PROTECTION OF GARDEN CROPS AGAINST FROST DAMAGE BY THE USE OF OVERHEAD IRRIGATION

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This is to certify that the

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PROTECTION OF GARDEN CROPS AGAINST FROST DAMAGE BY THE USE OF OVERHEAD IRRIGATION

By

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INTRODUCTION

Presentation of the Problem

Fruit and vegetable growers are plagued by both frost and drought. The total gross cash farm income in Michigan, including government payments, was $734,091,000 in 1951; of this, $81,739,000 is attributed to the sale of fruit and truck crops (1). The annual loss to Michigan farmers from frost damage is estimated to range from ten to twenty million dollars (2). Hence, frost protection for fruit and vegetable growers is of paramount importance.

A method which would be economical and easy to operate and would offer protection at low temperatures has long been sought. Some farmers are aware that a continual application of water to plants will protect them from freezing although the ambient air temperature is several degrees lower than that which the plants could normally withstand. They are using overhead irrigation sprinklers not only for drought control, but also for frost protection. This method is increasing in popularity since by the purchase of one system, protection from both frost and drought may be obtained.

To date an extensive attempt has not been made to study and evaluate protection of plants from frost through the use of water by overhead irrigation; hence, farmers are not aware of all the merits and limitations of this method. They do not know how to operate their equipment to get the most satisfactory results. The whole operation is one of trial and error.

Some factors which should be studied and evaluated to obtain optimum results from the application of water to plants for frost protection through the use of overhead irrigation are:

1. Minimum application rate.
2. Frequency of rewetting the plant surface.
3. Optimum spacing and arrangement of sprinklers.
4. Maximum amount of protection possible under field conditions.
5. Temperatures at which to begin and end irrigation.
6. Ice damage to the plants.
7. Application rate for minimum icing and adequate protection.
8. Value of watering until plants are completely free of ice.
9. Effect of water:
    a. on plant temperatures.
    b. on vertical air temperature lapse rates.
10. Relationship of air temperature to the temperature change of water droplet trajected through it.

11. Deleterious effect of water:

    a. on plant diseases.

    b. on soil nutrients removal.

    c. on soil temperatures.

    d. on quality of fruits and vegetables.

    e. on growth retardation of plants.

12. Effect of initial temperature of water on protection obtained.

13. Critical freezing temperature of plants.

14. Relationship of ice accumulation to the plant temperature.

15. Design of a satisfactory water applicator.

Of the above items, the following have been partially investigated in this study:

1. Minimum application rate of water for adequate frost protection.

2. Evaluation of the ability of different plants to withstand ice loads.

3. Optimum temperatures at which to begin and end sprinkling.

4. Effect of application of water on the vertical air temperature gradient.

5. Effect of the application of water on plant temperatures.

6. Critical freezing temperature of tomatoes.

7. Effect of water on soil temperature.

8. Design of a satisfactory sprinkler for frost protection.

Approach to the Problem

This study was set up to provide some answers to the above questions, and also to provide a basis for further investigation in this field at a later date. The study was carried out in two parts:

1. Field survey of Michigan farmers using irrigation for frost protection.

2. Test protection of a variety of fruits and vegetables from frost by overhead irrigation during the months of September and October, 1953.

Field survey. Because of adverse weather conditions, inadequate sampling of weather and crops, and insufficient area for field tests, measurements made thus far were only preliminary and are too limited for the purpose of making recommendations. A field survey of Michigan farmers was conducted in August, 1953, to obtain more information about farmers' practices and experiences under actual field conditions, and to determine the influence of this method of frost control on the economics of crop production.

Experiment. A "family" garden belonging to the Horticulture Department of Michigan State College was used for experimental purposes. It was ideal for frost-protection work since it contained most of the common varieties of Michigan garden crops which were planted late and therefore quite susceptible to fall frosts. In this study special attention was given to tomato plants, since they are considered quite susceptible to frost damage. In addition, it is a fruit which many farmers are interested in protecting from frost. This protection would be necessary either in the spring or in the fall. If a grower is interested in producing fruit for the early summer market, he must be prepared to protect his plants from spring frosts. On the other hand, some growers want to prolong the tomato harvest in the fall; this also necessitates frost protection.

REVIEW OF LITERATURE

Classification of Frosts

In general the frosts during which protection measures will be necessary may be divided into two classes (3).

1. Radiation frost. This is a local frost which occurs on a clear still night when the cooling is due principally to loss of heat by radiation. Such frosts usually follow moderately cool afternoons. The temperature falls rapidly during the early part of the evening but often does not reach a minimum until shortly before sunrise.

2. Freeze. This class of frost may occur during the day or the night with the influx of a mass of air that has a temperature below 32° Fahrenheit.[1] A cold wind and a cloudy sky often accompany it.

Latent Heat of Water

Angstrom (4) points out that a volume element within the atmosphere will lose heat through temperature radiation out to space,

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[1] "Fahrenheit" will be indicated hereinafter by the abbreviation "F."

and it will lose or gain heat through convection and conduction. In addition to these processes, there will often occur heat transference due to the change of state of water: evaporation, condensation, melting, and freezing.

The success of protecting plants from frost by sprinkling with water depends on heat transference due to the change in state of water from liquid to ice. This fact becomes more evident when it is pointed out that when one pound of water at 32° F. and at atmospheric pressure changes its state from a liquid to a solid, 144 British Thermal Units of heat are given off by the water; whereas, if one pound of water at standard atmospheric pressure changes its temperature 1° F., one British Thermal Unit of heat is given off (5). For pure substances the heat effects accompanying changes in state at constant pressure are known as latent effects because no temperature changes are evident (6).

Plants and Low Temperatures

Levitt (7) points out that some plants are incapable of surviving freezing temperatures, while others can become aclimated to frost to a greater or lesser degree. The frost death point is lowered slightly as a result of keeping the plants at temperatures near the freezing point for several days.

Miller (8) has found that under identical conditions the temperature of one kind of leaf is different from that of another, and that different regions of the same plant have different temperatures. The most important factors influencing the temperature of leaves are the temperature of the air, the supply of available moisture in the soil, the evaporating power of the air, currents of air, thermal emissivity of the leaf, intensity of light, and the angle at which it is incident to the leaf surface.

Lucas (9) reports that frost damage in citrus orchards depends upon many factors in addition to the minimum temperature attained by the tree parts. One prominent factor is subcooling; this is the extent to which tree parts cool below the freezing point without ice formation. The amount of subcooling appears in turn to depend upon many conditions. Checks were made on the rate of spread of freezing in a subcooled system comprised of a lemon stem with attached leaves and fruit. It was found that subcooling was followed by simultaneous freezing throughout the system. Ice nucleation occurred at one point only in the system, just as it does in a small volume of subcooled water. It was also found that freezing appears to be initiated near the surface of the lemons, and that rubbing of wet fruit surfaces to simulate weather conditions (i.e., wind and dew) reduces subcooling markedly. Fruits rubbed on water droplets had an average spontaneous freezing point of 27.4° F., whereas, if fruits were just rubbed without water droplets, the spontaneous freezing point dropped to 24.7° F. This explains why a combination of dew and wind lessens subcooling and increases frost damage.

Moblikowska (10) has found that a single spraying of a plant during frost results in temporary raising of the plant temperatures. The effect of such a spraying will be harmful if, following the spraying, the plant temperature still sinks to the damaging level. Wet plants are more susceptible to frost damage than dry ones. The effect of a single spraying will be beneficial if a damaging temperature has not occurred before spraying and the temporary rise of temperature, induced by the spray, is sufficient to keep the plant's temperature above the damaging level, even though the temperature of the air and of the unsprayed plants fall to or below this level which for the sprayed plants will be higher than for the unsprayed. The amount and duration of temperature rise will depend on how much water freezes on the leaves and on the ground, and also on the rate of air movement.

Rogers (11) asserts that from the point of view of maintaining the plant temperature, turning on the water at a temperature of

30° F. is probably reasonably safe; but in practice it is found safer to turn the water on at 32° F. to avoid the risk of blocking the nozzles with ice. He has found that there is no need to continue sprinkling once the air temperature has risen above 32° F. If the sun has risen and the air temperature is rising fast, it is probably safe to turn the water off at 30° F. with a consequent saving of water.

Temperature Inversion

Geiger (12) reports that the surface of the ground plays an important role in the cooling of the atmosphere. The lowest temperatures prevail between the boundary surface of the air and ground. The temperature increases upward in the adjacent air and increases downward in the adjacent earth. Since temperature decrease with increase of altitude is the rule, the nocturnal increase of temperature above the ground is called "temperature reversal" or "inversion." This inversion may extend several hundred yards up from the ground. The rate of temperature change, however, decreases rapidly with the distance from the surface of the ground in the boundary layer. This applies only to radiation frosts.

FIELD SURVEY OF MICHIGAN FARMERS USING SPRINKLER IRRIGATION FOR FROST CONTROL

Method of Conducting Survey

This survey was carried out in August, 1953. A 46-item questionnaire (see Appendix) served as its basis. Thirty-five farmers were interviewed by the author; most of them were farming in the western half of the state. They comprise a representative sample of irrigators in the state using irrigation for frost control. The number of individuals interviewed in each county are shown in Table I.

Findings and Interpretations

Acreage of crops irrigated. The range in acreage irrigated for frost protection was from 1/4 acre for hydrangeas to 60 acres for strawberries (Table II).

Protection obtained. Not all of the crops listed in Table II were successfully protected, due to extreme ice load or unadaptable crops. Of the thirty-five reports, only six stated crop damage occurred in the irrigated area. Exposed gladiolus petals and chrysanthemums suffered damage to a large extent. The slightest damage by

TABLE I

NUMBER OF FARMERS INTERVIEWED IN EACH COUNTY

County	No. of Individuals	County	No. of Individuals
Allegan	2	Kalkaska	1
Antrim	1	Manistee	10
Berrien	2	Mason	2
Branch	2	Otsego	1
Cass	3	St. Joseph	2
Grand Traverse . . .	1	Van Buren	6
Hillsdale	2		

TABLE II

CROPS IRRIGATED FOR FROST PROTECTION

Crop	No. of Individuals	Average Acreage
Strawberries	23	8
Strawberries and garden	1	7
Strawberries and tomatoes	2	14
Strawberries and cucumbers	1	6
Strawberries, tomatoes, and corn	1	3/4
Strawberries and gladiolus	1	6
Celery	1	2
Celery and spinach	1	1-1/2
Gladiolus	2	4
Chrysanthemums	1	1/3
Hydrangeas	1	1/4

ice or frost to a flower will cause it to lose its aesthetic value. Two celery growers were forced to discontinue irrigating after one night because the heavy ice load bent the outer stems. Several reported damage only where a plant had been stepped on when it was covered with ice.

Reported damage was evidently due to crop sensitivity and ice load. Damage due to operational technique (that is, when the system was started or shut off) was evident in two instances. In many cases an entire acreage was protected against frost and a comparison between protected and nonprotected areas could not be made. Table III indicates the damage that occurred in nonprotected areas.

Value of irrigation system for frost protection. Perhaps a better criteria of the adaptability of this method of frost control would be an opinion of the value of an investment in an irrigation system for frost protection alone. All of those answering the questionnaire believed an irrigation system was a worth-while investment; however, only eighteen out of thirty believed that an investment in an irrigation system for frost protection alone would be economically sound. This opinion was definitely divided geographically; 80 per cent of those in the northern counties thought it would be a sound investment,

TABLE III

CROP DAMAGE OUTSIDE PROTECTED AREA

Extent of Damage	No. of Individuals Reporting
30% to 50%	3
50% to 80%	2
80% to 100%	1
100%	9

while only 43 per cent of those in the southern counties concurred (Table IV).

Economic considerations. Growers felt that one of the advantages of irrigation for frost protection is the fact that a grower can plant earlier and harvest later to take advantage of a more favorable market. Only four of those interviewed had this opportunity, due to the type of crop grown. One grower stated that he now planted a week earlier than usual, one two weeks earlier, and one three weeks earlier. Another grower stated that harvest was prolonged two weeks due to the protection offered against an early frost.

TABLE IV

TIME FOR SYSTEM TO PAY FOR ITSELF IN FROST PROTECTION

Length of Time	No. of Individuals
One night	3
One year	13
Two years	2
Depends on weather	7
Never	5

Frequency of use. Of interest in analyzing the economics of irrigation for frost protection is the frequency of use, or the number of years protection has been necessary. Because of the variation in the number of years the growers have had their irrigation systems, the number of years the system was used for protection and the number of years they have had their system is expressed as a ratio. This ratio varied from one year out of seven, to twelve years out of twelve. The average for the entire group was about three years out of four. There appeared to be no relation of frequency of use to location in the state; however, some expressed the opinion that elevation was a deciding factor.

The number of times within an individual year that an irrigation system was used for frost control varied from zero to eight;

the average number of times per year was approximately twice. A majority of the growers stated that frost protection was necessary, on the average, only once each year.

Labor requirements. The length of time the irrigation system is operated for frost protection is of prime importance in planning labor requirements, in analyzing water supplies, and in computing the cost of this method of frost protection. The length of time of operation will depend on the severity of the temperature drop and on operational technique.

The average operating time for all conditions was approximately 7.6 hours. Regardless of the operating time, the labor requirement remained about the same (Table V). It appeared that labor varied somewhat with the area protected. Thirty growers stated that only one man was required to operate the system. This does not include the labor required to set it up, however. Five men were also required to set up and operate the system on the 60-acre area.

Effects of excess water application. Application of excess water was reported by twenty-seven growers. Seven of these stated the following harmful effects resulting from the over application of water:

TABLE V

OPERATING TIME REQUIRED

No. of Hours	No. of Individuals	No. of Acres Protected (by order of magnitude)
3	1	1-1/2
4	4	3, 3, 2, 1-1/2
5	5	7, 6, 6, 3
6	4	20, 8, 5, 2, 1-1/2
7	3	10, 3, 1-1/2
8	2	6, 2-1/2
9	3	8, 5, 1
10	1	60
13	4	16, 12, 2, 1/2
14	1	1/4
24	1	2

1. Delayed bacterial action and maturity of strawberries.

2. Puddled soil, and tomatoes became soft and spotted.

3. Celery and spinach turned yellow and required supplement of nitrogen.

4. Field became boggy after three successive nights of running.

5. Robinson strawberries became leaf spotted after five successive nights of operation.

6. Soil became excessively wet when high capacity sprinklers were used.

7. Four successive nights of operation resulted in removal of nitrogen by leaching.

Frost warning used. Five growers reported using a "bell alarm system" to warn of low temperature. An additional three growers had thermoswitches which had not been installed at the time of the survey. The remainder relied on an alarm clock, a mercury thermometer, and the weather forecast. About half of the growers read the thermometer near the house and the other half went out to the field and read temperatures at various conditions of exposure. The practice adopted usually depended on the topography of the land and on the distance of the field from the house. If the crop to be protected was a considerable distance from the house, or situated at a lower elevation than the house, farmers checked the temperature in the area requiring frost protection.

Temperatures protected against. Minimum temperatures reported during the time frost control practice was being carried out varied from 15° F. to 30° F. The majority of the growers operated at or above 20° F. Gladiolus and chrysanthemum growers reported damage when the temperature at plant level reached a minimum of 25° F. At this temperature the large accumulation of ice on the plants caused damage. Two celery growers reported minimum temperatures of 15° F. They reported that a heavy ice load formed and bent over the outer stalks. Other growers reported that hydrangeas were completely protected down to 20° F., strawberries down to 18° F., and tomatoes to 20° F.

Arrangement of sprinklers. Of the thirty-five growers reporting, twenty-five used triangular spacing while ten used rectangular spacing of the sprinklers. The growers preferred the former since this arrangement provided a more complete coverage of the area with water.

APPARATUS AND METHODOLOGY

Introduction

During the survey, growers expressed their desire to obtain more detailed information pertaining to the use of overhead irrigation for frost protection of fruits and vegetables. This section of the study pertains to field tests of the above method of frost protection.

Apparatus

Study area. The plot on which this investigation was carried out was located on the Horticulture Department farm, Michigan State College, East Lansing, Michigan. The garden was set up primarily for class demonstration and it contained most of the fruits and vegetables commonly found in a family garden (Figure 1). The soil was a Hillsdale sandy loam.

Irrigation system. Water was pumped from a well 220 feet deep which was located about 1,200 feet from the study area. The temperature of the water was 51° F. It was brought through an underground pipe to the hydrant, which was located in the east

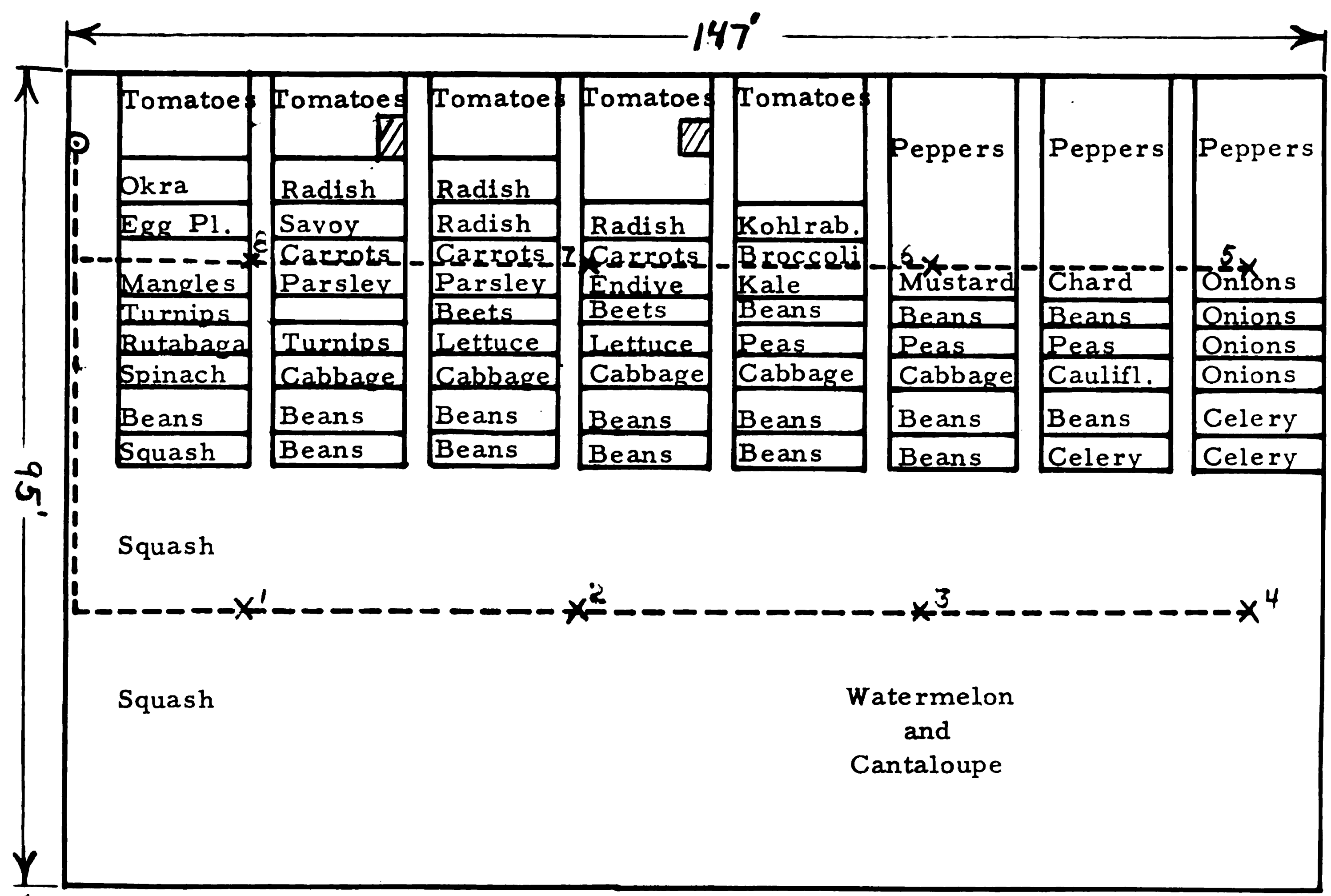

Figure 1. Layout of experimental test area.

✕ Sprinkler
⊙ Hydrant
▨ Location of Thermocouples
1/20" = 1'

border of the garden. Two parallel 3-inch laterals, spaced 40 feet apart, were extended from a 3-inch main into the test garden (Figure 2). Sprinklers were spaced at 40-foot intervals along the two laterals (Table VI). A pressure gage was located in a lateral line.

Water distribution measurement. One-quart oil cans with the tops cut away were placed in strategic locations in the garden and were used to measure distribution of water. After each irrigation the depth of water in the cans was measured and recorded; the cans were then emptied and reset. At least one can was placed within 1 foot of each thermocouple.

Temperature-measuring devices. Two 16-point Brown self-recording potentiometers were used to record the temperature changes. Each potentiometer recorded a complete cycle every four minutes, and had a chart speed of 8 inches per hour. They were sheltered in a covered trailer located about 50 feet south of the southeast corner of the garden. Thermocouples were made of No. 24 gage (Brown and Sharp Gauge) copper and constantant wire. Each potentiometer had a common constantan wire.

Radiation shields. Radiation shields were not used in this experiment. It was concluded that such shields would be difficult to

Figure 2. Layout of irrigation main and laterals in study area.

TABLE VI

DESIGN OF SPRINKLERS[1] IN TEST AREA

Sprinkler No. (in ref. to Fig. 1)	Size of Nozzle	Approx. r.p.m. at 42 p.s.i.	Angle of Nozzle	Type Sprinkle
1	5/32''	5	23°	Full circle
2	3/16''	2	23°	Full circle
3	9/32''	6	23°	Full circle
4	7/32''	3	7°	Full circle
5	3/16''	3	7°	Full circle
6	5/32''	4	23°	Part circle
7	5/16''	2	23°	Part circle
8	5/32''	4	23°	Full circle

[1] All sprinklers were Rainbird, with one nozzle.

duplicate, since positioning of the shields has a bearing on the temperature of the termocouple. The only shields used were those that prevented water from the sprinklers from coming in contact with the thermocouples measuring vertical gradient air temperatures (Figure 3).

Figure 3. Water shield for the thermocouples measuring vertical air temperature.

Methods of Procedure

Location of thermocouples. The use of the two 16-point potentiometers made it possible to record the temperature at 32 points. Many temperature recordings were duplicated thereby offering a replication on the results.

The thermocouples in the treated area were placed as shown in Figure 1. Those used to study temperature changes on the surface of tomato leaves, in the fruit, in the ground, and at varying distances up from the ground were placed about 22 feet from a rotary sprinkler. Water from only one sprinkler reached any one thermocouple. Unirrigated area temperatures were taken about 90 feet south of the study area.

Vertical gradient air-temperature measurements in protected area. Thermocouples were placed at 0, 1/2, 6, 18, 36, and 72 inches respectively above the surface of the ground. A 1-inch square wooden pole supported the thermocouples which had the hot junctions extended 3/4 of an inch from the pole. A water shield made of heavy roofing paper was placed vertically along the pole to shield the thermocouples from contact with the water from the sprinklers.

The side of the shield facing the thermocouples was covered with aluminum foil and the opposite side was black (Figure 3).

Air-temperature measurements in unirrigated check area. Two thermocouples were placed 8 inches above the ground in the check area. One of these thermocouples was placed above a covering of straw spread out to simulate conditions in a strawberry bed. The other thermocouple was placed over bare ground, the grass having been scraped away. A distance of 6 feet separated these two thermocouples. A height of 8 inches was chosen as this was the average height of placement of the thermocouples in the plants in the irrigated area.

On October 12 rearrangement of the thermocouples was made in order to compare the vertical air temperature of the treated area with that of the check area. The vertical spacing of the six thermocouples in the check area was the same as that in the treated area. A similar vertical shield was placed alongside these thermocouples. This was done to simulate the wind interference afforded by the water shield to the thermocouples in the treated area.

Ground-temperature measurement. In the treated area two thermocouples were placed 1/2 inch below the ground surface and two were placed 6 inches below the ground surface. On October 12 one thermocouple from each depth was removed and placed in the check area at the corresponding depth.

Plant-temperature measurement. One thermocouple was placed on the top and another on the bottom of the same tomato leaf to measure the temperature differences between the two sides. A large tomato leaf was chosen and each thermocouple was inserted through the leaf in safety-pin fashion and was laid against the leaf. The two thermocouples on the same leaf were kept as close together as possible. These measurements were taken on three separate tomato leaves. Mechanical fasteners were not used, since they would interfere by heat conduction with the true measurement of the surface temperature of the leaf.

A thermocouple was also placed in the center of a green tomato and another under the skin of the same tomato. This was done with only two tomatoes.

Minimum application rate. Six thermocouples were placed 4, 10, 16, 22, 28, and 34 feet respectively from a sprinkler. Each was placed 8 inches above the ground with the junction touching the plant. In order to hold them in position, the thermocouple wire was twisted once around the stem of the tomato plant. One-quart oil cans were placed within 6 inches of each thermocouple to measure the quantity of water applied during any one irrigation.

Operation of equipment. The two self-recording potentiometers were left in operation continuously. In order to determine the time of day at which the temperatures were recorded, the time to the nearest minute was noted on the temperature chart three to five times every 24 hours. The time of starting and stopping the irrigation system was also noted on the chart. After the irrigation system was started and everything was operating satisfactorily, only periodic checks during the night were required. These were made at 1- and 2-hour intervals at which time the potentiometers, sprinklers, pressures, and the gasoline engine driving the irrigation pump were observed. A record was also made of the weather conditions. A continuous pressure of 42 pounds per square inch was maintained at the sprinklers.

DISCUSSION OF RESULTS

Analysis of Data

During September and October water was applied for frost protection on nine different nights. A summary of the more immediate facts for each night that frost protection was necessary is presented in Table VII. Detailed temperature analyses were made for three periods:

1. The night of October 7, on which the lowest air temperature of the entire study period was reached.

2. The night of October 29, on which the tomato plants were partially damaged by frost.

3. The night of November 3, on which the irrigation system was not turned on and the less frost-hardy plants were completely destroyed.

The temperatures were read to the nearest one-half degree Fahrenheit from the temperature recording chart at either 10- or 15-minute intervals, depending on rate of temperature change. Special care was taken to include the peak points that might have occurred during this interval of time.

TABLE VII

SUMMARY OF PERTINENT DATA FOR THE TEST RUNS IN FROST PROTECTION BY SPRINKLING

Date	Operation Time	Low in Check Area (° F.)	Maxi-mum Ice	Type Frost	Frost Damage
Sept. 26	1:00 a.m.- 7:15 a.m.	27	thin film	rad.	none
Oct. 5	3:40 a.m.- 7:25 a.m.	27.5	thin film	rad.	none
Oct. 7	1:35 a.m.- 8:50 a.m.	27.5	1/16"	rad.	none
Oct. 7-8	9:30 p.m.- 10:30 a.m.	21.5	1/4"	rad.	2 rows beans
Oct. 8-9	10:15 p.m.- 7:40 a.m.	26.5	1/32"	rad.	none
Oct. 12-13	10:00 p.m.- 9:40 a.m.	24	1/4"	rad.	none
Oct. 14	12:10 a.m.- 8:40 a.m.	28	thin film	rad.	none
Oct. 29	12:50 a.m.- 11:00 a.m.	28	1/4"	rad.	none
Oct. 29-30	9:35 p.m.- 9:05 a.m.	28.5	thin film	rad.	tomato plants
Nov. 3-4	--	23	none	freeze & rad.	com-plete

TABLE VII (Continued)

Air Temp. (°F.) Water On	Air Temp. (°F.) Water Off	Leaf Temp. (°F.) Water Off	Remarks
32	36	-	Sky clear at 9 p.m.; at 4 a.m. light clouds appeared on w. horizon.
31	35	33	Clear night; thick dark clouds appeared on e. horizon at sunrise.
32	45	31.5	Sky clear; some mustard plants bent by ice load.
30	61	38	Clear still night; at 4:30 a.m. heavy clouds appeared on horizon; ice load bent mustard & pepper plants.
32	39	32	Clear still night; thin film of ice on plants when system shut off.
36	55	47	Fog in low areas at 4 a.m., temp 28F when fog lifted, temp. down to 24F.
35	42	40	Still clear night.
33.5	57	50	Clear night; light breeze.
34	48	49	Clear night; light breeze; tomato plants damaged between 8:00 & 8:30 p.m.
-	-	-	Clear night; light breeze; rapid temp. drop between 6:00 & 7:00 a.m.

Minimum Application Rate

The lowest temperature of 21.5° F. in the check area 8 inches above bare ground occurred on the night of October 7. The minimum application rates of water giving satisfactory protection for the lowest temperature are pertinent, and are presented in Table VIII. The minimum application rate of water on beans at the above temperature was between 0.04 and 0.1 inches per hour. Those receiving 0.04 inches of water per hour were very severely injured by the frost, whereas those receiving 0.1 inches per hour suffered no damage whatsoever.

The beans that were damaged were not on the periphery of the protected area. They had been prevented from getting the full effect of the water application by the interference of the tall mustard plants which were between them and the nearest sprinkler. This experience indicates the importance of proper layout design of an irrigation system. The sprinklers should be so arranged that tall plants do not hinder the water distribution. In many instances where the layout of the system cannot be altered to overcome this problem, it can be corrected by using higher risers for the sprinklers or by using higher angle sprinklers.

TABLE VIII

MINIMUM WATER APPLICATION RATE ON THE NIGHT OF OCTOBER 7, 1953

Plant	Minimum Application (in./hr.)	Frost Damage
Tomatoes	0.12	none
Peppers	0.23	none
Beans	0.04	severe
Beans	0.10	none

No apparent damage to any of the other crops occurred because of frost during the night. All of the plants appeared to be in excellent condition when observed the following afternoon. The tomatoes, peppers, melons, beans, and other plants susceptible to frost damage were completely frozen in the surrounding unprotected areas of the Horticultural Farm.

Figure 4 indicates the relationship between tomato plant temperature and three different rates of application of water: 0.38, 0.21, and 0.12 inches of water per hour for the night of October 7. There were no appreciable plant temperature differences at the three application rates. The temperature of the plants was 30° F. (±0.5°)

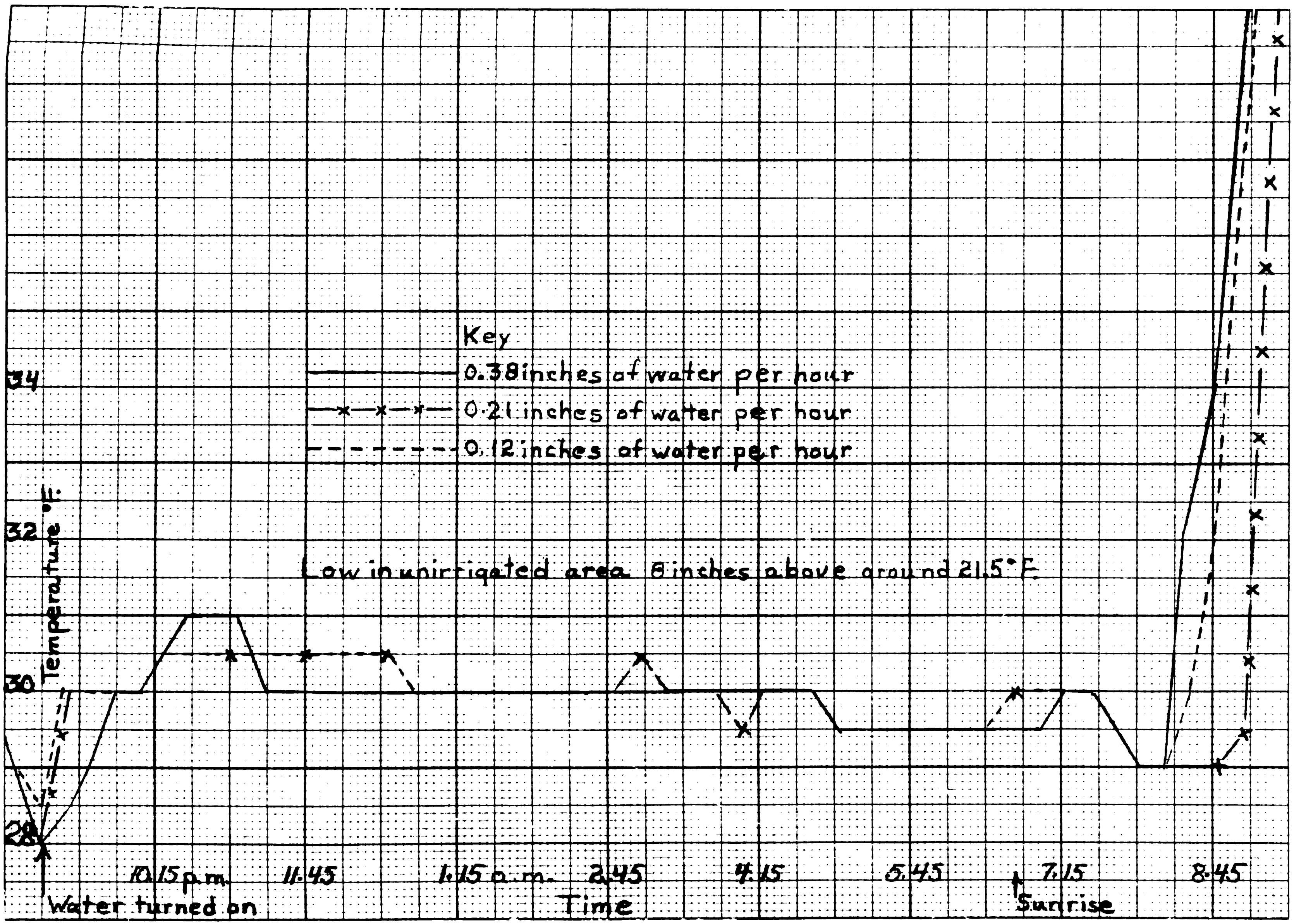

Figure 4. Plant temperature vs. application rate for night of Oct. 7.

throughout the night. The above indicates that the rate of freezing of water was not greater than 0.12 inches per hour for the conditions of this experiment. Consequently, any rate of application greater than 0.12 inches per hour resulted in the water running off or infiltrating into the ground. Heat from an area having a greater rate of application of water will also be convected to an area whose temperature is lower; hence, the over-all temperature will have a tendency to equalize over the entire area.

Ice Damage to Plants

The maximum ice accumulation on the plants was approximately 1/4 inch. Only the peppers and the mustard plants were damaged by the ice load. Some branches were broken off the bushy pepper plants. The mustard plants, which were about 3 feet tall, were severely bent over. The following series of ice accumulations broke them down completely.

In general, noticeable ice damage during the nine frost protection runs was negligible. When the plants had dried off by noon, they appeared to be in excellent condition despite the ice load of the previous night (Figures 5, 6, and 7). From the experience with the mustard plants, ice formation could be a serious problem

Figure 5. Ice accumulation on pepper plants after a frost irrigation.

Figure 6. Ice load on tomato plants at sunrise.

Figure 7. Tomato plants after the melting off of the ice.

in trying to protect plants that are tall, or harder still, tall and bushy, by this method. The ice load is not a serious problem with plants that grow quite close to the ground. A great deal of the ice formation on the plants is in the form of icicles. If the plant is quite short the icicles being formed will reach the ground and prevent the branches from further bending and eventual breakage (Figure 5). Tall plants will have many of the upper branches broken off before the icicles reach the ground to provide support.

Temperatures at Which to Begin and End Sprinkling

On the night of October 7, the water was turned on when the air temperature was 30° F. at 6 inches above the ground and 27.5° F. on the surface of the leaf. Although these temperatures were maintained for approximately 20 minutes, frost damage did not result. On the night of October 29, the air temperature 6 inches above the ground was 29.5° F. and that on the surface of the leaf was 27.5° F. for a period of approximately 10 minutes before rising above 27.5° F. (Figure 8). Water was not being applied when the temperature drop occurred. The following day frost damage was quite apparent on the tomato plants. Other plants did not appear to be injured by this low temperature.

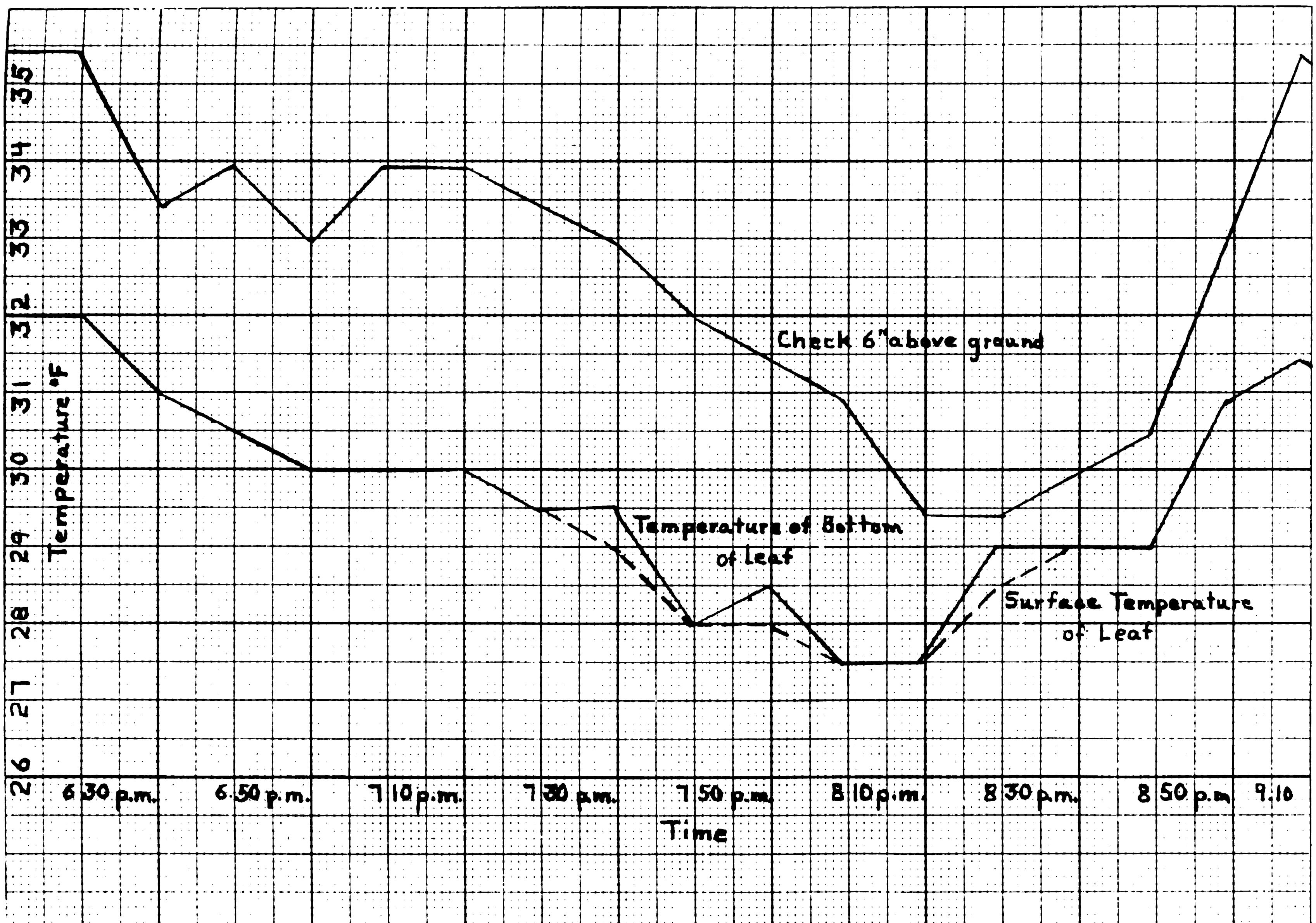

Figure 8. Temperature gradient during the frost on the night of October 29, during which tomato plants were damaged by frost.

This would indicate that when protecting tomatoes, water should be turned on before the air temperature reaches 30° F. 6 inches above the ground or at plant height. There will be occasions on which the air temperature could be considerably lower, and yet the tomato plants would suffer no damage. This would depend considerably on how favorable conditions were for supercooling of the plants. There would be less risk involved if the water was turned on when the temperature reached 32° F. at plant height. Experience has shown that after starting the irrigation system, operational difficulties are quite often encountered which necessitate shutting off the water in order to make the necessary adjustments. During the time adjustments are being made, the air temperature could be dropping. As the temperature falls below 32° F., there is still the added danger that the sprinklers and the water in the pipes may freeze. Faulty gaskets and faulty connection of pipes were the most frequent source of difficulty just after starting the sprinkler system. Whenever frost protection was anticipated, it was found to be a good practice to check all of the pipe connections and the engine before dark. If the irrigation system has not been operated for several days, it would be advisable to operate it for a short time during the day. Such a check and any necessary repairs can be made much more quickly and satisfactorily in daylight than during the night.

Figures 9 and 10 show the relationship between the temperature of the air and that of the leaf surfaces. It is apparent from the above figures that the air temperature can be 10° to 15° F. above the leaf temperature while there is still ice on the plant. Hence, it would not be wise to stop sprinkling as soon as the sun appears over the horizon. It has also been noted that the rate of melting of ice is accélerated if water application continues after the sun rises. When the ice has melted, normal environmental conditions are resumed. The application of water after sunrise not only accelerates melting, but also causes the ice to melt more evenly, since the sun melts it most rapidly on the sun side. This resulting uneven distribution of ice pulls the plant to one side, causing it to become distorted and branches broken.

From this study, specific temperatures at which to turn off the water cannot be given. However, the amount of ice accumulated, the air temperature, and the freezing temperatures of the plants are the three variables that should be considered. If the ice accumulation consists of only a thin film on the plant, the water can be turned off as soon as the air temperature is a few degrees above freezing.. If there is a considerable amount of ice, however, it would be advisable to continue sprinkling until the ice has melted.

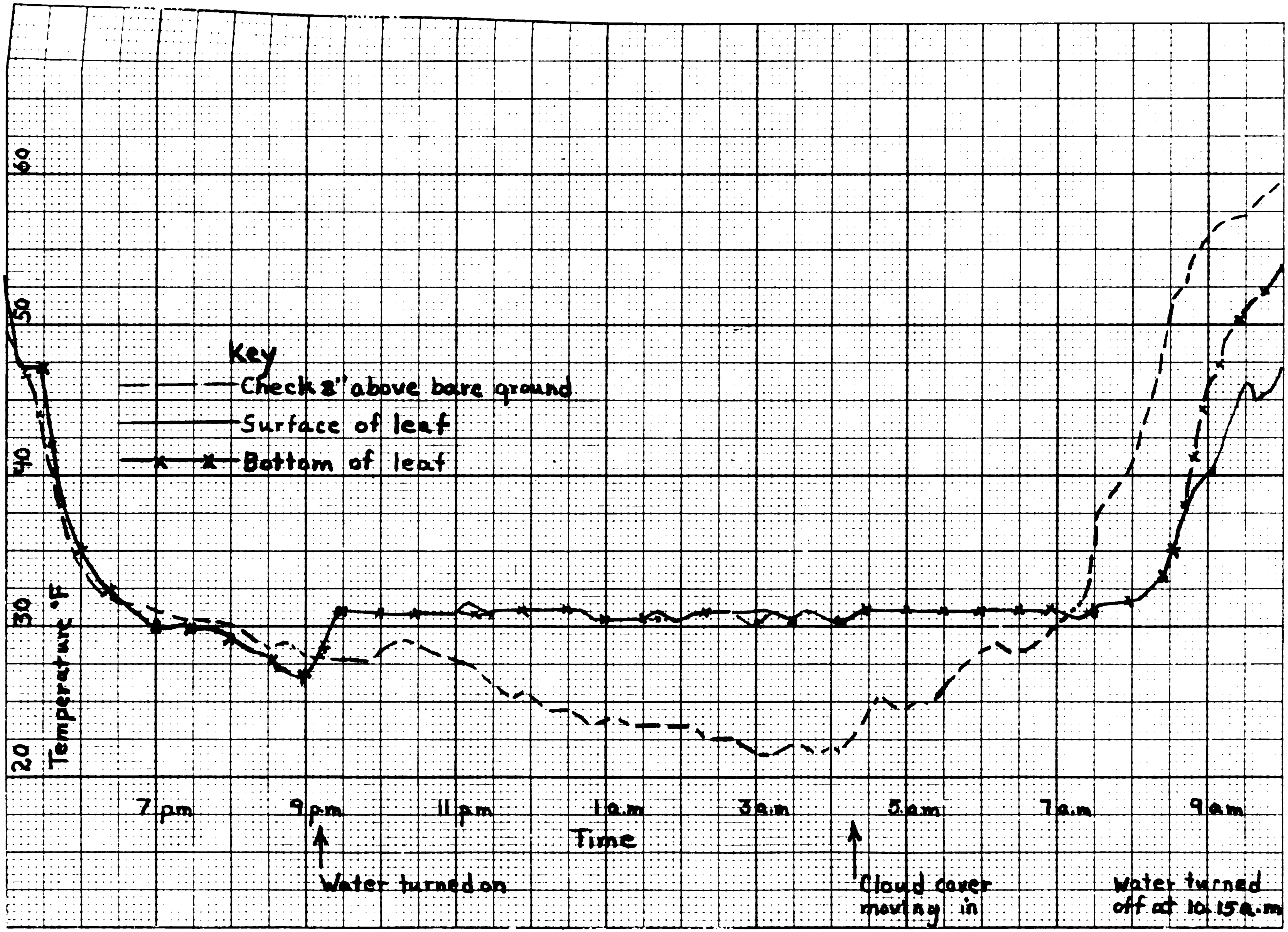

Figure 9. Surface temperatures of tomato leaf for night of October 7.

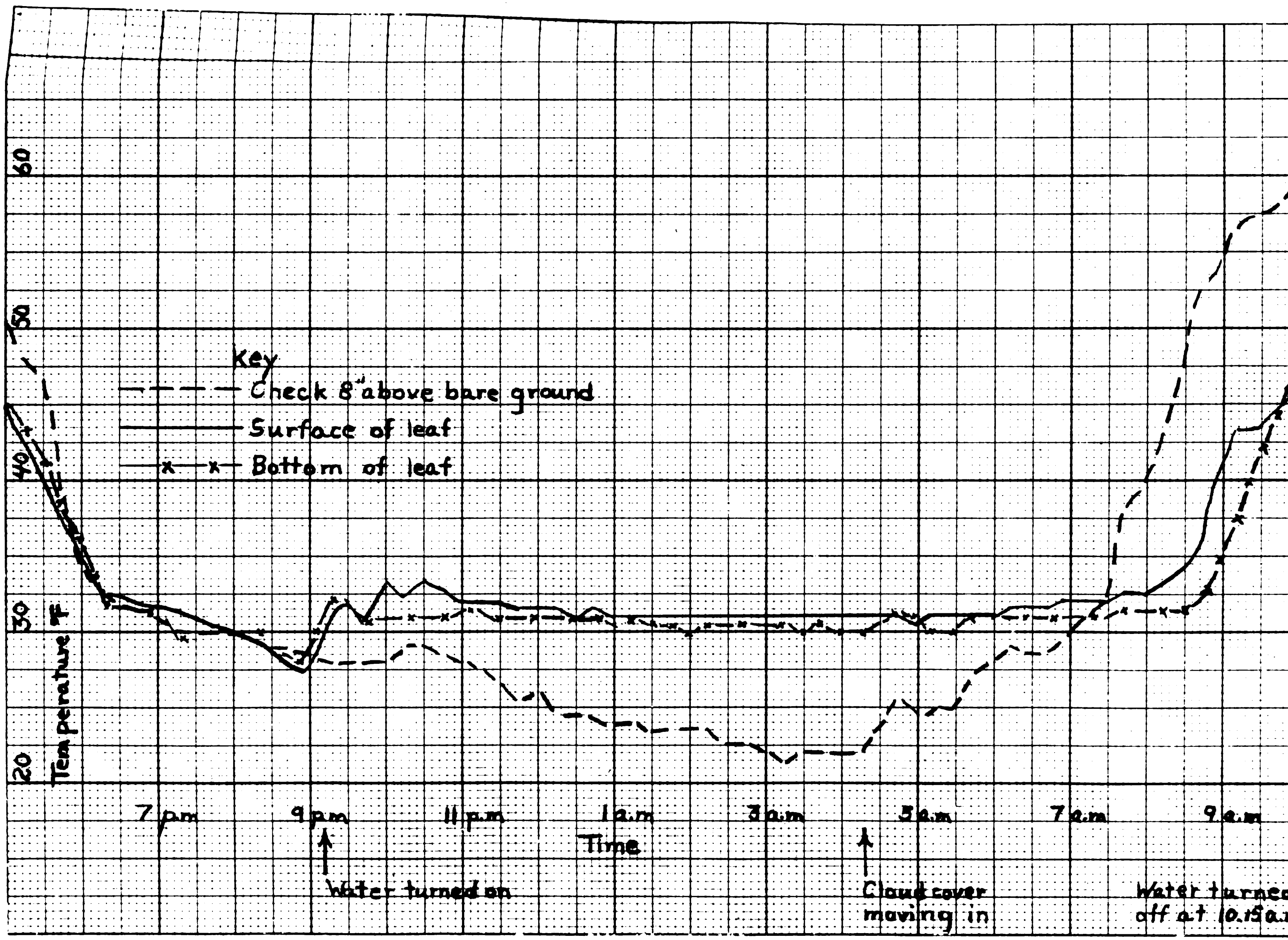

Figure 10. Surface temperatures of tomato leaf for night of October 7.

This might not occur until the air temperature reaches 50° F. or above.

Effect of Water on Plant Temperatures

The temperatures of the surface and of the bottom of two tomato leaves and of the control 6 inches above bare ground on the night of October 7 are shown in Figures 9 and 10. Before the sprinkler system was turned on, the temperature of one leaf reached 27.5° F. on both the top and on the bottom surface, while the air temperature 6 inches above the ground was 30° F. At the same time the temperature of another leaf reached a low of 27.5° F. on the top surface and 28° F. on the bottom. When the water was turned on the surface and undersurface temperature of one of the leaves rose rapidly to 32° F. and then dropped slowly to 31° F. The surface and undersurface temperature of the other leaf rose rapidly to 31° F. Despite the eventual low air-temperature of 21.5° F., the surface temperature of the leaves remained at 31° F, while the undersurface temperature fluctuated between 31° F. and 30.5° F., occasionally dropping to 30° F. The temperature difference between the surface and undersurface of the leaf seldom varied over 0.5° F. The rate of application of water in the area in which the air temperature was measured was 0.20 inches per hour.

The temperatures under the skin and in the middle of a green tomato on the same night are shown in Figure 11. In general, the two temperatures remained almost equal throughout the night at 30.5° F. (±0.5°). The surface leaf temperature was about the same as that in the fruit. The above temperatures of the leaf and fruit indicate that difficulty would be encountered in attempting to use this method of frost protection for plants that have a critical freezing point of 31° F.

Critical Freezing Temperature of Tomatoes

Partial frost damage of the tomato leaves occurred on the night of October 29. As is evident from Figure 8, there was a sudden drop of temperature between 6:30 p.m. and approximately 8:20 p.m., at which time an air temperature of 29.5 F. was attained. The corresponding leaf temperature was 27.5 F. After this, the temperature began to rise above the danger point and remained above 32° F. for the rest of the night. The following morning from 5 to 10 per cent of the outside leaves of the tomato plants were found to have been severely injured by the frost.

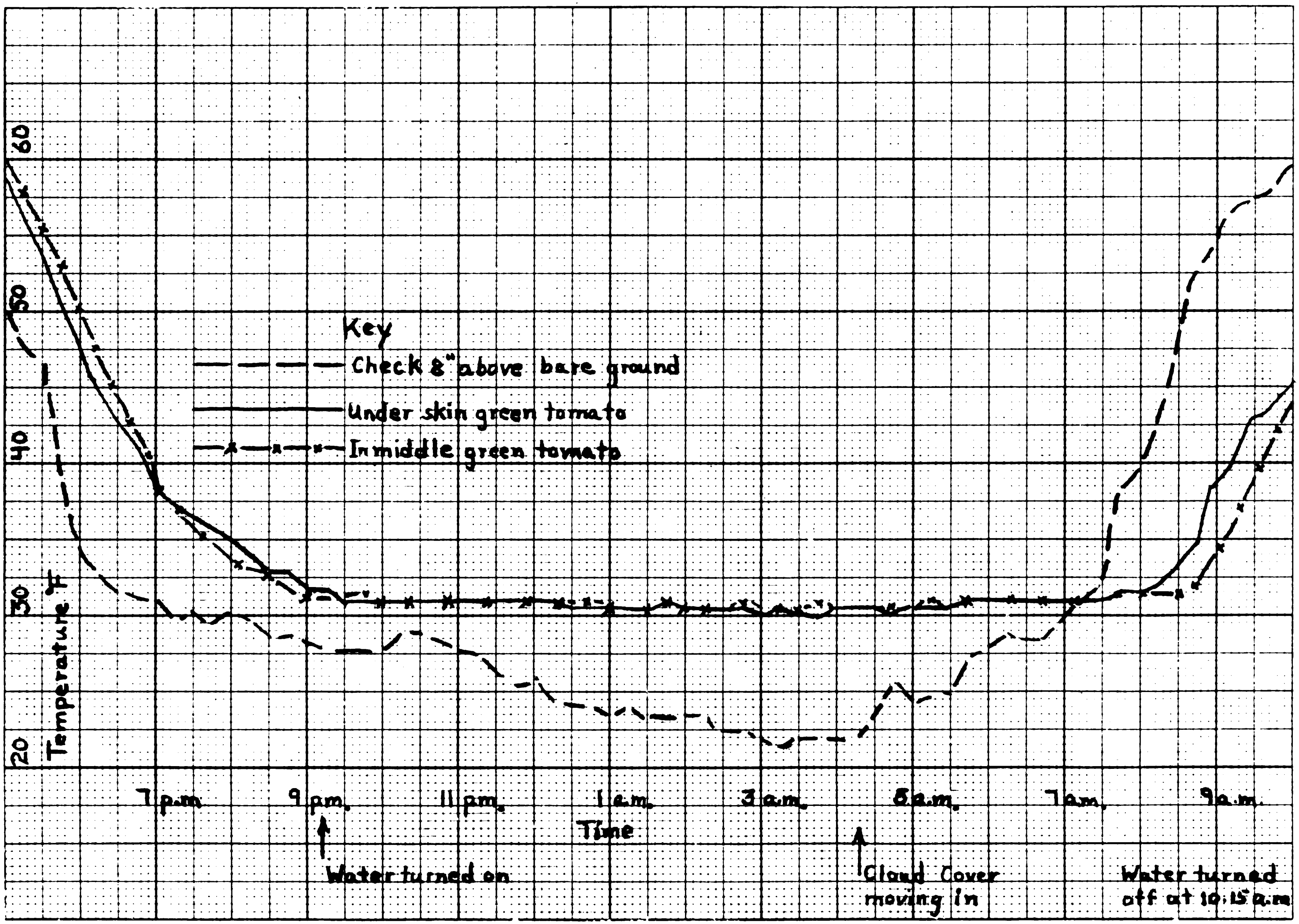

Figure 11. Temperatures in the middle and under the skin of a green tomato for the night of October 7.

Effect of Water on Vertical Air Temperatures

The vertical air temperatures in the treated area on the night of October 7 are presented in Figure 12. In the check area the low for that night was 21.5° F. 8 inches above bare ground. The low in the treated area was 25.5° F. 6 inches above the ground. It is significant to note the absence of the usual temperature inversion that accompanies a radiation frost. The highest temperatures in the treated area were recorded on the surface of the ground. This is due to the fact that most of the latent heat of the water was given off at the surface while changing from liquid to ice. This latent heat offset the heat given off from the surface of the ground by radiation. The lowest measured temperature in the treated area was at a height of 6 feet. This was the highest vertical point measured.

The modification of vertical air temperature of an area by application of water indicates that the amount of frost protection afforded to plants by any given rate of water application will depend on the stillness of the air and the size of the area. The larger the area being protected at a given application rate, the less chance the warmed air in the area will have to mix with the surrounding colder air in the unprotected area. Also, any breeze present will

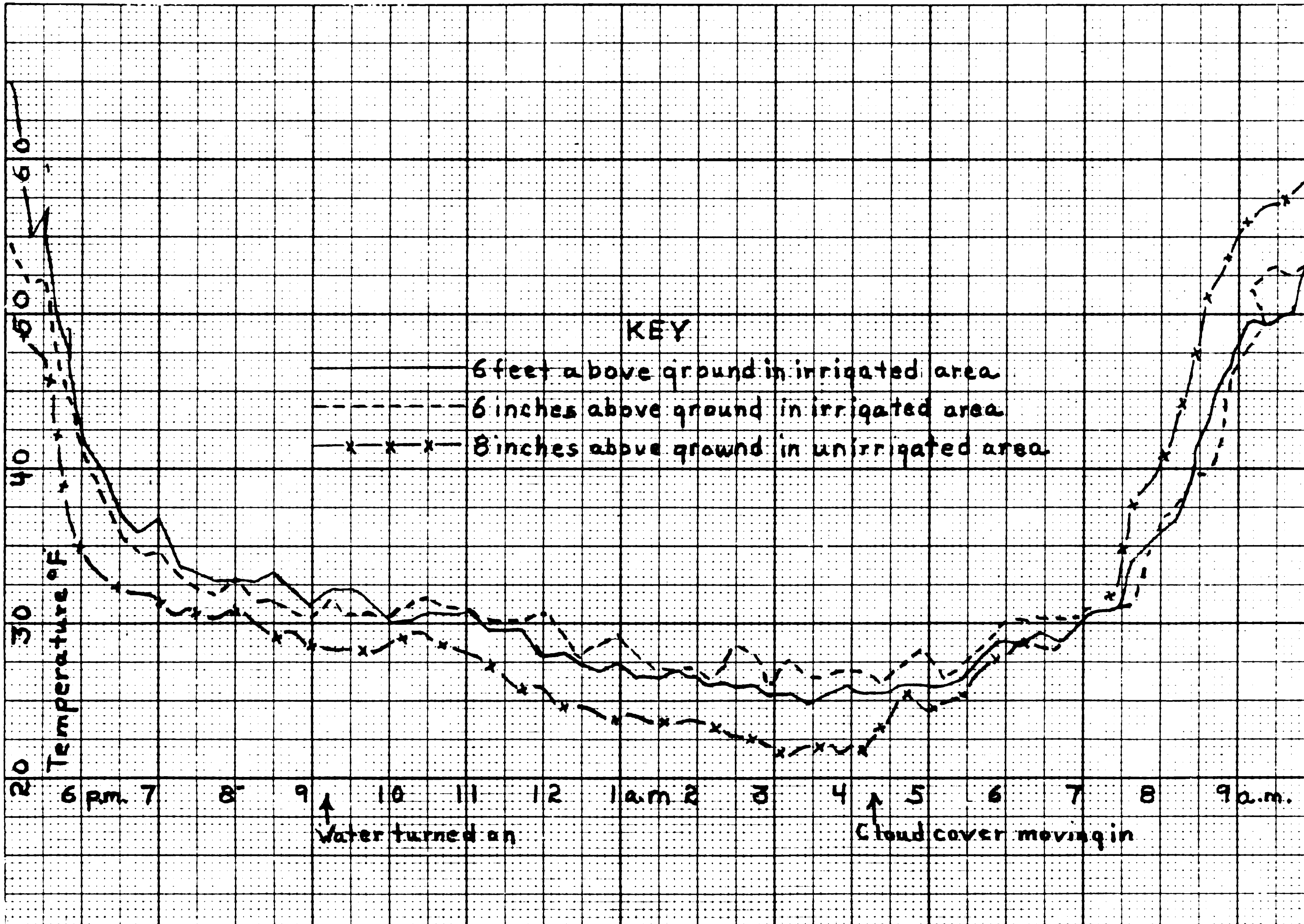

Figure 12. Vertical air temperatures for the night of October 7.

have a tendency to move the warmed air from the protected area, hence, continually bringing in colder air.

If the protected area is of appreciable size and there is very little air movement, the plants there will be surrounded by a higher ambient air temperature than those in an unprotected area even though water is not falling directly on them. The temperature difference between the air in the protected and unprotected area at 6 and 8 inches above bare ground, respectively, was 4° F. for the night of October 7.

Such a modification of vertical air temperature by water indicates that this method of frost protection might be employed to advantage in orchards. The water, when sprinkled under the trees, would modify the ambient air temperature a few degrees Fahrenheit. A temperature difference of a degree or two often makes the difference between frost damage and no frost damage in an orchard.

Effect of Water on Soil Temperatures

Figure 13 shows the soil temperature at depths of 6 inches and 1/2 inch in both the control and the treated area on the night of October 29. At 7:00 p.m. the temperature of the soil at a depth of 6 inches in the treated area was 45° F., and 43° F. at the corresponding time and depth in the untreated area. At 1:00 a.m. both soils at a

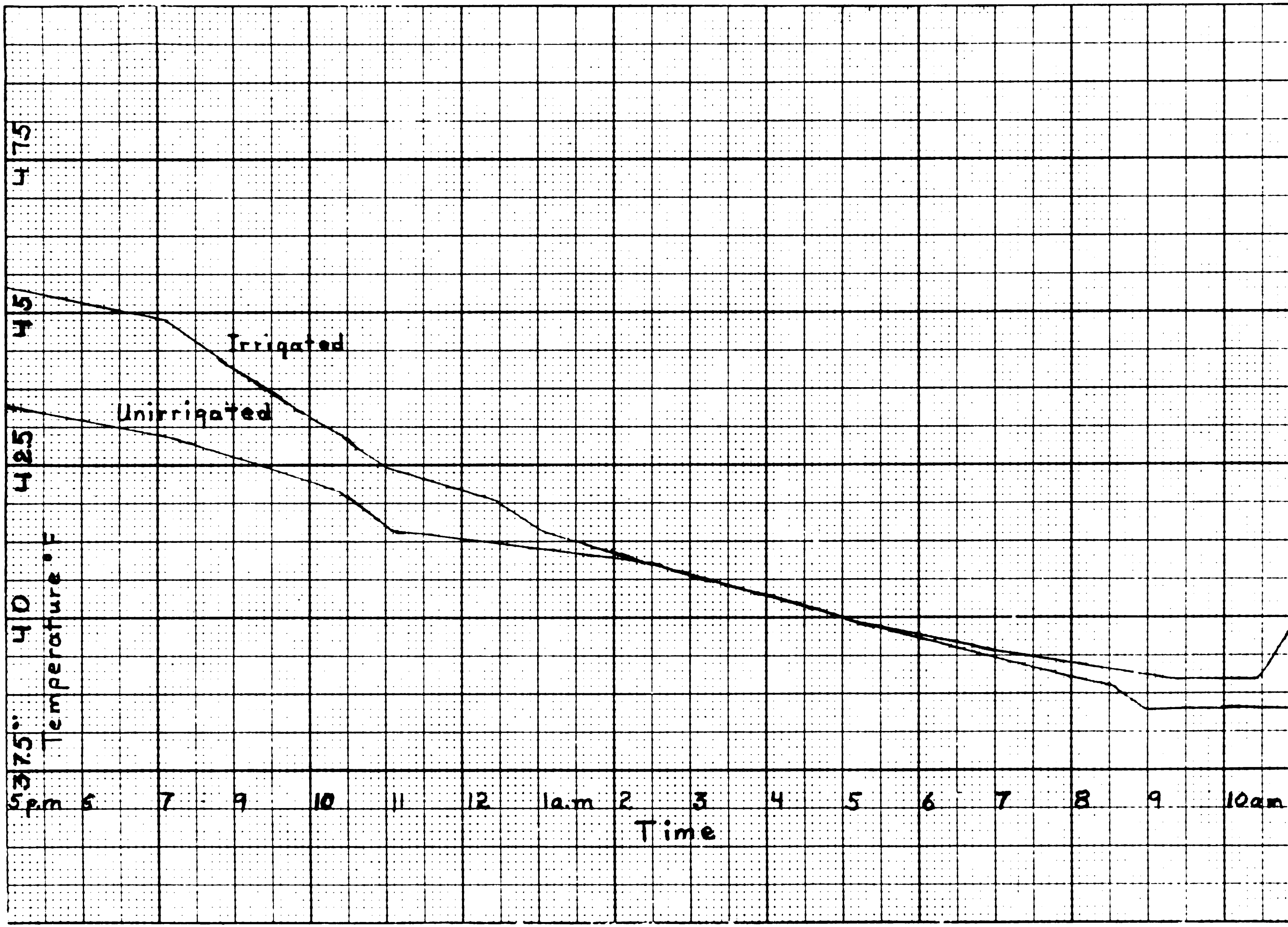

Figure 13. Soil temperature at a depth of 6'' in treated area and check for night of October 29.

depth of 6 inches reached 41° F. By 8:00 a.m. the two soil temperatures had reached 38.5° F. The temperature difference for the two soils was negligible. This could be attributed partially to the fact that the soil in the check area was quite moist. Figure 14 shows the soil temperature gradient for the night of October 7. The air temperature in the check area reached a low of 21.5° F. 8 inches above bare ground. The low on the surface of the ground was 32.5° F., at a depth of 1/2 inch it was 34.5° F., and at a depth of 6 inches it was 41° F. The above figures indicate that the soil temperature at a depth of 6 inches is maintained well above air temperature despite the application of air-cooled water.

Design of Sprinkler

The high angle sprinklers gave more satisfactory performance than the low angle sprinklers. Water from the low angle sprinkler had a greater tendency to wet the side of the plant facing it, since the water was trajected more nearly horizontally, whereas water from the high angle sprinklers was dispersed at a higher elevation, thereby giving a more even distribution of water over the top surface of the plants.

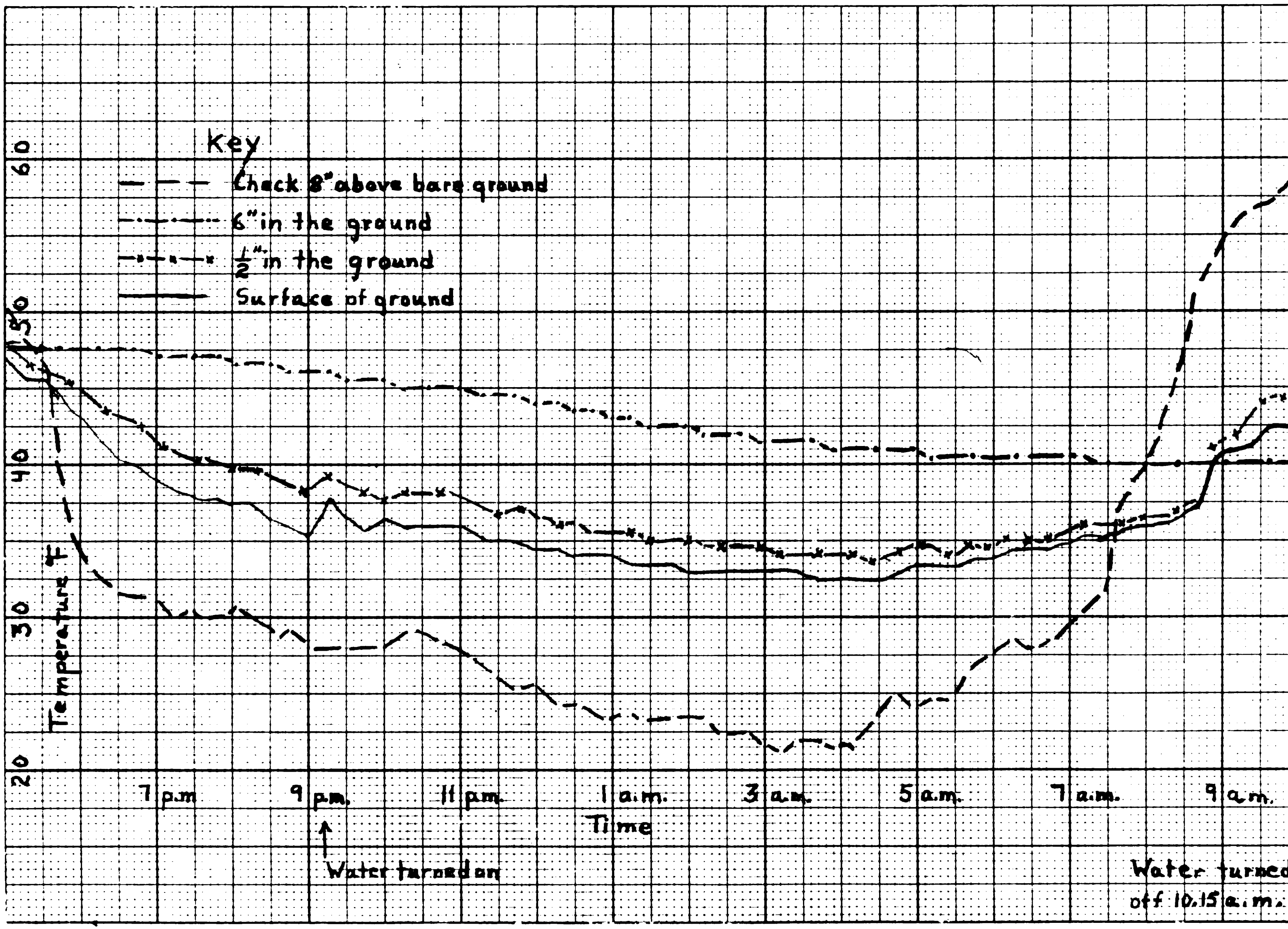

Figure 14. Ground temperatures in treated area for night of October 7.

SUMMARY

The lowest temperature recorded in the check area during the test period was 21.5° F. 8 inches above bare ground. An application rate of 0.04 inches of water per hour failed to protect the beans at the same temperature.

Ice load does not appear to be a serious problem with low-growing plants like tomatoes. However, it can be a serious problem with tall bushy plants. These plants will have some branches broken off or have stalks bent and broken.

When protecting tomato plants, or plants with a similar freezing temperature, sprinkling should be started before the air temperature reaches 30° F. It would be desirable to start when the air temperature is 32° F. to allow for the possible danger from cold air pockets or operational difficulties. If there is only a thin film of ice on the plants, sprinkling may be discontinued as soon as the air temperature is above freezing. If, however, there is a considerable amount of ice on the plants, it would be best to continue sprinkling until all of the ice has melted off regardless of the air temperature. This will result in faster and more even melting of the ice.

By the application of water to tomato plants, a temperature difference of 10° F. was obtained between the leaves of the tomato plants and the air temperature in the check area. During the entire study period the application of water maintained the temperature of the tomatoes above their freezing point. The temperature under the skin, and in the middle of a green tomato, is approximately the same as the temperature on the surface of the tomato leaves.

Partial frost damage to the tomato plants occurred when the air temperature was 29.5° F. for a period of about 20 minutes.

The application of water to an area modifies the vertical air temperature of that area in that the usual temperature inversion during a radiation frost is absent near the ground. This modification might be utilized to some extent in the frost protection of orchards.

Soil temperatures were not altered seriously in a treated area by the application of water if the soil is quite moist before the commencement of sprinkling.

A high angle sprinkler is more satisfactory for general frost protection than a low angle sprinkler.

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APPENDIX

Frost Protection Through Irrigation,
September, 1953

______________________________ ____________________________________
Name Mailing address

________________________ ______________________ __________________
County Township Section

1. Year system was purchased.

2. Main object of buying system: drought _____ frost protection ____.

3. For which has sytem proved more useful: drought _____ frost protection _____.

4. Number years actually used for frost protection.

5. Number of times each year it was used for frost protection.

6. Number of acres system can protect.

7. Number of men to operate system for frost protection and why?

8. Spacing of sprinklers: triangle or rectangle.

9. Size of sprinklers used for frost protection (nozzle size).

10. Does the above size seem satisfactory; if not, larger or smaller.

11. What size pump (   ) power unit.

12. What make irrigation system.

13. Where water obtained.

14. What size laterals (   ) size of main (length).

15. Pressure at end of line _______ or pump.

16. What crops protected.

17. Lowest temperature protected against ______ (where recorded).

18. Duration protection.

19. What air temperature start sprinklers ______ (where taken).

20. What air temperature when system is stopped.

21. Lowest temperature in protected area.

22. Approximate date system used (month and date).

23. Because of system how many days earlier do you plant.

24. What warning used to watch for frost (Thermoswitch, alarm).

25. When is system layed out in field.

26. Type soil.

27. What difficulties encountered with water logging.

28. General weather when system was used: windy, cloudy.

29. Amount of damage to plant by ice (compare treated to untreated).

30. Approximate speed rotation of sprinklers.

31. Did you feel above speed was satisfactory--if not, slower, faster.

32. Where was most damage to plants in protected area--close to sprinkler, middle, etc.

33. What part of plant damaged most.

34. % crop loss in protected area.

35. Are you going to expand the system.

36. Cost system.

37. Do you think it was a worth-while investment.

38. How long before this system pays for itself in frost prctection.

39. Would the system be worth while investing in for frost protection alone?

40. Applications rate.

41. Accumulated ice thickness (under what conditions).

42. Have you tried on trees.

43. Difference in variety resistance.

44. Water temperature (source)

45. Have you used other methods _______. What success, satisfactory? _______

46. Comments.