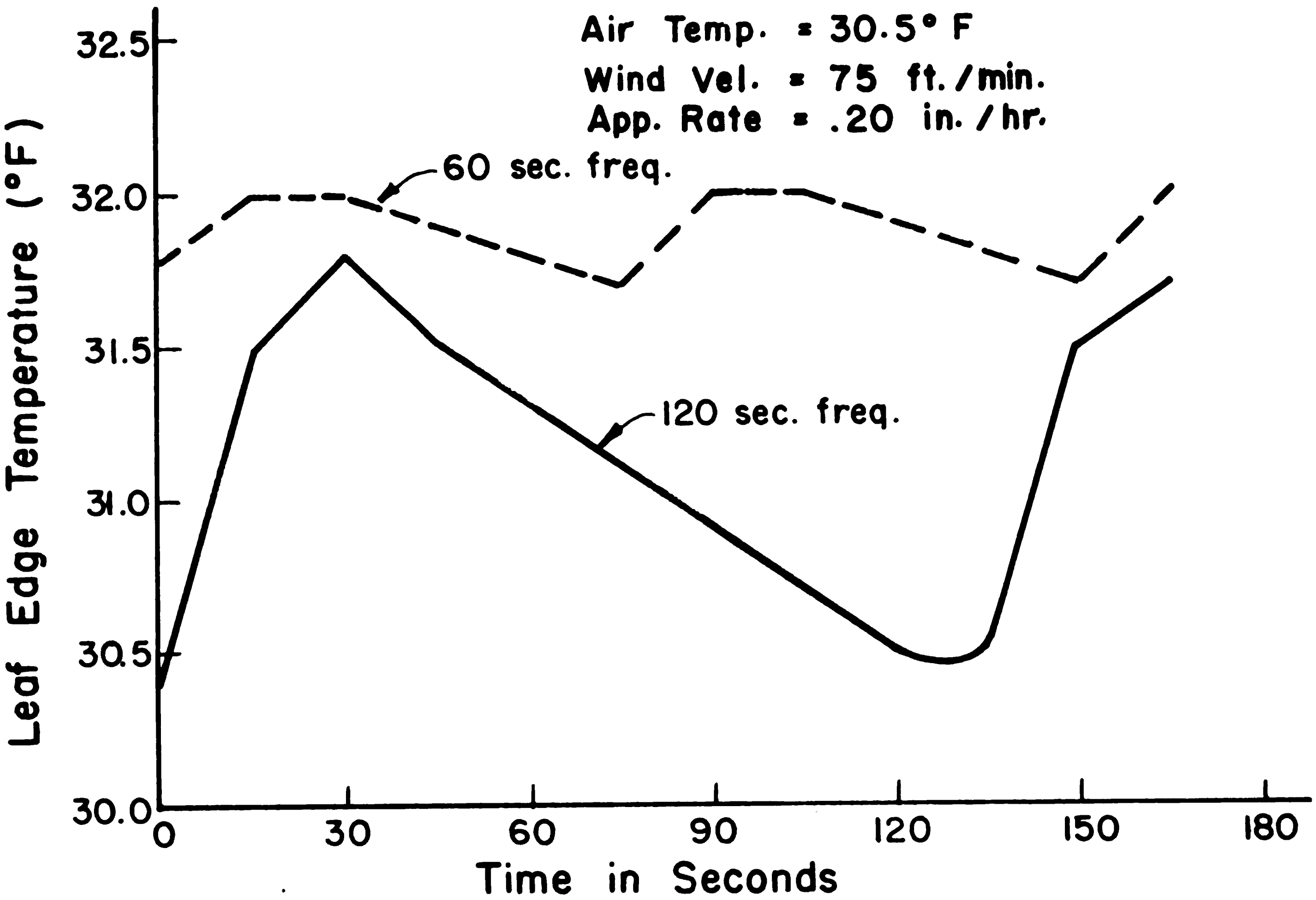

FIG. 17 EFFECT OF FREQUENCY OF APPLICATION ON LEAF EDGE TEMPERATURE.

and air temperature. See Figs. 11 through 17. In general an increase in wind speed increases the minimum air temperature to which frost protection can be achieved, or a decrease in temperature decreases the maximum wind speed from which a plant may be kept from freezing by a particular application rate and frequency of application.

Effect of Wet Bulb Temperature

Besides the cooling effect of cold air movement over a plant surface there is the cooling effect of evaporation. Evaporation will take place from an ice or water covered surface as long as the vapor pressure of the ice or water is above that of the air. This condition exists during frost protection even though the relative humidity of the air may be 100 per cent, because the temperature of the surface will be above that of the air. Very often the relative humidity is below 100 per cent during frost protection operations, at which time the wet or ice covered plant surface could be cooled, by evaporation, below the temperature of the surrounding air. Carrier (3) has stated that "a wetted surface unaffected by external heat, other than that of the air, tends to approach the wet bulb temperature." This statement is true for either an ice or water covered surface as long as sufficient air movement is present (about 900 feet per minute for a wet bulb thermometer) (3).

Wet bulb temperatures are plotted in Fig. 18 for the various dew point and dry bulb temperatures. As can be seen from this graph the wet bulb temperatures are always between the dry bulb and dew point temperatures, except at 100 per cent humidity. This figure also shows that it is possible to have wet bulb temperatures below 32° F. when the air temperature is above freezing. In this graph the wet bulb is assumed to be ice covered for all temperatures except 32° F. in which case it does not matter whether it is ice or water covered. The dew point temperature is figured for the vapor pressure of water, as is done by the United States Weather Bureau. This explains why the 100 per cent relative humidity line does not have a 45 degree slope.

In this experiment the moisture content of the air was not controlled, however, the wet bulb temperatures were recorded for all of the tests. Fig. 19 shows the leaf edge temperature for an ice covered leaf for 6-1/2 minutes after the water was shut off. In this case the temperature of the leaf continued to rise for about 1/2 minute after the water was shut off, then it fell rapidly for about 1 minute, at which time it started a steady but slower decline. After about 3-1/4 minutes of elapsed time it had fallen to the air temperature of 28° F. It continued to fall at the same steady rate toward the wet bulb temperature of 25° F. until after 6-1/2 minutes of elapsed time the leaf edge temperature was down to about 26.7° F. and it was still falling.

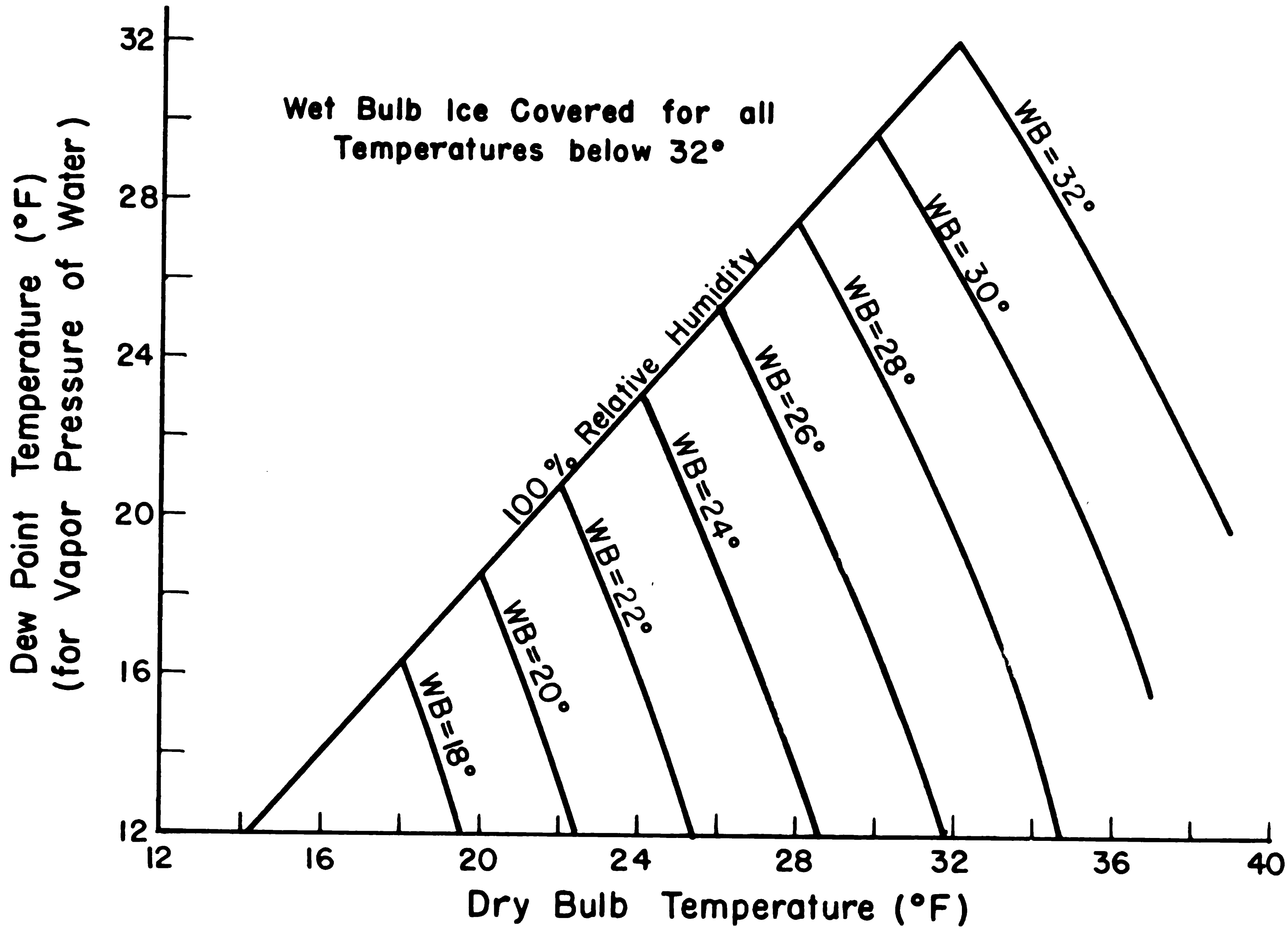

FIG. 18 WET BULB TEMPERATURES °F FOR VARIOUS DRY BULB AND DEW POINT TEMPERATURES

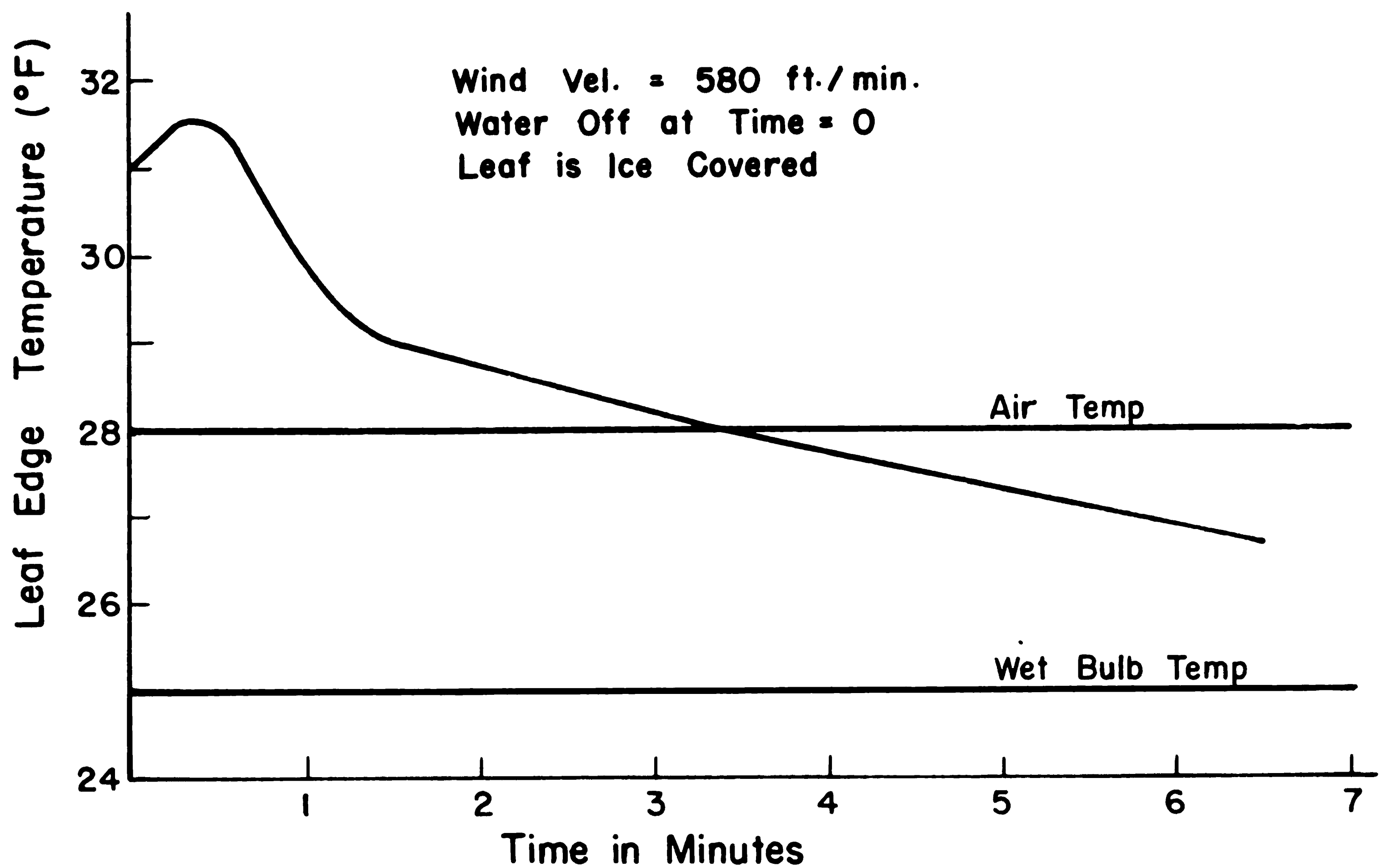

FIG. 19 EFFECT OF WIND SHOWING THE LEAF EDGE TEMPERATURE APPROACHING THE WET BULB TEMPERATURE WHEN SPRINKLING IS STOPPED.

The cycling of the leaf edge temperature for a wind speed of 240 feet per minute, an application frequency of 120 seconds, an air temperature of 24.5° F., a wet bulb temperature of 23.1° F., and a high application rate of 0.37 inches per hour is shown in Fig. 20. The temperature rose to almost 32°, fell rapidly to the air temperature in about 80 to 85 seconds, and continued falling almost to the temperature of the wet bulb before a repeat application of water at 120 seconds.

To further check the effects of the wet bulb temperature a few tests were conducted with the air temperature at or slightly above 32° F. The results of one of these tests, when the air temperature was 32° F., is shown in Fig. 21. This figure shows that for the 60 and 120 second frequencies of application the minimum temperature of the leaf edge thermocouple very nearly approached the wet bulb temperature. This figure is also a good example of the effect of frequency of application.

Throughout this test no ice was formed on the leaf even though the thermocouple on the leading edge measured temperatures below 29° F. The absence of ice in these tests probably indicates the presence of super-cooled water, a phenomenon commonly observed in the determination of wet bulb temperatures under similar conditions. It is the author's opinion that super-cooled water is not likely to exist under field conditions of frost protection because

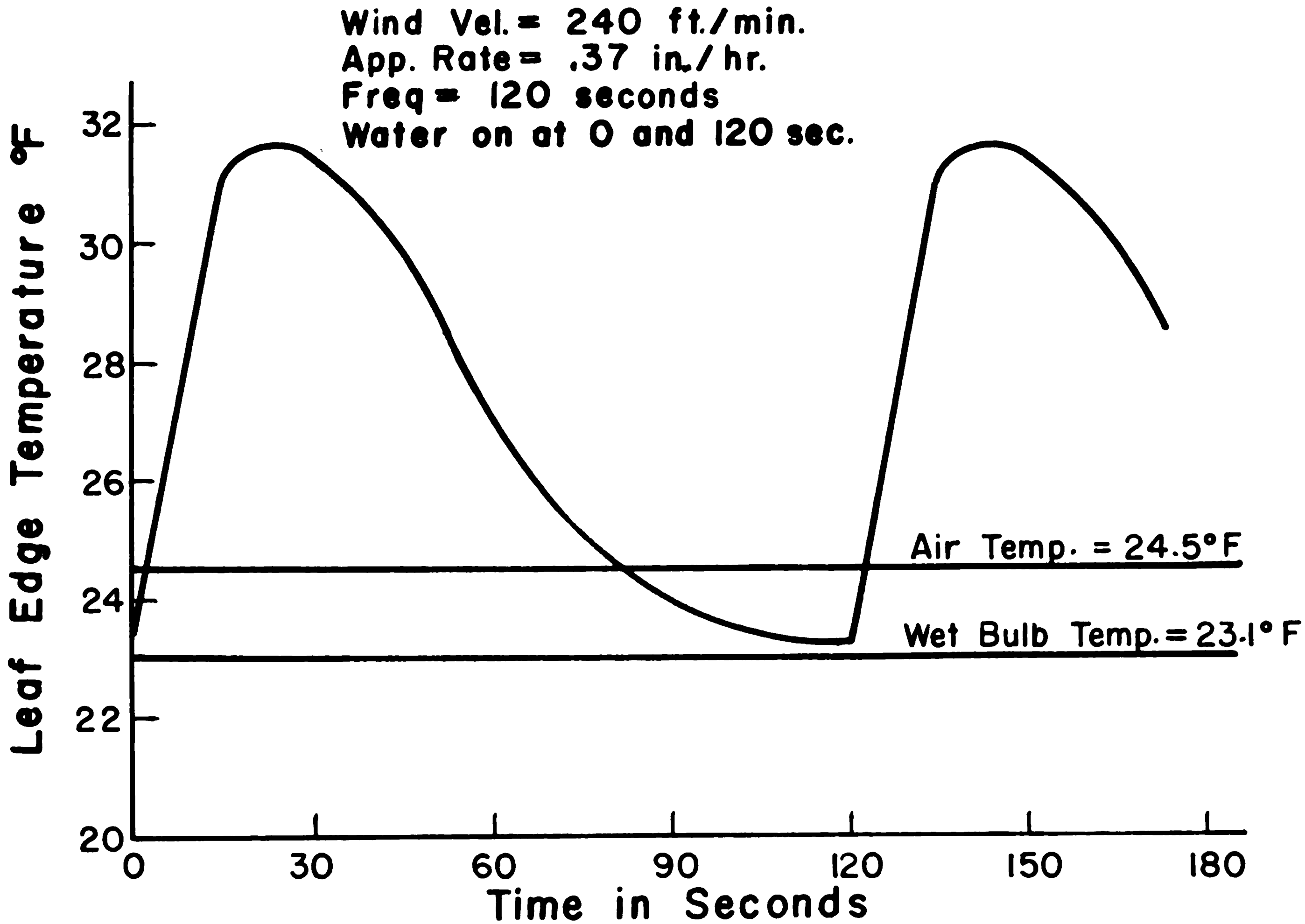

FIG. 20 EFFECT OF WIND AND WET BULB TEMPERATURE SHOWING THE LEAF EDGE TEMPERATURE APPROACHING THE WET BULB TEMPERATURE FOR 120 SECOND FREQUENCY OF APPLICATION

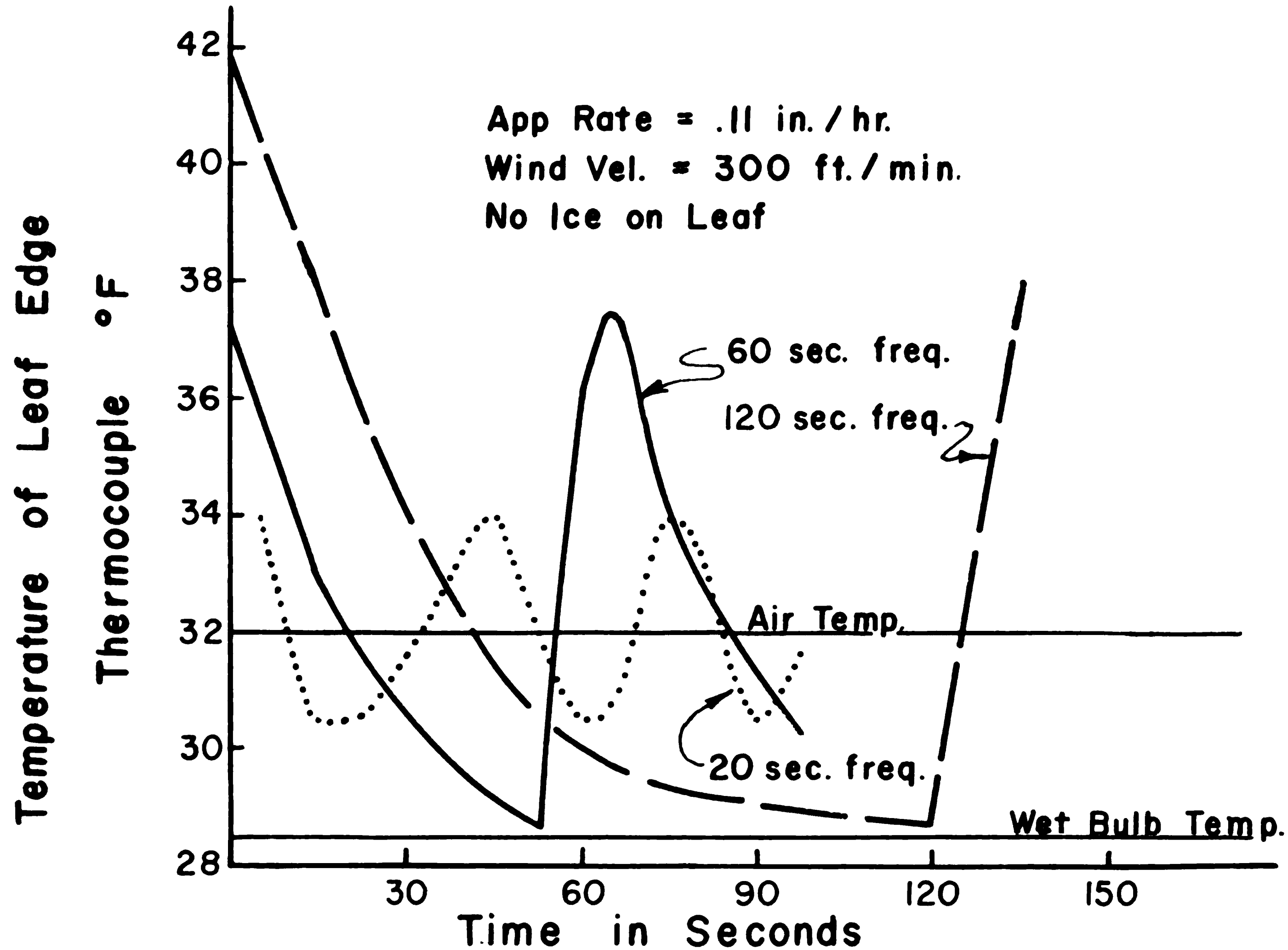

Fig. 21 Effect of Wind, Wet Bulb Temperature and Frequency of Application on the Temperature of the Leaf Edge Thermocouple

of more vibration produced by the larger drops from the sprinklers and the presence of dirt and spray particles. Both vibration and foreign particles encourage the formation of ice instead of super-cooled water.

Effect of Leaf Angle

In a theoretical analysis, Beahm (1) calculated the heat load on a flat plate in the wind. He determined that the maximum heat load on the plate occurred when the plate was perpendicular to the wind. This of course is the total heat load on the plate. He also pointed out that for a flat plate parallel to the wind the film coefficient is infinity at the leading edge.

Two preliminary tests were run to determine the effect of the leaf position with respect to the wind. One was made with the leaf at 45 degrees and the other with the leaf at 90 degrees to the wind. When the leaf was changed to a position other than parallel to the wind, the edge temperature tended to warm up while the center temperature tended to fall slightly. While these were only preliminary tests and no conclusions can be drawn from them, they indicate that the leaf edge temperature is the most critical when the leaf is parallel to the wind.

CONCLUSIONS

1. An increased application rate protected the plant leaf from lower air temperatures and/or higher wind speeds. A 20 second frequency of application gave protection at temperatures and wind speeds that a 60 second frequency would not and a 60 second frequency protected the leaf under more severe conditions than a 120 second frequency of application would.

2. Other conditions remaining the same, the maximum wind velocity from which the plant can be protected by a particular application rate and frequency is reduced by a lower air temperature, or a higher wind speed raises the minimum air temperature to which protection can be accomplished.

3. A wet or ice covered leaf tends to approach the wet bulb temperature when no heat is added.

4. For the longer frequencies of application the leading edge of the leaf tended to approach the wet bulb temperature between applications.

5. When the leaf is horizontal to the wind the leading edge is the most difficult to protect.

6. Preliminary trials indicate that it is more difficult to protect the leading edge of the leaf when it is horizontal to the wind than when the leaf is at a 45° or 90° to the wind.

SUMMARY

A small test tunnel was constructed in which plant leaves could be placed and sprinkled with various application rates and frequencies of application. The tunnel was insulated so that there was no radiation in the studies. The wind speed in the tunnel could be controlled between 75 and 600 feet per minute. Outdoor air was used as a source of cold air and this sometimes limited the minimum temperature that could be obtained. Most of the tests were conducted with temperatures between 25° and 30° F. Wet bulb temperatures were also taken.

Three frequencies of application (20, 60, and 120 seconds) were used. Protection was accomplished with the longer frequency only at relatively high temperatures and low wind speeds. The 20 second frequency gave protection to lower temperatures and higher wind speed than could be obtained with the 60 second frequency.

Application rates of 0.04, 0.11, and 0.20 inches per hour were studied. A few tests were made with rates of 0.17, 0.28, and 0.37 inches per hour. An increase in application rate gave protection to lower temperatures and higher wind speeds. Rates over 0.11 inches per hour produced rapid build-up of ice on the plant leaf and large icicles were formed by the water which ran off.

An increase in wind speed required either raising of the temperature with constant application rate and frequency or an increased application rate or frequency if the temperature remained constant. When the leaf was parallel to the wind the leading edge temperature was often several degrees lower than the temperature at the center of the leaf. The leading edge temperature tended to rise and the center temperature to fall when the leaf was placed at some position other than parallel to the wind.

The moisture content of the air was not controlled in this experiment; therefore, the effects of the wet bulb temperature could not be completely evaluated. It was found, however, that the temperature of the ice covered leaf fell below the air temperature and approached that of the wet bulb if the water was shut off. This also happened between the applications of water with the longer frequencies of application and when the air temperature was near 32° F. and ice had not formed on the leaf. In several of these tests temperatures two or three degrees below freezing were measured by the thermocouple near the leading edge of the leaf yet ice did not form and no frost damage to the leaf was observed.

SUGGESTIONS FOR FUTURE STUDIES

1. More information is needed about the critical temperatures of plants at their various stages of growth.

2. A determination of wind speeds in various cultures during frost or freezing conditions is needed.

3. The requirements for protection of a plant from freezing injury during a combined radiation and wind-borne freeze should be determined.

4. The effect of evaporation on the plant temperature needs to be evaluated.

5. A means of determining the proper time to start sprinkling for frost protection under windy conditions needs to be developed.

6. Additional studies are needed

    a. with the leaf in positions other than parallel to the wind,

    b. of other shapes, and

    c. of frequencies of application, particularly less than 60 seconds.

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