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ACKNOWLEDGMENTS

The nature of this study makes it practically impossible to give due recognition to all individuals who contributed so materially to its success. Those mentioned below were considered to be deserving of special acknowledgment and without whose help this project could not have been conducted.

Special recognition is given to Professor A. W. Farrall, Head of the Agricultural Engineering Department, Michigan State College, for his encouragement and inspirational advice and for his efforts in securing and making available the necessary funds for this investigation.

Special recognition is also given to Professor D. E. Wiant for his untiring guidance in the experimental work and continued interest in the preparation of this manuscript.

Dr. W. M. Carleton, Professor H. F. McColly and Mr. E. H. Kidder of the Agricultural Engineering Staff offered many helpful suggestions.

Appreciation is extended to Messrs. Drayton Kinard, Paul Kline and George Cheklich of the Agricultural Engineering Department for their valuable assistance in the field testing.

The Evans Products Company, Plymouth, Michigan and Wright Stone and Sons of Beulah, Michigan contributed funds and equipment used in this investigation.

Mr. James B. Cawood and the Agricultural Engineering Research Laboratory Staff aided greatly in this investigation by their valuable assistance in the construction and installation of equipment.

Donald Peyton Brown

candidate for the degree of

Doctor of Philosophy

Final examination, December 12, 1952, 8:00 A.M., Agricultural Engineering Conference Room

Dissertation: Prevention of Frost Damage in Orchards by Utilizing Temperature Inversion With and Without Supplemental Heat

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Minor Subject: Mechanical Engineering

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PREVENTION OF FROST DAMAGE IN ORCHARDS BY USING WIND MACHINES TO UTILIZE TEMPERATURE INVERSION WITH AND WITHOUT PETROLEUM BURNERS

By

Donald Peyton Brown

AN ABSTRACT

Submitted to the School of Graduate Studies of Michigan State College of Agriculture and Applied Science in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

Year 1952

Approved Howard F. McColly

In the United States frost is defined as the formation of ice crystals which occurs when the dew point of the air is below 32 degrees Fahrenheit and moisture condenses directly from the gaseous to the solid state.

The only place in the United States where frost has never occurred is on some of the Florida Keys. The greatest losses from frost damage occur in the fruit and truck crop producing areas. Approximately three percent of all tillable land in Michigan is devoted to fruit growing and one percent to truck crops. The annual loss to Michigan farmers from frost damage is estimated to range from 10 to 20 million dollars.

Frost prevention measures are most effective on nights during which radiation frosts occur. The natural temperature inversion on such nights is usually sufficient to provide enough warm air to prevent frost damage provided it can be made to move to the ground. Natural inversions in Michigan on clear, calm nights usually amount to 10 to 11 degrees Fahrenheit up to 300 feet elevation.

On nights subject to radiation type frosts, it is possible to increase the temperature over a limited area with the helicopter type wind machine. The main objection to this type of wind machine is that it will not force the air in a horizontal direction, consequently the temperature rise extends over only a small area. The wind machine should not be operated unless the temperature can be maintained above freezing.

When a natural temperature inversion of approximately 10 degrees Fahrenheit does not exist, it may be necessary to add supplemental heat from either small orchard heaters or larger units such as the "Frostguard."

The redesigned "Frostguard" units were trouble-free in operation and after 30 hours of burning showed no signs of failure. It was possible to increase the temperature inversion from 11 degrees Fahrenheit to 24 degrees Fahrenheit with six "Frostguards" spaced at equal intervals on a circle of 165 feet radius.

Frost prevention equipment must be selected to meet the requirements of the situation. In some instances air movement is the most economical, in some the addition of heat, in some water application and in still others the combination of air movement and supplemental heat.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

PREVENTION OF FROST DAMAGE IN ORCHARDS BY USING WIND MACHINES TO UTILIZE TEMPERATURE INVERSION WITH AND WITHOUT PETROLEUM BURNERS

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INTRODUCTION

A. Review of the Need for Frost Prevention

1. Definition of Terms

In the United States frost is defined as the formation of ice crystals which occurs when the dew point of the air is below 32 degrees Fahrenheit and moisture condenses directly from the gaseous to the solid state. The term frost is not used in the same sense in England. There, frost denotes freezing weather, and degrees of frost is the term used to signify the number of degrees that the temperature falls below freezing.

2. Susceptibility to Frost Damage of Various Parts of the United States

There is no great part of the continental United States which is entirely immune from frost; however, in the southern half of Florida, in certain limited areas in California and Arizona, and in a small area in southern Texas, frosts are sufficiently rare to permit the growth of citrus fruits and winter vegetables but with occasional losses. The Hawaiian Islands are entirely free of frost at elevations below 2,500 feet and Puerto Rico is without frosts (1). On some of the Florida Keys freezing temperatures have never occurred.

These are the only localities in the United States that are entirely free from frost. Throughout most of Florida, along the coast of the Gulf of Mexico, and in favored localities in Arizona and California, the average growing season is more than 260 days. Along the northern margin of the Cotton Belt it is about 200 days, and in the northern part of the Corn Belt from 140 to 150 days. In northern Maine and northern Minnesota where hay, potatoes, oats and barley are the principal crops, it is about 100 days, and in the higher altitudes in the west it is less than 90 days (2).

Killing frost may be expected to occur in half of the years during the first ten days of April as far south as central South Carolina, northern Georgia, northern Alabama, central Arkansas and central Oklahoma; however, by the end of April the normal frost line has receded to the northern Ohio Valley, southern Iowa and southeastern Nebraska. However, during the first half of April killing frosts may be expected, on an average of one year in ten, as far south as the southern parts of Georgia, Alabama, Mississippi and the central portions of Louisiana and Texas. After the end of May, frost occurs on an average in only a few localities of the extreme northeast and the Upper Great Lake Region. In extensive elevated areas west of the Great Plains the average date is later than May 31. However, temperatures as low as freezing may be expected in early May as often as one year in ten as far south as New Jersey, the central portions of Maryland and Virginia, the most western part of North Carolina, central Kentucky and the southernmost parts of Indiana, Illinois and Missouri (3).

The parts of the United States which are subject to the greatest losses from frost damage are those that are devoted to the production of high valued crops, such as citrus, truck crops and fruit orchards. Approximately 3 percent of all tillable land in Michigan is devoted to fruit growing and 1 percent to truck crops. The annual loss to Michigan farmers from frost damage alone is estimated to range from ten to twenty million dollars (4).

3. Susceptibility to Frost Damage of Various Fruits

The following table shows the susceptibility of various fruits at different blossom stages that coincide with the frost period.

Table I

SUSCEPTIBILITY TO FROST DAMAGE OF VARIOUS FRUITS (5)

Fruit	Buds Closed But Showing Color Degrees F.	Full Bloom Stage Degrees F.	Small Green Fruits Formed Degrees F.
Apples	25	28	29
Peaches	25	27	30
Cherries	28	28	30
Pears	25	28	30
Plums	25	28	30
Apricots	25	28	31
Walnuts	30	30	30

B. Climatic Conditions Favorable to Frost Damage

1. Radiation Frosts

In general, the nights during which frost prevention measures will be necessary may be divided into two classes. The first class includes those nights on which a local frost occurs, when the cooling is due principally to the loss of heat by radiation. These are commonly referred to as "radiation frosts." Such nights usually follow warm afternoons. The temperature falls rapidly during the early part of the evening but often does not reach a minimum until three to five o'clock in the morning.

2. Freezes

The second class of nights on which frost damage is likely to occur includes the "freeze" nights. The preceding afternoons are usually cold and windy, often with a cloudy sky. The temperature falls below the danger point early in the night and usually remains there until sunrise. "Freezes" are usually accompanied by an influx of a cold air mass making them very difficult and expensive to combat. This study was limited primarily to radiation type frosts.

3. Radiation Received by Earth

A clear understanding of the process by which the earth's surface cools at night and of the factors which influence the rate of cooling will do much to insure the successful operation of all frost protection methods, from the simplest to the most complicated.

Heat and light travel from the sun through interplanetary space to the earth in the form of radiation. The average intensity of solar radiation is found to be about 1.94 calories per square centimeter per minute, at the average distance of the earth from the sun, which is approximately ninety-three million miles, when measured on a surface perpendicular to the solar beam. This value accounts for the loss in passing through the atmosphere. If it is assumed that in the course of a year only half of the energy which is expressed in the solar constant reaches the earth at latitude 40 degrees, the energy received would amount to more than five million kilowatt hours per acre. The following table shows the net radiation received by the earth at 40 degree latitude on clear days during the warmest months of the year.

Table II

NET RADIATION RECEIVED BY THE EARTH AT 40 DEGREE LATITUDE
ON CLEAR DAYS DURING THE WARMEST MONTHS OF THE YEAR
IN B.T.U. PER SQUARE FOOT PER HOUR (6)

	Vertical Surfaces			Horizontal Surfaces
Time	E	S	W	
6:00 A.M.	72	--	---	15
9:00 A.M.	191	26	---	214
12:00 Noon	---	78	---	300
3:00 P.M.	---	26	191	214
6:00 P.M.	---	--	174	15

4. Radiation Losses from the Earth

A portion of this energy is reradiated, but the greater part is absorbed, raising the temperature of the surface which it strikes. The surface of the earth is continually emitting long wave-length radiation at a rate depending on its temperature (7). This process is continuous both day and night, but on a clear day, the energy received from the sun is usually much greater than the amount which is lost by radiation; consequently, the surface temperature rises. The air that is in immediate contact with the earth becomes warmed by the process of conduction. Air is a poor conductor of heat; consequently, only a thin layer is warmed at first. However, as soon as a small depth of air becomes warmer than the air above and around it, its density is lessened and it is forced upward while the cooler, more dense air settles downward. This dense air is warmed also by conduction from the ground, and the process is repeated. The air that has been warmed by contact with the ground continues to rise until it reaches a point where its temperature is the same as that of the air above it. When this process continues until near sundown, the temperature of the air will be highest near the ground and decrease at a more or less uniform rate with an increased distance above the ground to a height of a thousand feet or more (8).

After the sun passes below the horizon, the radiation received from the atmosphere is usually insufficient to counterbalance the loss by outgoing radiation. Therefore, the surface temperature of the earth falls below that of the layer of air in contact with it. As soon as this occurs, the air begins to lose heat to the earth by conduction. As the air becomes cooler, it also becomes more dense and tends to cling to the earth rather than rise as it did during the day. Over a level plain on a clear, calm night, a relatively thin layer of cold air is found near the ground. An increase in temperature occurs with an increase in altitude from the ground to between three hundred and eight hundred feet (9).

If there were no atmosphere, the loss of heat to cold space by radiation would be so excessive that frost would form every night. An example of this is seen in the measurements, by Pettit and Nicholson (10), of the surface temperature of the moon where no atmosphere exists during an eclipse. They found a change from plus 160 degrees Fahrenheit to minus 150 degrees Fahrenheit in two hours. This is practically independent of the amount of heat that is stored within the solid because of the low thermal conductivity of the dust layer on the surface. On the earth, with the same exposure in sunshine and cold space, without the atmosphere, the nocturnal cooling rate before sunrise would be about 5 degrees Fahrenheit per hour, instead of the observed average of 1 degree Fahrenheit. This is because the outgoing radiation loss from a surface is reduced about four to one by the downward radiation from the atmosphere. Thus the earth's atmosphere, as an extensive heat source radiating back to the ground, restricts typical radiation frosts in citrus areas to those few calm, clear nights having cold or dry atmosphere aloft (11).

5. Effect of Water Vapor in Atmosphere

A water droplet cloud acts as a radiation shield and, when at a low level, radiates at a temperature not much colder than the air temperature during the day. Radiometer observations at Riverside, California on the night of January 12, 1939 showed clearly the sudden stopping of radiation cooling by clouds. These observations also indicated that coincidentally the surface ground temperature rises when the previous temperature gradient, developed to provide full radiation loss, is no longer needed to meet the reduced net radiation demand of the sky (12).

Large variations in the amount of solar radiation received at different locations are caused by latitude, altitude, season and adjacence to large bodies of water. Air pollution over industrial centers will have a marked effect. For that reason, observation stations in the United States have been located, insofar as possible, to minimize this effect. Industrial effects have been noted most especially in the solar radiation records of New York City, Pittsburgh and Chicago. The investigations of Crabb (13) indicated that the presence of water vapor in the atmosphere is the most significant factor in the variance of receipt of solar radiation and is the factor most difficult to anticipate and correct for. This factor is probably accentuated in Michigan by the fact that the state is surrounded on three sides by bodies of water.

The curve of the normal daily total of solar and sky radiation for East Lansing, Michigan, covering five years' data, shows a distinct leveling off at about 365 gram calories per square centimeter during the month of May with a peak of 530 gram calories per square centimeter during the latter part of June (14).

C. Methods Used for Frost Prevention

Frost protection methods that are utilized in the United States can, for the most part, be grouped under the following general principles:

1. Conserving Heat.
2. Adding Heat.
3. The Application of Water Spray.
4. Air Movement, a Mixing or Stirring of the Air.
5. A Combination of Air Movement and Supplemental Heat.

1. Conserving Heat

The practice of blanketing the vegetation with a protective covering of some sort to sufficiently reduce the radiation losses will prevent the temperature from falling below the danger point on a radiation frost night. Several materials have been used with varying degrees of success.

a. Covering with glass. Glass is very effective in screening the plants from frost damage. The panes of glass allow the incoming radiation to pass through but serve as an effective screen against outgoing radiation. This is the case because a large part of the radiation of the sun that reaches the surface of the earth consists of the visible waves and the short infrared. The very short (ultraviolet) and the very long (infrared or heat) waves are largely absorbed by the atmosphere. The glass, being very transparent to these infrared waves, admits them, and their energy is converted into heat when they strike the object below. As the object warms up, it becomes a radiator; however, since the temperature is not high, the object emits only very long waves. This is shown by the Stefan-Boltzmann Law. The radiation from a black body is proportional to the fourth power of its absolute temperature

$$E = \sigma T^4$$

where T = absolute temperature (degrees Kelvin) of the body and E is in ergs per square centimeter per second when σ is given as $5.672 \pm 0.003 \times 10^{-5}$. (15)

Wien's Displacement Law defines the maximum of the radiation curve and the shift toward shorter wave lengths as temperature is increased. The wave length in microns of the peak radiation is

$$\lambda_m = \frac{A}{T}$$

T is again degrees Kelvin, "a" being a constant for a particular surface.

a = 2960 for a black body

a = 2630 for platinum (16)

Glass is athermanous to heat waves longer than about 1.5 μ; hence these longer waves can not pass through (17). The cost of covering with glass, however, is too great for anything except the very expensive plants and flowers.

b. Cloth screens. Many attempts have been made, none of which have been successful, to protect orchards from frost by covering them with various fabrics. It is possible to maintain air temperatures 2 to 6 degrees Fahrenheit higher than outside, if a heavy fabric cover is placed over several trees in such a manner that it does not touch the trees, and if there is little air movement (18). All devices of this sort must be removed to allow sunshine to reach the trees, making the cost of such protection prohibitive.

A covering of a single thickness of burlap laid over three-fourths of an acre of strawberry vines in full bloom furnished adequate protection against light frosts, but the cost, which amounted to approximately $117 per acre per year, was almost prohibitive. There was no evidence of frost damage to the crop, although the outside minimum temperature, registered in a standard instrument shelter on the ground, was 28.6 degrees Fahrenheit (19).

Tin cans or other metal coverings should not be used in an attempt to protect plants from frost damage. Metals are good radiators and conductors of heat, and the temperature is likely to fall as low under metal coverings as in the outside air (20).

c. Lath screens. Lath screens, made from lath fastened together with wire in order to allow open spaces about the width of the lath between them, have been used successfully on nursery stock. However, they should not be used on mature trees, since the trees will suffer from a lack of sunlight during the day.

d. Paper. Bags made from heavy, water-proof paper have been used to enclose entire citrus trees as a protection against frost damage. Minimum temperatures on cold nights averaged only about 1.5 degrees Fahrenheit higher inside the tents than at the check station outside (21). Paper caps are used quite extensively in the Imperial Valley in California for the protection of vegetables. Maximum temperatures during the day are about 23 degrees Fahrenheit higher under the caps than at the same level in the open. Minimum temperatures registered under the caps are only about 2.5 degrees Fahrenheit higher than temperatures registered by standard alcohol minimum thermometers exposed to the sky. The labor and material cost of covering with paper caps amounted to about $16 per acre in 1947 (22).

e. Miscellaneous. Various other types of materials have been used in an attempt to conserve heat. These include cornstalks, arrowweed, smoke screens, etc.

Military smoke-screen generators have been used but have been found to be of no value for long-wave screening. This is because the 0.7 micron smoke-screen droplet is at least 20 times too small in diameter. The necessary large-particle fog generators are not yet available, because a very uniform particle size is needed to avoid too rapid settling of the fog. The inflow of the cold air at the screen border would depend upon how extensive an area is covered (23). A number of counties and municipalities in California have passed ordinances to outlaw certain types of orchard heating equipment that cause objectionable soot and smoke (24).

2. Adding Heat

The second principle of frost prevention is that of adding heat to the air near the ground to replace that lost by radiation. This has been accomplished in the past by several different methods, utilizing many different types of burners and fuels. In the North of India, in a district where deciduous fruits grow well, it has been reported that good results were experienced in a vineyard by smudging the vines against a radiation frost. The concentration of fires, burning dried dung and litter, was enormous, being 400 to the acre. As much as 10 degrees Fahrenheit added warmth was claimed for the operation. There would be considerable difficulty in starting and maintaining such a large number of small fires (25).

a. Small orchard type heaters. Heating equipment has been designed and installed in orchards for many years. As far back as 1912-13 artificial heat was used to raise dangerously low temperatures. Small, open heaters were credited with saving lemons in a large lemon grove in southern California where frost damage to both fruit and trees was widespread. During the period 1922-25 nine hundred thousand heaters were sold to California citrus growers. In 1950 three counties reported 1,448,327 heaters in operation (26). The spacings and fuel consumption vary considerably according to the type of heater. Some of the more common types are: (a) Return Stack, (b) Jumbo Cone, (c) Exchange - 7-inch, (d) Lazy Flame - 24-inch, (e) Lazy Flame - 18-inch and many others. Considerable research has been done on this type of heater at the California Agricultural Experiment Station and is reported in their various publications.

b. Small propane frost prevention burner. In 1949 development work was started at Michigan State College on a small burner of the radiation type which operates on liquified petroleum gases (LPG). This burner is discussed to a greater extent in other sections of this report.

c. Large, infrared, radiant energy type burner. In 1945 the fundamental research which was later to lead to the development of a commercial frost protection burner was started by members of the Agricultural Engineering Department at Michigan State College. This protective device is known commercially as the Evans "Frostguard" and will be discussed further in other sections of this report.

d. The use of electrical energy. References are made to the use of electrical energy for frost prevention in orchards as early as 1924. Experiments conducted by the New Zealand Department of Agriculture showed that the process of orchard electrification had a tendency to prevent frost injury in orchards. Experiments conducted at the Utah Station prior to 1924 indicated that approximately 14 watts per square foot were required to obtain 1 degree Fahrenheit rise in temperature (27).

Experiments which were conducted at Michigan State College in 1948 indicated that three watts per square foot was the energy required to offer protection to crops during a typical radiation type frost. Laboratory studies under room conditions and near freezing conditions indicated that a radiation intensity of 50 microvolts, measured with the Eppley radiation meter, will, when falling on an exposed plant leaf, produce a temperature rise of 1 degree Fahrenheit within the leaf.

The frost protective effect of infrared heat lamps indicated that an input of one kilowatt would protect 80 square feet from typical frosts. The primary factor which limits the use of electrical energy for protection of relatively large areas from frost damage is the great power requirement. The high operating cost would discourage the use of electrical units on any but high-valued crops (28).

3. Application of Water Spray

Considerable experimental work has been done on the application of water spray for frost prevention. Growers have reported successful prevention of frost damage with temperatures as low as 22 degrees Fahrenheit by the use of overhead irrigation. The application of water for such a purpose should be continued until all of the ice, which has formed on the leaves, has melted off. The minimum application rate required to prevent damage has not as yet been determined. However, tests made during a 24-degree Fahrenheit frost in October, 1950 showed that 0.07 inch per hour was not sufficient to prevent frost damage to tender, young bean plants. Considerable waterlogging can be expected on some soils, if it becomes necessary to apply water for frost control several nights in succession (29). For other than low growing crops the ice load may become excessive and cause damage due to breakage.

4. Air Movement

Any method that will prevent the air from stratifying will usually help in the prevention of a radiation type frost. Machines that are used for this purpose are commonly called "wind machines." The principle of their operation is to pull the warmer air downward from above the tree tops and to mix it with the cooler air near the ground, thereby raising the temperature above the danger point. Previous to 1945 wind machines were not considered of much importance in frost prevention. According to one report, wind machines were used in Tulare County, California, as early as 1920, although most of the early machines were abandoned after a short period of use (30). Today there are over 2,700 wind machines in use in California with smaller numbers in many of the other fruit producing states.

There are two known instances of a helicopter having been used in an attempt to cause sufficient air circulation to afford frost protection. In 1945 the United States Army Air Force sent a helicopter to Michigan State College to be used in circulating the air by flying at low altitudes over the areas to be protected (31). In 1948 a night-flying, Model 47D, helicopter flew to Batavia, New York, to assist with the protection of 45 acres of tomatoes. The object of the mission was to mix the warmer air (approximately 36 degrees Fahrenheit) to be found at an altitude of 50 to 100 feet with the colder blanket of air (close to 32 degrees Fahrenheit) settling down over the tomatoes (32).

5. Combination of Air Movement and Supplemental Heat

The wind machine alone can not be expected to add heat to the air but must depend upon a supply of warmer air which it causes to circulate and mix with the cooler air that is nearer to the ground. If this supply of warm air is not available, due to the natural temperature inversion, or if the temperature difference is not great enough, it may be necessary to add supplemental heat in addition to the action of the wind machine. Recent tests and field experience indicate that the combination of wind machines with uniformly distributed heaters gives a response greater than the sum of the normal response from the heaters alone plus the response from the wind machine alone. In tests during two nights in February 1950 at the Citrus Experiment Station, Riverside, California, the combined response from a 90-horsepower wind machine plus 15 heaters per acre was 20 to 30 percent greater than the sum of the individual responses (33).

PURPOSES OF THE STUDY

The purposes of this study were as follows:

1. To conduct further field tests on a horizontal rotor type machine that had been built and partially tested by staff members of the Department of Agricultural Engineering at Michigan State College. These tests were to be conducted with and without the use of supplemental heat.
2. To field test a ground powered, horizontal, rotor type wind machine using discarded helicopter blades. These tests were also to be conducted with and without the use of supplemental heat.
3. To conduct field tests on a redesigned liquid petroleum burner known as the "Frostguard".
4. To conduct heat balance studies on a small propane burner for frost prevention.

EXPERIMENTAL WORK

A. Wind Machine Number One

1. Description

A helicopter type wind machine was constructed in the Agricultural Engineering research laboratory in 1949, as illustrated in Figure 1. The rotor, 22 feet in diameter, having the National Advisory Committee for Aeronautics Air-force Section 15-H-15 with 11.5-inch chord, was made from ponderosa pine.

Figure 1. Wind Machine Number One with 15-horsepower gasoline engine

This rotor was mounted on a pipe tripod tower 20 feet high and was operated in much the same manner as a helicopter when hovering. The first model of this machine was belted to a 15-horsepower gasoline engine, as shown in Figure 1.

2. Results of Previous Testing

During March 1951, this machine was installed in the Thornhill Orchard which is owned by Wright Stone and Sons, Beulah, Michigan. A report of the test of this machine indicates the following results.

In the early morning of May 4 a minimum temperature of 31.4 degrees Fahrenheit was measured near the ground. At this time the temperature 300 feet above the ground was 37.9 degrees Fahrenheit. Shortly after the rotor was started the temperature 40 feet out from the machine rose from 31.4 to 36.0 degrees Fahrenheit, with the temperature increase diminishing to zero at 170 feet. The average temperature rise over the area with a radius of 170 feet was 3.5 degrees Fahrenheit. Seventy-eight heaters in a circle which had a radius of approximately 150 feet from the machine were then lighted. These heaters raised the temperature from 31.4 to 31.9 degrees Fahrenheit over the area. When the heaters and wind machine were used together, the temperature at a distance of 40 feet from the machine increased from 31.4 to 37.2 degrees Fahrenheit. No increase in temperature was measured beyond 180 feet. The average temperature rise was 4.6 degrees Fahrenheit for the area affected.

Since the average temperature rise for the wind machine alone was 3.5 degrees Fahrenheit and for the heaters alone 0.5 degree Fahrenheit, a probable increase of 4.0 degrees Fahrenheit for the wind machine and heaters operating at the same time would be expected. However, the average temperature rise was 4.6 degrees Fahrenheit, an increase of 0.6 degree Fahrenheit above that which was expected. This increase is believed to be due to recirculation of the heat given off by the heaters.

A more severe frost occurred on the night of May 11. The lowest temperature at the ground level was 26 degrees Fahrenheit. The temperature at 300 feet above the ground was 48 degrees Fahrenheit. Approximately one-half hour after the rotor was started the temperature 40 feet out from the machine had risen from 26 to 35 degrees Fahrenheit. No temperature increase was recorded beyond 170 feet northwest from the machine.

The temperature increase brought about through the use of 178 heaters was 1.7 degrees Fahrenheit. When the machine and heaters were used together the temperature at 40 feet from the wind machine rose from 26 to 38 degrees Fahrenheit. No temperature increase was recorded beyond 170 feet in a northwesterly direction from the machine.

The average temperature rise for the machine alone was 5.1 degrees Fahrenheit, and that for the heaters was 1.7 degrees Fahrenheit, making a probable increase of 6.8 degrees

Fahrenheit if both were used together. The actual temperature rise, however, was 8.0 degrees Fahrenheit, representing an increase of 1.2 degrees Fahrenheit, no doubt due to the recirculation of heat given off by the heaters. During this test the wind machine replaced approximately 200 heaters (34).

3. Changes in Design

After studying the original design of this wind machine and holding conferences with those who were responsible for its operations and testing, it was decided that the power train of the unit could be improved. The changes suggested included the replacement of the stationary engine with a farm tractor. The reason for this was obvious. A wind machine is a piece of specialized equipment and since its yearly hours of use are small, it should not incorporate the use of expensive equipment such as a stationary engine. This would be used only a comparatively few hours each year and, in some instances, not at all. The farm tractor has replaced practically all other sources of field power on Michigan farms and orchards, and most of our Michigan growers, who might be potential owners of wind machines, already have farm tractors available. The demand for power by a wind machine will come at night when the tractor is not needed for other operations, such as spraying, etc.

In the tests conducted in the Thornhill Orchard electric motors could not be used because electric service to the orchard was not available.

The basic idea was to keep the installation simple and easy to move.

In the original machine the power unit was on the ground. The $1\frac{1}{4}$-inch drive shaft was attached to one of the three legs of the steel tower in order to transfer the power from this unit to the rotor on top of the 20-foot tower. It was thought that the drive shaft in this location was the cause of excessive vibration in the tower when the machine was running. This situation was corrected by changing the drive shaft to the center of the tower with suitable pillow blocks attached to the angle iron braces extending to each of the tower legs. The vertical drive shaft was attached by means of universal joints and keys to the propellor hub at the top of the tower and to the speed reduction unit at the bottom, as shown in Figure 2.

Figure 2. Speed reduction unit for Wind Machine Number One

This speed reduction unit was made from an old Plymouth automobile differential that provided a speed ratio of 3.8 to 1 and also made a right angle turn in the power train. Earlier models of this wind machine had utilized a belt drive from the power source to the speed reduction unit. The belt drive was discarded in favor of the power-take-off, which proved to be much more satisfactory. When the tractor power-take-off was operating at the standard speed of 540 revolutions per minute, this speed reduction provided a speed of 142 revolutions per minute to the rotor blades. Since it was possible to adjust the angle of attack of the rotor blades on this machine, it was decided to set them at 18 degrees. This value was chosen because it was slightly less than the angle at which the lift coefficient of a lifting vane section starts to decrease rapidly, and the drag coefficient starts to increase rapidly. The angle of attack at which this occurs is known as the beginning of the "stall." The "stall" is the condition of the lifting vane in which it is operating at an angle of attack greater than the angle of attack at maximum lift. At the "stall" the fluid separates from the vane and forms a marked eddying wake (35).

Preliminary investigations indicated that this set of blades with the indicated angle of attack and speed should require approximately 20 horsepower. This calculation was proven to be correct by the gasoline consumption of the tractor as a power source.

After the desired corrections were made to the wind machine, it was reassembled and painted in the Agricultural Engineering research laboratory. Each bolted joint was painted a different color in order to make assembly of the tower easier for inexperienced personnel.

4. Location and Method of Erection

On May 2, 1952 this wind machine was installed in the Thornhill Apple Orchard of Wright Stone and Sons. The contour map of the orchard (Figure 3) shows the location of this wind machine, which will be referred to throughout this text as Wind Machine Number One. Two men and one tractor assembled and raised this wind machine very easily. The tower was bolted together and the blades were attached with the tower in a horizontal position on the ground. Holes six inches deep were dug in the ground at the base of the two legs that were resting on the ground. These holes allowed the base of the legs to dig in and hold when the machine was being raised. The machine was raised to a vertical position by attaching one end of a 40 to 50 foot cable to the top of the tower and pulling on the other end with the tractor drawbar. The machine was levelled as nearly as possible so that it was not necessary to stake or anchor it down.

This wind machine was driven by a Caterpillar "22" tractor, as shown in Figure 4.

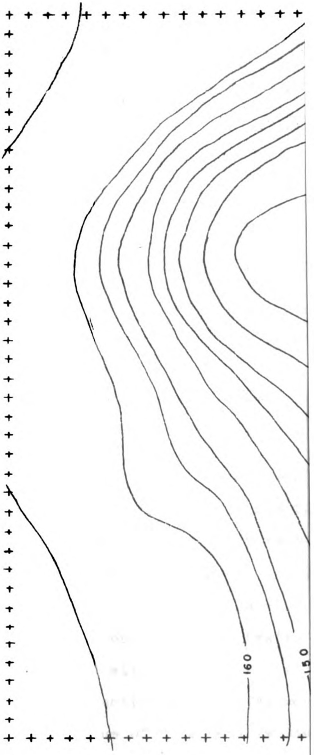
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Figure 4. Caterpillar "22" tractor in operating position at Wind Machine Number One

5. Tests Conducted

This wind machine was first operated for the 1952 season on May 2. Complete temperature records were not possible, but a minimum of 18 degrees Fahrenheit was registered immediately outside the area of the wind machines. Wind Machine Number One was operated from twelve midnight until six o'clock in the morning with a reported low of 26 degrees Fahrenheit inside the effective area of the machine. This indicated a temperature rise of 8 degrees Fahrenheit. Personnel and equipment were not available to measure the temperature inversion. Orchard heaters had been placed in the orchard during the previous day but had not been filled with oil. The apple blossoms were in the pink stage and considerable damage was reported.

On May 6 a low of 25 degrees Fahrenheit was recorded by a "Brown" recording thermometer at a check point outside the area of the wind machine. The wind machine was operated from 11:00 P.M. until 6:00 A.M. on May 6 with supplemental heat from small oil burning orchard heaters. Old rubber tires from automobiles, trucks and tractors were also burned. It was observed that the wind machine pulled the smoke from the fires down to approximately the base of the wind machine and dispelled it outward. At daybreak a visible frost line was observed approximately 90 feet from the base of the machine. Temperature measurements were made throughout the night, and all of them are recorded in the section of this report entitled "Results."

On May 15 a low of 26 degrees Fahrenheit was recorded at the check point. High cirrus clouds were present during the day, but they dissipated completely at sundown. The wind machine was operated with orchard heaters and tire fires supplying supplemental heat. Complete temperature records were not available, but at daybreak it was observed that the action of the wind machine had drawn a dense accumulation of smoke from the burners into an area of approximately three acres around it.

On May 16 a low of 31 degrees Fahrenheit was recorded at the check point. High cirrus clouds were present during the day but dissipated at sundown. The sky was clear until 4:20 A.M. on May 17. The sky quickly became completely overcast at 4:30 A.M. Tire fires were started at 1:20 A.M., but no orchard heaters were lighted. A slight drift from the southwest was recorded.

The temperatures for this series of tests were recorded by an 8-point "Brown" recording potentiometer. The temperature was measured at 24 locations by welded copper-constantan thermocouples. These thermocouples were made into three lines of eight thermocouples each. The lines were made using a 5-foot leader from the main line to each thermocouple so that the temperature could be measured five feet above the ground. A constantan lead wire, common to all eight thermocouples, was used with the copper lead wires from the eight thermocouples to form the main cable. The eight copper lead wires and their common constantan were soldered to the female terminals of an SC 3105A part from an airplane communication system, as shown in Figure 5. The corresponding leads from the terminal block of the "Brown" recording potentiometer were soldered to the male terminals of this same apparatus, as shown in Figure 5.

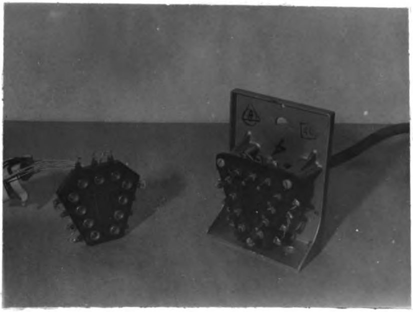

Figure 5. Connectors used to change from one thermocouple line to another

This arrangement made it possible to easily shift from one thermocouple line to the other. The thermocouples were located 20 feet apart on each of the three main lines and were held in position five feet above the ground by a 1-inch by 1-inch wooden stake which was driven into the ground. The three lines extended radially from the wind machine at

120-degree intervals. Calibrated mercurial thermometers were used at any odd points where it was desired to measure the temperature.

The temperature inversion records were taken with the 12-point "Brown" recording potentiometer. The thermocouple line for the vertical temperature measurements was similar to that used for the lateral measurements except that the 5-foot leaders were omitted, and the thermocouple junctions were made by twisting and soldering the copper lead wire to the common constantan wire directly. This cable was held suspended in a vertical position by a hydrogen filled balloon four feet in diameter as shown in Figure 6.

The thermocouples were held at the heights indicated in the following table.

Table III

HEIGHT ABOVE GROUND OF VERTICAL THERMOCOUPLES

Thermocouple Number	Height Above Ground
1	1 inch
2	7 inches
3	1 foot 7 inches
4	3 feet
5	5 feet
6	8 feet
7	15 feet
8	30 feet
9	65 feet
10	125 feet
11	200 feet
12	300 feet

Figure 6. Hydrogen filled balloon used to suspend vertical thermocouples

B. <u>Wind Machine Number Two</u>

1. Description

The second wind machine, as shown in Figure 7, was constructed in the Agricultural Engineering research laboratory during the spring of 1952. This machine was built as a result of a joint agreement between Professor A. W. Farrall, Head of the Agricultural Engineering Department, Michigan State College, and Wright Stone and Sons of Beulah, Michigan.

Figure 7. Wind Machine
Number Two

This wind machine utilized a pair of damaged helicopter blades which had been secured from the Bell Aircraft Corporation.* These blades carried the following designation:

Bell Aircraft
Model 47
47 110 120 30
Part # Chg AP
Type 10
Wgt 91.4#
Serial #1080
Install in pair with blade #1079
c.g. 119" from tip
c.g. 3.3" from L.E.
-1/4° Tip incid.
4¼° Root incid.

*Post Office Box One, Buffalo 5, New York

This machine was designed and built with the fundamental idea of maintaining simplicity and ease of erection. The helicopter rotor blades were bolted to a welded hub with a permanent angle of attack of 18 degrees. This angle was chosen for the same reasons as outlined in the discussion of Wind Machine Number One. These blades were 16 feet long and weighed 91.4 pounds each. The hub to which these blades were bolted was keyed to the end of a $1\frac{1}{4}$-inch drive shaft. The shaft was supported by a 25-foot length of 6-inch iron pipe and was held in position by means of self aligning pillow blocks and thrust bearings.

The 6-inch pipe was held in a vertical position by two $1\frac{1}{4}$-inch steel pins that extended through a 4-inch pipe on each side of the 6-inch, as shown in Figure 8.

Figure 8. Base for Wind Machine Number Two

The $7\frac{1}{2}$-foot, 4-inch pipe supports were set $7\frac{1}{2}$ inches apart and $2\frac{1}{2}$ feet deep into a block of concrete which was three feet in diameter and three feet deep. Two spacers, which also served to anchor the pipes in the concrete, were made from scrap boiler plate and welded to the two 4-inch pipes. This setting allowed the 4-inch pipes to extend five feet up on two opposite sides of the 6-inch pipe. One of the steel cross pins was located six inches above the ground level and the other $4\frac{1}{2}$ feet above the ground.

2. Location and Methods of Erection

This machine was installed on May 2, 1952 in the Thornhill Orchard and located so that the air movement would not affect or be affected by Machine Number One and so there would be no border effect. This location is indicated in Figure 9. Wind Machine Number Two was located approximately 300 feet inside the west and south borders and 200 feet to the south of the outlet of the small ravine, as indicated in Figure 3.

The two pieces of 4-inch pipe that served as a support were placed in their concrete base on April 18, 1952. The first step in the installation of the wind machine was to fasten the pillow blocks of the vertical drive shaft to their brackets, which had been welded to the 6-inch pipe support. The hub was then keyed to the top end of the shaft. With the upper end of the pipe resting on a truck bed in such a position that the blades could be installed, the bottom was placed in

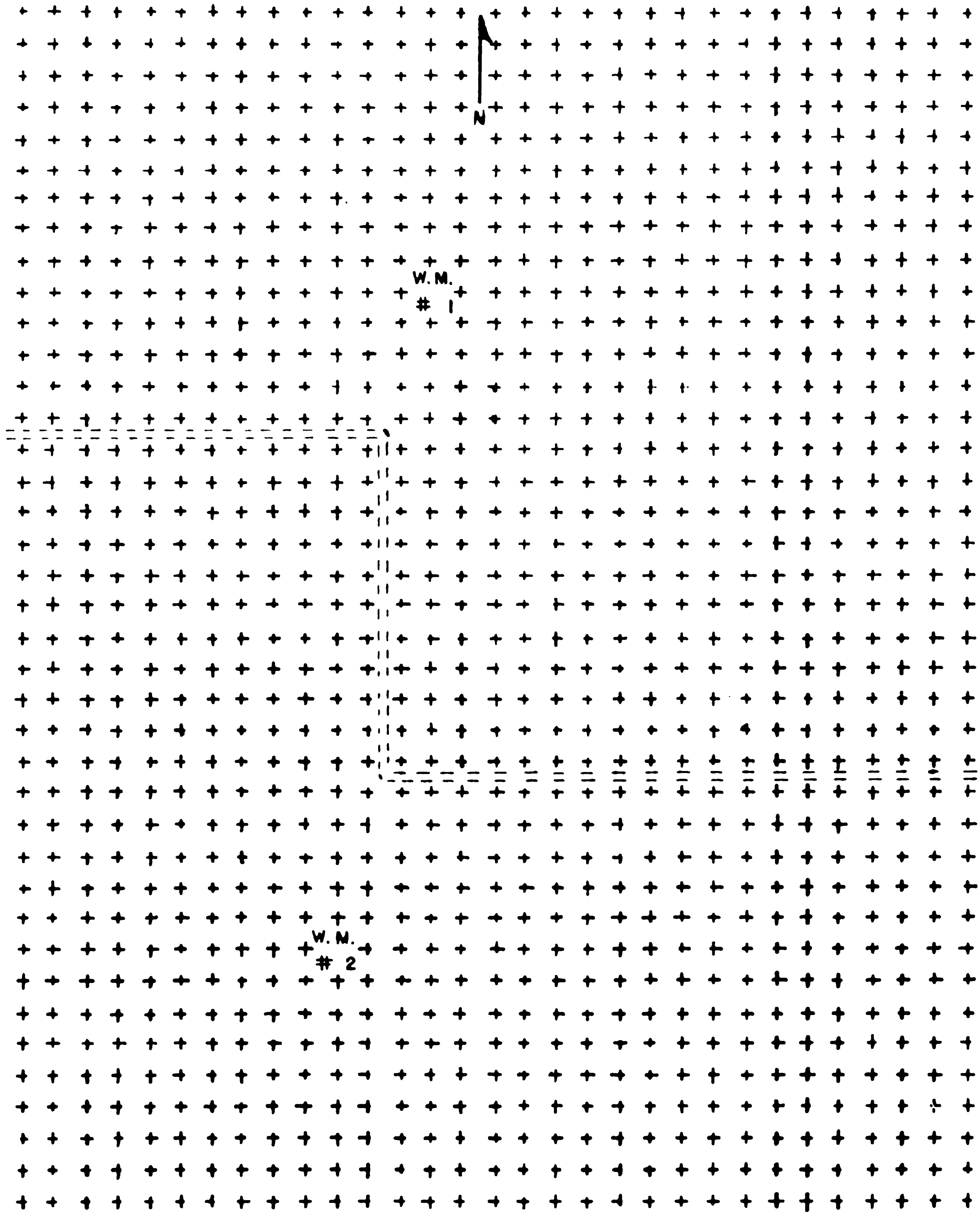

Figure 9. Map showing location of wind machines in Thornhill Orchard. Trees planted on 36 foot centers.

position between the two 4-inch pipes and the bottom pin was inserted. The blades were then bolted to the hub and three 1-inch wire rope guy wires, 60 feet long, were attached by means of cable clamps to a steel ring welded to the top of the pipe, as shown in Figure 10.

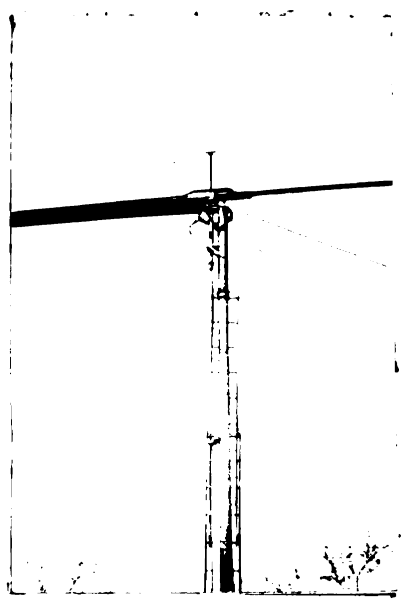

Figure 10. Top of Wind Machine Number Two

One of these guy wires served as a tow line to raise the pipe to a vertical position. The pipe was raised with a Caterpillar "22" tractor. When the pipe was in the proper position, the top pin was inserted through the two 4-inch pipes and the 6-inch, thus securing it in position. The guy wires were then spaced at equal intervals and each attached, through a turnbuckle, to the trunk of an apple tree. The wind machine was brought into an exact vertical position and anchored there by tightening and adjusting the turnbuckles.

The speed reduction unit was then keyed to the end of the drive shaft and bolted to the boiler plate brackets that had been welded to the 6-inch pipe. The power-take-off drive assembly was then fastened to the speed reduction unit, as shown in Figure 11.

Figure 11. Power-take-off drive and speed reduction unit of Wind Machine Number Two

This wind machine was driven by a Case "D" tractor which is shown in Figure 12.

Figure 12. Tractor attached to Wind Machine Number Two

3. Tests Conducted

This machine was first operated for the 1952 season on the night of May 2 when the blossoms were in the pink stage. Complete temperature records were not possible due to the lack of personnel and equipment, but a minimum of 18 degrees Fahrenheit was registered immediately outside the area of the wind machines. Wind Machine Number Two was operated from twelve midnight until six o'clock in the morning with a reported low of 26 degrees Fahrenheit inside the effective area. This indicated a rise of 8 degrees Fahrenheit. Personnel and equipment were not available to measure the temperature

inversion. Orchard heaters had been placed in the orchard during the previous day but had not been filled with oil. The apple blossoms were in the pink stage and considerable damage was reported.

This wind machine was not operated again until the night of May 15 when a low of 26 degrees Fahrenheit was recorded at the check point. Tire fires and orchard heaters were burning, but complete records were not available. At daybreak it was observed that the action of the wind machine had drawn a dense cloud of smoke from the fires and had caused it to accumulate in an area of approximately four acres surrounding the machine.

On the night of May 16 a low of 31 degrees Fahrenheit was recorded at the check point. Complete temperature records of the action of the wind machine were obtained. High cirrus clouds were present during the day but dissipated at sundown. The sky was clear until 4:20 A.M. but became completely overcast by 4:30 A.M. No orchard heaters were lighted; however, tire fires were started at 1:20 A.M. A slight drift from the southwest was recorded.

On the night of May 17 a low of 29 degrees Fahrenheit was recorded at the check point. High cirrus clouds were present during the day but dissipated at sundown. The wind machine was operated, and a complete set of temperature records was obtained. No supplemental heat was added. Near daybreak a dense fog settled over the area west and southwest of the orchard. A light frost formed in the lowest areas of the orchard outside the effective area of the wind machine.

The temperature records for this series of tests were obtained in the same manner as those for Wind Machine Number One except that a 12-point "Brown" recording potentiometer was used instead of an 8-point.

C. Redesigned Evans "Frostguard"

The "Frostguard" is a kerosene burning orchard heater that is manufactured and sold by the Evans Products Company of Plymouth, Michigan, and is shown in Figure 13.

Figure 13. "Frostguard" units in operation

1. Original "Frostguard", Unsatisfactory Features and Improvements Made

The original design work on this heater was performed by the Agricultural Engineering research staff of Michigan State College. The main consideration in the design of this unit was that it would radiate a large portion of its energy to the vegetation in the surrounding area. The unit consists of a rigid tubular steel tripod on top of which is a stainless steel combustion chamber, three feet in diameter. When the unit is in operation, this chamber is heated to a bright red at approximately 1750 degrees Fahrenheit. A 7-foot circular aluminum reflector, located at the top of the unit, directs the infrared rays toward the ground. This unit utilizes a generating type burner, as shown in Figure 14. The fuel is pumped from the ground level and delivered under pressure to the generating coil by a small gear pump. The motor requires 5.6 amperes from a 6-volt storage battery or can be operated on 115 volts a.c.

Figure 14. Redesigned "Frostguard
Burner

The earlier models of this unit had presented some difficulties and undesirable features. These were given further study and changes were made in an attempt to correct them. Difficulties had been experienced with the generating coils in that they would become filled with carbon and fail to operate. This was remedied by changing the coil design and placing the coil higher in the combustion chamber.

The burning off of the legs that supported the generating coil inside the combustion chamber had also been too frequent. This was remedied by placing metal shields on them as indicated in Figure 15.

Figure 15. Protection shields on generator coil support legs

3. Tests Conducted

On September 30, 1952 six of the "Frostguard" units carrying the improved features were installed in the Thornhill Orchard at Beulah, Michigan. These units were spaced at equal intervals on the circumference of a circle of 240-foot

radius from Wind Machine Number Two. If the heat losses from the stack of the "Frostguard" units helped to build up a temperature inversion, this warm air could be recirculated by the action of the wind machine. The 240-foot distance from the wind machine was selected as an initial setting with the belief that this would be beyond the extreme practical spacing for the "Frostguard" units, as shown in Figure 16. The plans called for conducting tests on the operation of the wind machine and the "Frostguard" units operating individually and in conjunction with each other. The "Frostguards" were to be moved 40 feet closer to the center after each night's test until they were 120 feet from the wind machine. Unsuitable weather prevented the conducting of any tests in the Thornhill Orchard other than the 240-foot spacing.

On October 8 and 9 the six "Frostguard" units and Wind Machine Number One were moved to the Michigan State College Horticulture Orchard and spaced, as shown in Figure 17. Tests were conducted on October 17 with the "Frostguards" 165 feet from the wind machine and October 20 at 120 feet. Lateral and vertical temperature readings were taken at one hour intervals. Measurements of the air temperature change were made for the "Frostguard" and wind machine operations independently and in conjunction with each other. The same thermocouple lines were used for these tests as those used in the Thornhill Orchard. These lines were located as shown in Figure 18. Due to inaccuracies in the "Brown" recording

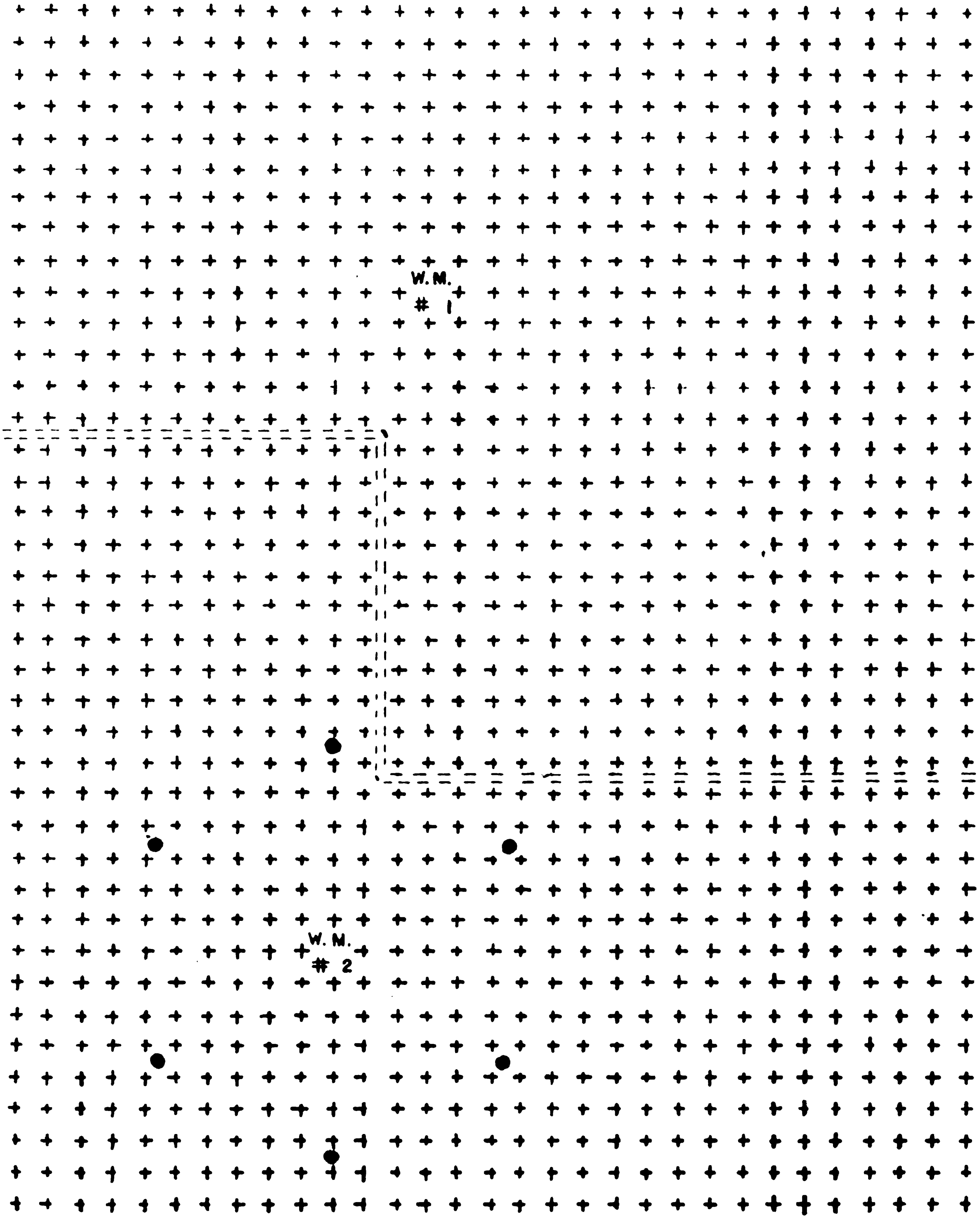

Figure 16. Location of "Frostguards" in Thornhill Orchard. ● indicates "Frostguard."

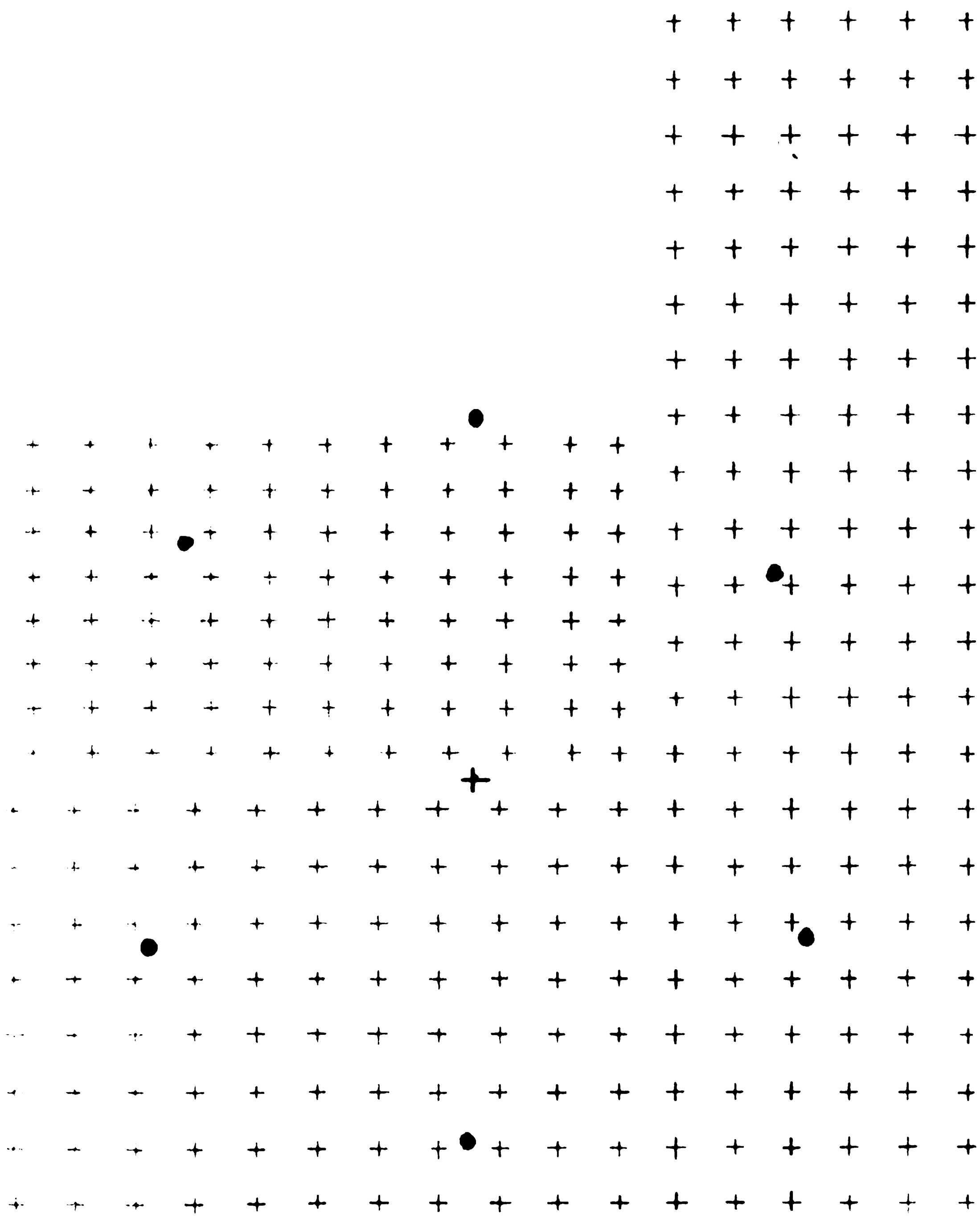

Figure 17. "Frostguards" located 165 feet from wind machine in Michigan State College Orchard. ● indicates "Frostguards."

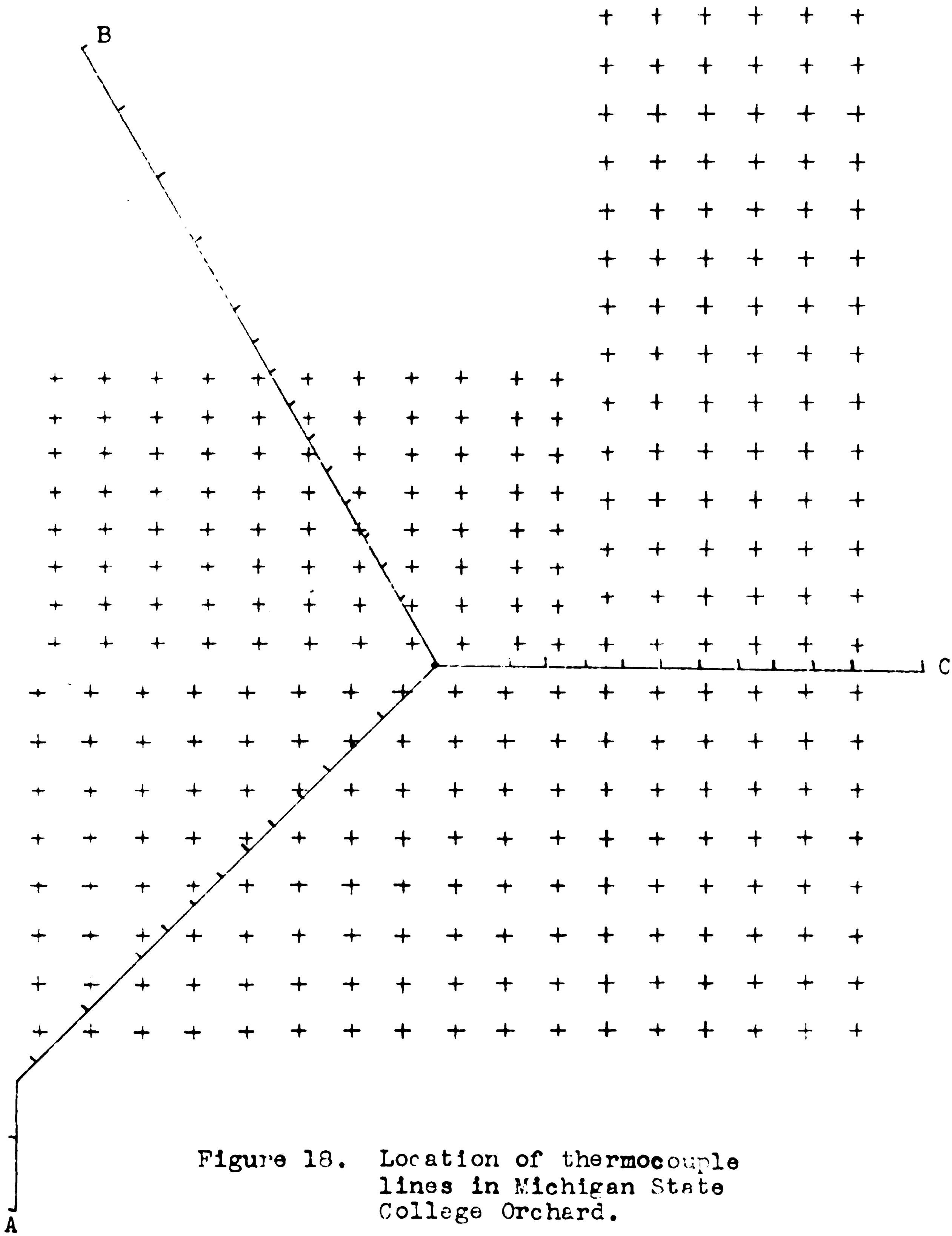

Figure 18. Location of thermocouple lines in Michigan State College Orchard.

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potentiometer at the time of these tests, a Leeds and Northrop potentiometer was used to measure the emf. generated by the thermocouples. Calibrated mercurial thermometers were used to measure the temperature at 20-foot intervals on a chord between two "Frostguards" and on a radius beyond one "Frostguard", as shown in Figure 19. These thermometers and thermocouples were located five feet above the ground. A recording thermometer, which operated continuously, was located outside the area affected by either the "Frostguard" or wind machine. Wind velocity records covering the period of both tests were obtained from the East Lansing office of the United States Weather Bureau.

In addition to the temperature records, data were obtained on each "Frostguard" unit as to burning time, fuel consumption and difficulties encountered.

Differential level lines were run for each of the three thermocouple lines in order to obtain the difference in elevation between the points of temperature measurement, as shown in Figure 20.

D. Studies to Determine the Practicability of the Propane Burner

Preliminary investigations on the development of a liquified petroleum gas burner for the generation of radiant energy for frost control have shown that this type of heat source is applicable to certain situations. The high flame temperature, clean burning characteristics and ease with which

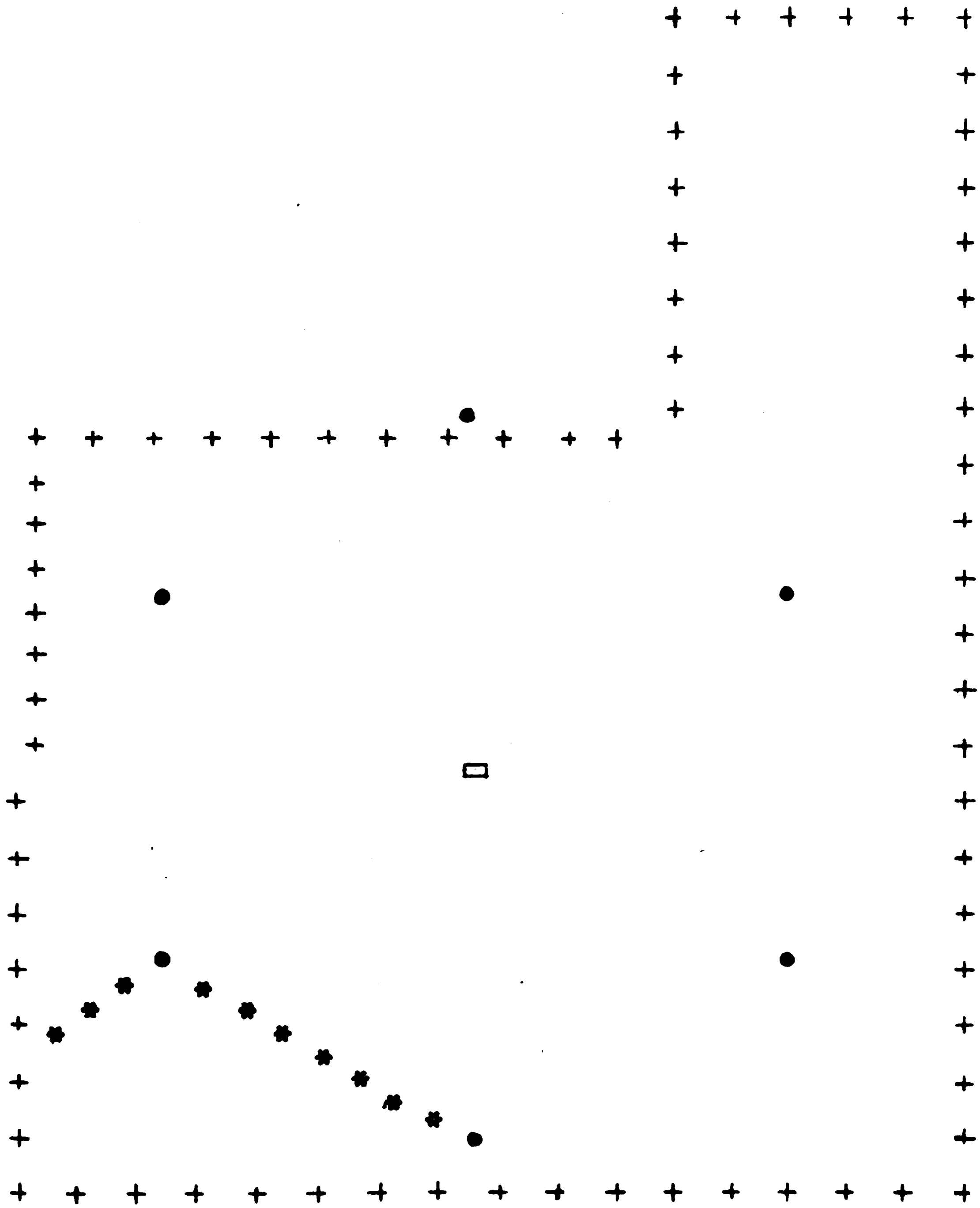

Figure 19. Location of mercurial thermometers, Michigan State College Orchard, October 17, 1952.

• indicates "Frostguards"
* indicates thermometers
▭ indicates wind machine

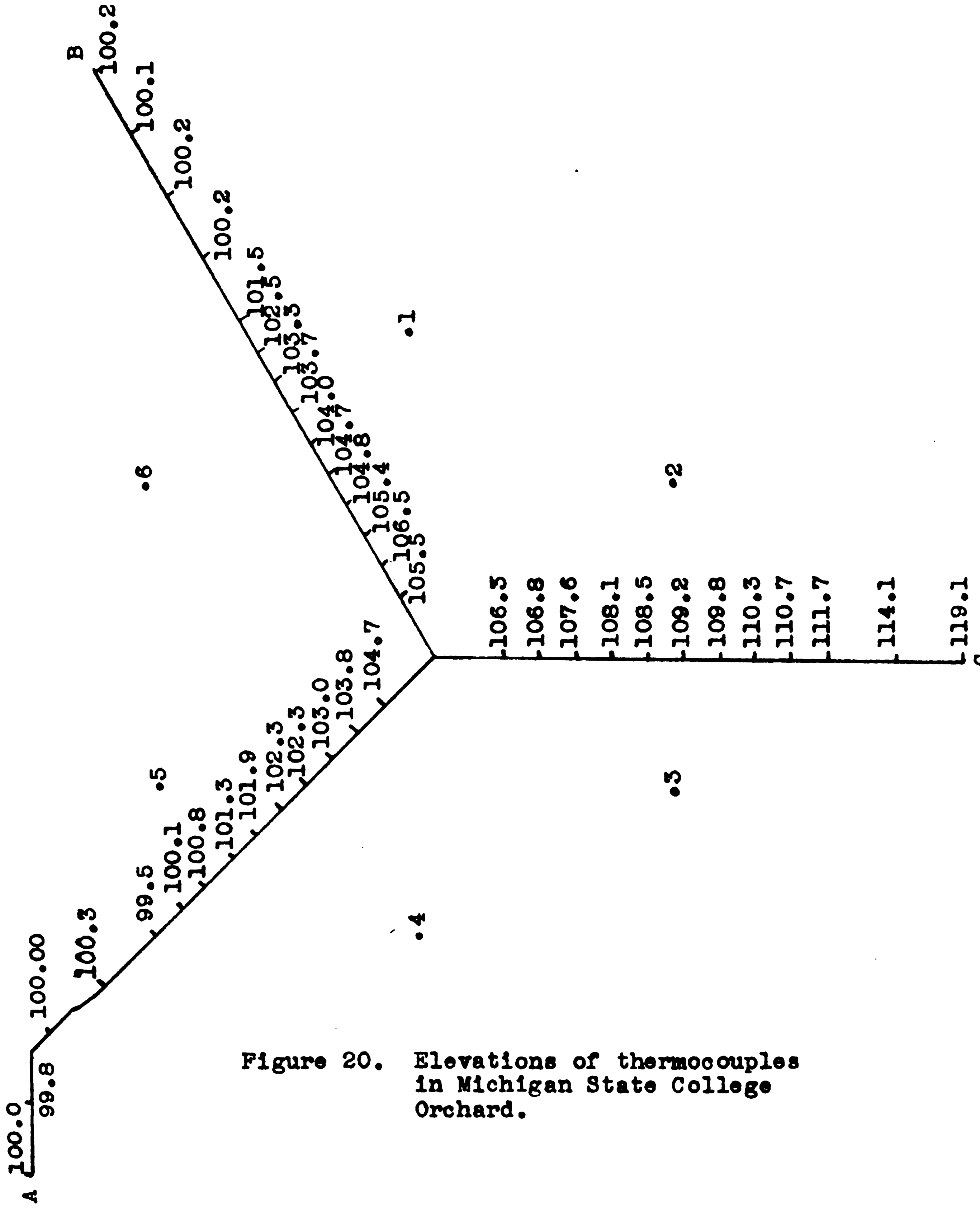

Figure 20. Elevations of thermocouples in Michigan State College Orchard.

it combines with air make the liquified petroleum gas (LPG) an ideal fuel for frost prevention measures. At the present time the cost of the fuel is the largest limiting factor. This cost varies considerably with the amount of fuel used per year, which is indicated in Table IV.

Table IV

VARIATION OF THE COST OF PROPANE
WITH VOLUME USED PER YEAR

Amount (Pound Tanks Per Season)	Cost (Per Pound)
2 - 100	$ .10
3- 5 - 100	.09
5-11 - 100	.07
11-18 - 100	.065

Field tests conducted on the propane heater, shown in Figure 21, were conducted by members of the Agricultural Engineering research staff at Michigan State College in the fall of 1951. With four burners operating on an area of 6,400 square feet, it was possible to increase the air temperature from 31 degrees Fahrenheit to 39 degrees Fahrenheit, representing an 8-degree Fahrenheit rise.

The units were used in a dahlia plot and caused no damage to the foliage in bloom in direct line of radiation from the burner. Check plants of similar varieties outside the protected area were completely destroyed by frost damage. Each of the heater units used in this test burned about 38 pounds

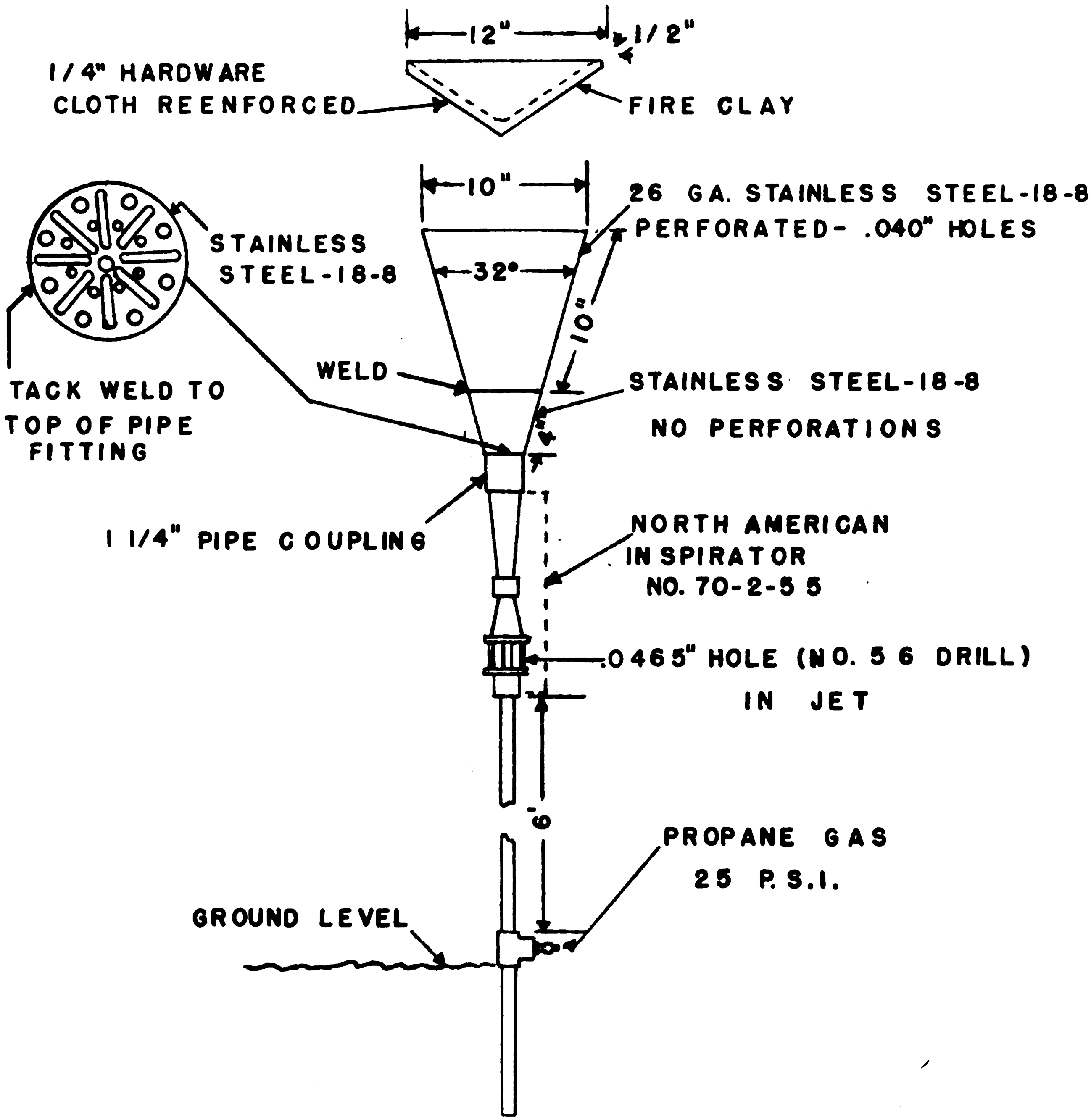

Figure 21. Experimental propane heater.

of fuel in 8½ hours at a cost of from $2.40 to $4.00 depending upon the quantities used per year (36).

It has been proven that this burner has definite possibilities as a frost prevention unit; however, additional experimental work will be necessary before it is entirely satisfactory.

During the summer of 1952 heat balance studies of this unit were made in the Agricultural Engineering research laboratory. The results of these studies are included in the section entitled "Results."

RESULTS

A. Wind Machine Number One

1. Without Added Heat - Thornhill

Wind Machine Number One was operated on May 6, 1952 in Thornhill Orchards. The machine was started at 11:04 P.M. when the air temperature was between 29 and 30 degrees Fahrenheit, as indicated in Table V. Figure 22 shows the temperature rise and the area affected by the wind machine alone at 11:40 P.M. This shows a rise of 3.5 degrees Fahrenheit over an area of 0.60 acre surrounding the wind machine. No temperature rise was indicated beyond a line enclosing 1.26 acres surrounding the wind machine. The egg shaped pattern of the area within which the temperature was increased was caused by a slight southwest air drift. The curves in Figure 23 show that the temperature inversion up to an elevation of 300 feet was 11 degrees Fahrenheit at 10:30 P.M. Ten degrees of this inversion occurred in the first 80 feet above the ground.

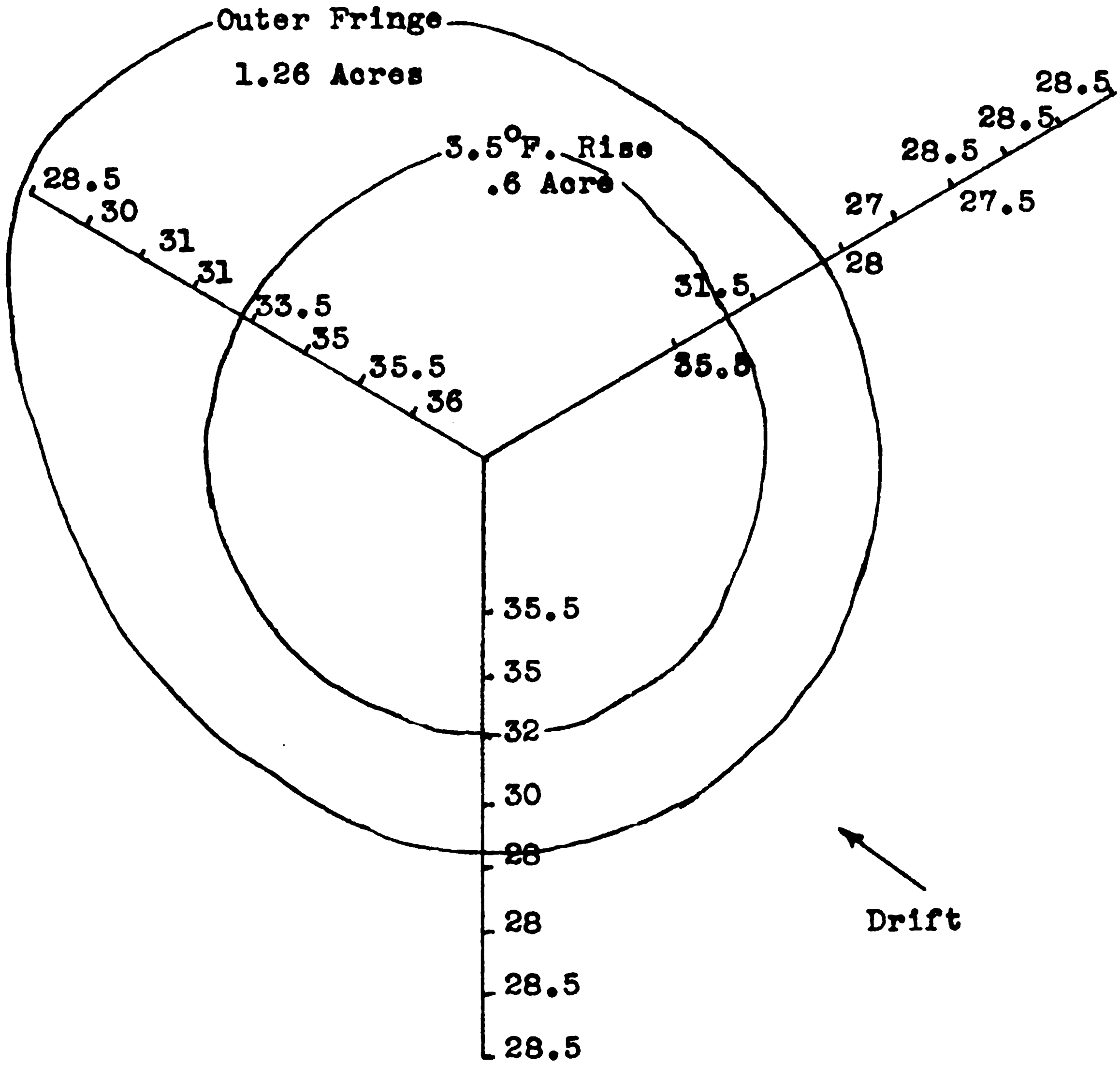

Figure 22. Temperature rise and area affected by Wind Machine Number One at 11:40 P.M., May 6, 1952.

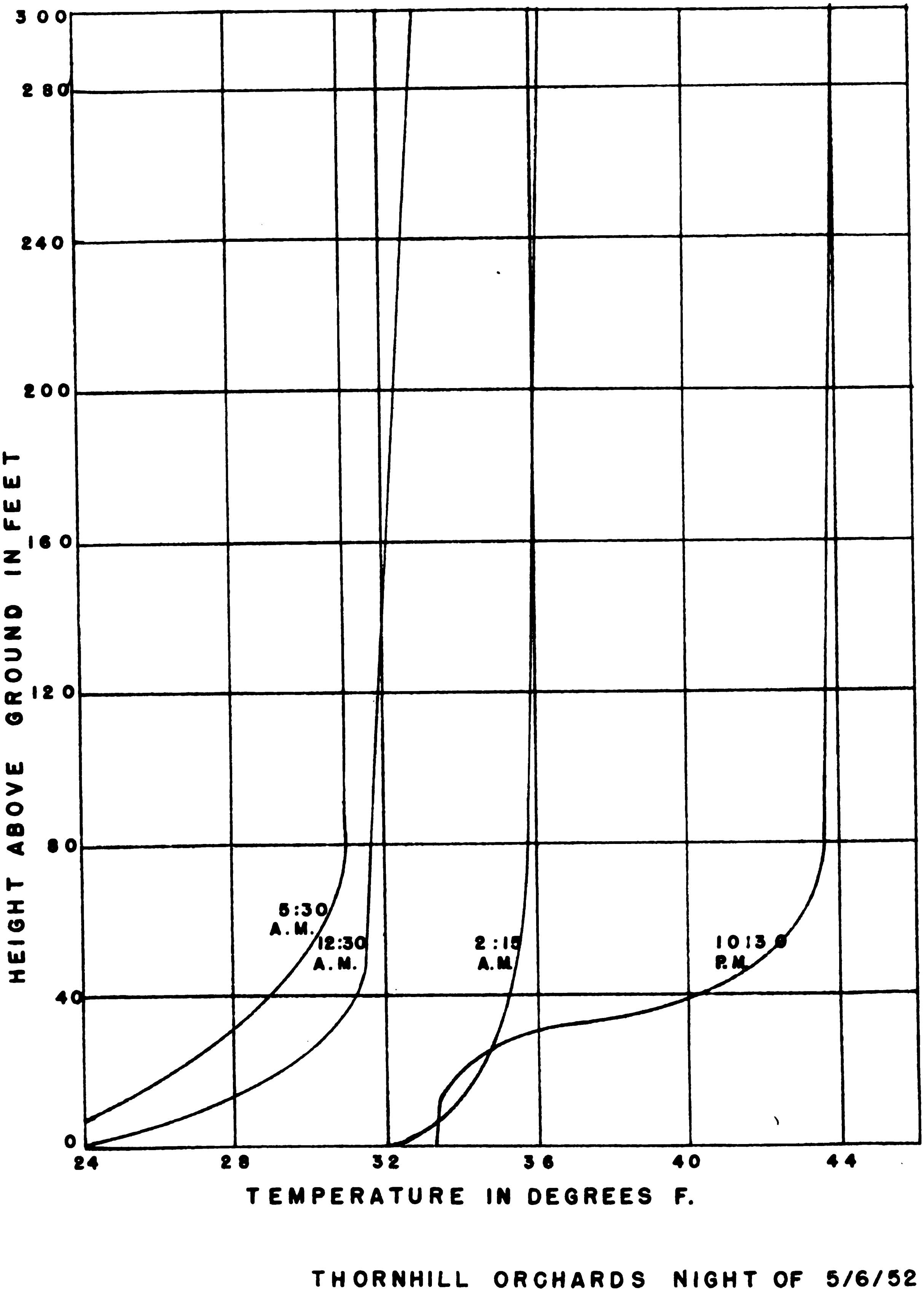

Figure 23. Inversion curves for Thornhill Orchard, May 6, 7, 1952.

Table V

AVERAGE OF THE TEMPERATURES MEASURED BY THE THREE LATERAL THERMOCOUPLE LINES IN THORNHILL ORCHARD, MAY 6, 1952 9:50 P.M. TO 11:04 P.M. INCLUSIVE

Time (P.M.)	Thermocouple Line A	B	C
9:50		31°F.	
9:55			32°F.
10:05	31.5°F.		
10:10		30.5	
10:20			31
10:25	30.5		
10:30		29.5	
10:40			30
10:45	29.5		
10:50		29.0	
10:55			30
11:04	29.5	Wind machine started	

2. With Small Orchard Heaters - Thornhill

By 2:15 A.M. on May 6 the inversion was only 4 degrees Fahrenheit, as indicated by the curve in Figure 23. Beginning at 4:00 A.M., 34 orchard heaters per acre were fired. At 5:30 A.M. the temperature inversion was 8 degrees Fahrenheit. Figure 24 shows the combined effect of the wind machine and 34 heaters per acre. The temperature measurements at this time showed a rise of 3.5 degrees Fahrenheit over an area of 0.81 acre. No temperature rise was indicated beyond a line enclosing two acres surrounding the wind machine.

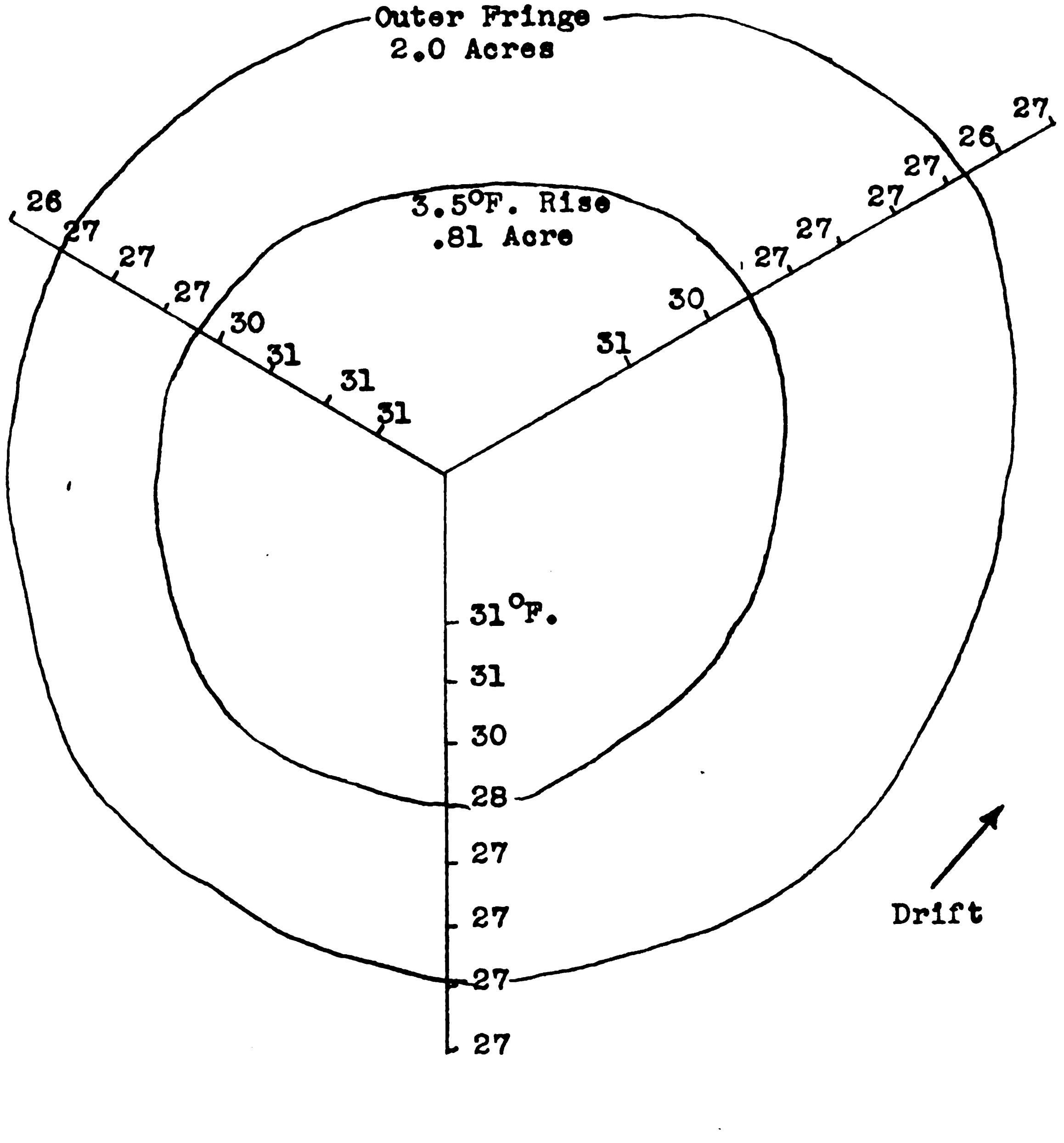

Figure 24. Combined effect of Wind Machine Number One and 34 orchard heaters per acre, Thornhill Orchard.

B. Wind Machine Number Two

1. Without Added Heat - Thornhill

High cirrus clouds were present during the afternoon of May 16, 1952, but they dissipated at sundown. At 9:00 P.M. the temperature inversion, up to 300 feet, was 10 degrees Fahrenheit. At 9:10 P.M. the average air temperature five feet above the ground was 39 degrees Fahrenheit. At 11:30 P.M. the inversion was still 10 degrees Fahrenheit. At 11:40 P.M. the average air temperature five feet above the ground was 37 degrees Fahrenheit, and at 12:40 A.M. the air temperature had fallen to 31 degrees Fahrenheit. Wind Machine Number Two was started at 12:45 A.M. At 12:55 A.M. the temperature had increased six degrees over an area with a radius of 140 feet from the wind machine or approximately 1.4 acres. The minimum temperature at the check point, outside the area affected by the wind machine, was 31.0 degrees Fahrenheit. The wind machine operation was discontinued at 4:30 A.M.

High cirrus clouds that dissipated at sundown were present during the day of May 17. The "Brown" recording potentiometer was operated on the vertical thermocouple line continuously from 9:30 P.M. until 1:30 A.M. and intermittently thereafter until 5:15 A.M. on May 18. The curves shown in Figure 25 were plotted from these data and show the relationship between temperature, height above the ground, and time.

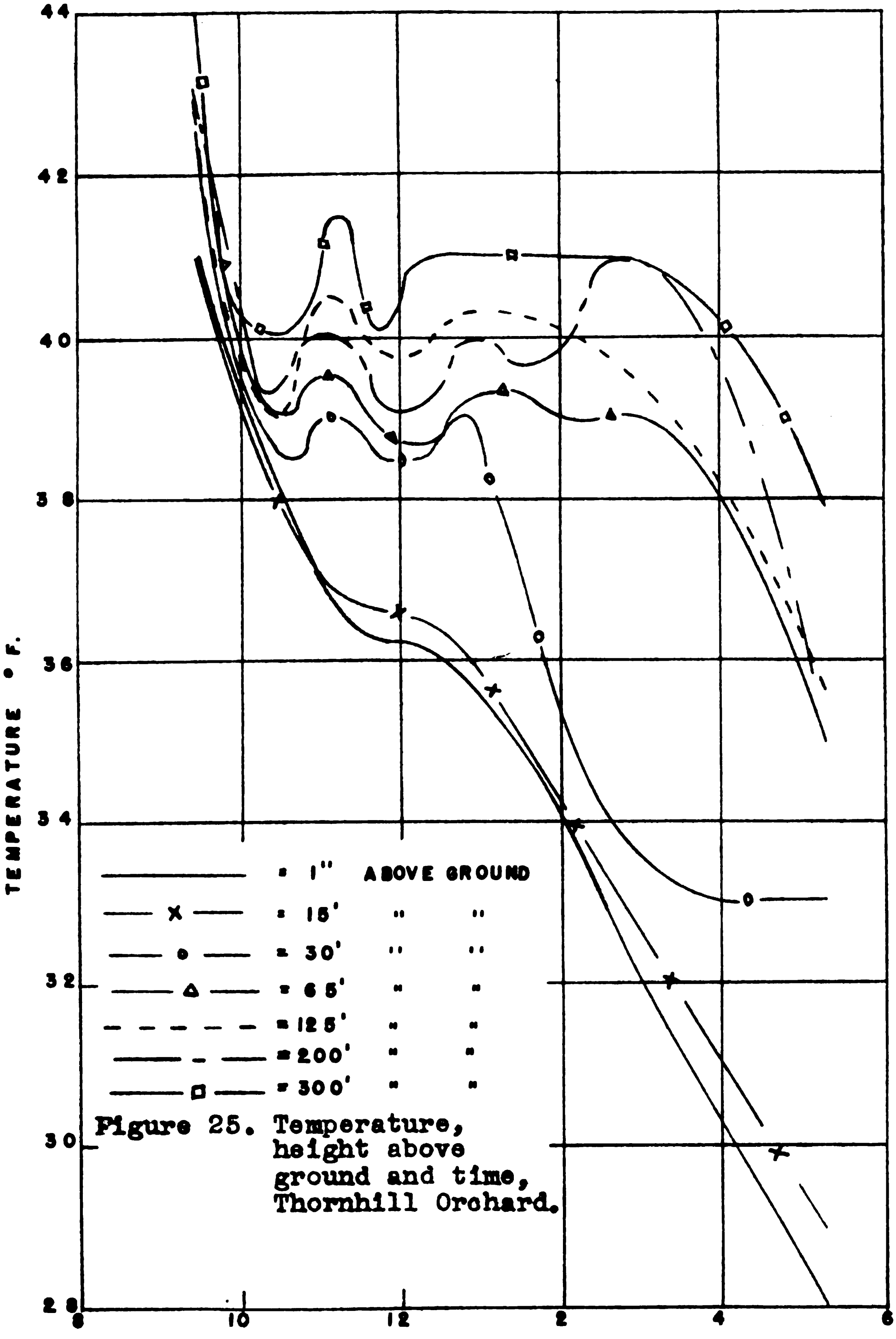

Figure 25. Temperature, height above ground and time, Thornhill Orchard.

Wind Machine Number Two was started at 2:00 A.M. on May 17. At that time the lateral thermocouples indicated an average temperature of 33.5 degrees Fahrenheit. At 2:05 A.M. the temperature had increased 4 degrees Fahrenheit over an area having a radius of 160 feet from the wind machine or approximately 1.9 acres. The wind machine was turned off at 3:00 A.M.

At 5:18 A.M. the inversion was 10 degrees Fahrenheit with an average lateral temperature of 31.5 degrees Fahrenheit. The wind machine was started at 5:18 A.M. and at 5:24 A.M. the temperature had risen to 37 degrees Fahrenheit over an area having a radius of 140 feet or approximately 1.4 acres. The temperature did not fall below 32 degrees Fahrenheit over an area having a radius of between 140 feet and 220 feet from the wind machine.

2. With "Frostguard" Units - Thornhill

On the night of September 29, 1952 Wind Machine Number Two was operated at Thornhill Orchard in conjunction with three "Frostguard" units at the spacings shown in Figure 16. The "Frostguards" were started at 11:30 P.M. The thermocouple lines extended far enough beyond the "Frostguards" so that it was possible to measure the air temperature in the area unaffected by the "Frostguards". At 2:10 A.M. the lateral thermocouple measurements were as shown in Table VI. The temperature inversion at this time was 20.3 degrees Fahrenheit up to 300 feet.

Table VI

AIR TEMPERATURE MEASUREMENTS IN THORNHILL ORCHARD
WITH THE "FROSTGUARDS" OPERATING
2:10 A.M., SEPTEMBER 30, 1952

Distance from Wind Machine (Feet)	Average of Three Thermocouple Readings (Degrees Fahrenheit)
40	34.0
60	34.8
80	33.6
100	33.6
120	34.0
140	32.3
160	33.5
180	33.6
200	33.3
220	33.6
260	33.8
300	33.9
340	34.0
380	34.6

Wind Machine Number Two was started at 2:30 A.M. At 3:00 A.M. the lateral thermocouple measurements were as shown in Table VII. The temperature inversion at this time was 12.2 degrees Fahrenheit up to 300 feet.

The thermocouple lines extended from the wind machine radially between the "Frostguards", as shown in Figure 26. The leaves were still on the apple trees and shielded the thermocouples from the radiation from the "Frostguards." No attempt was made to measure the radiation pattern from the "Frostguard" units in this location.

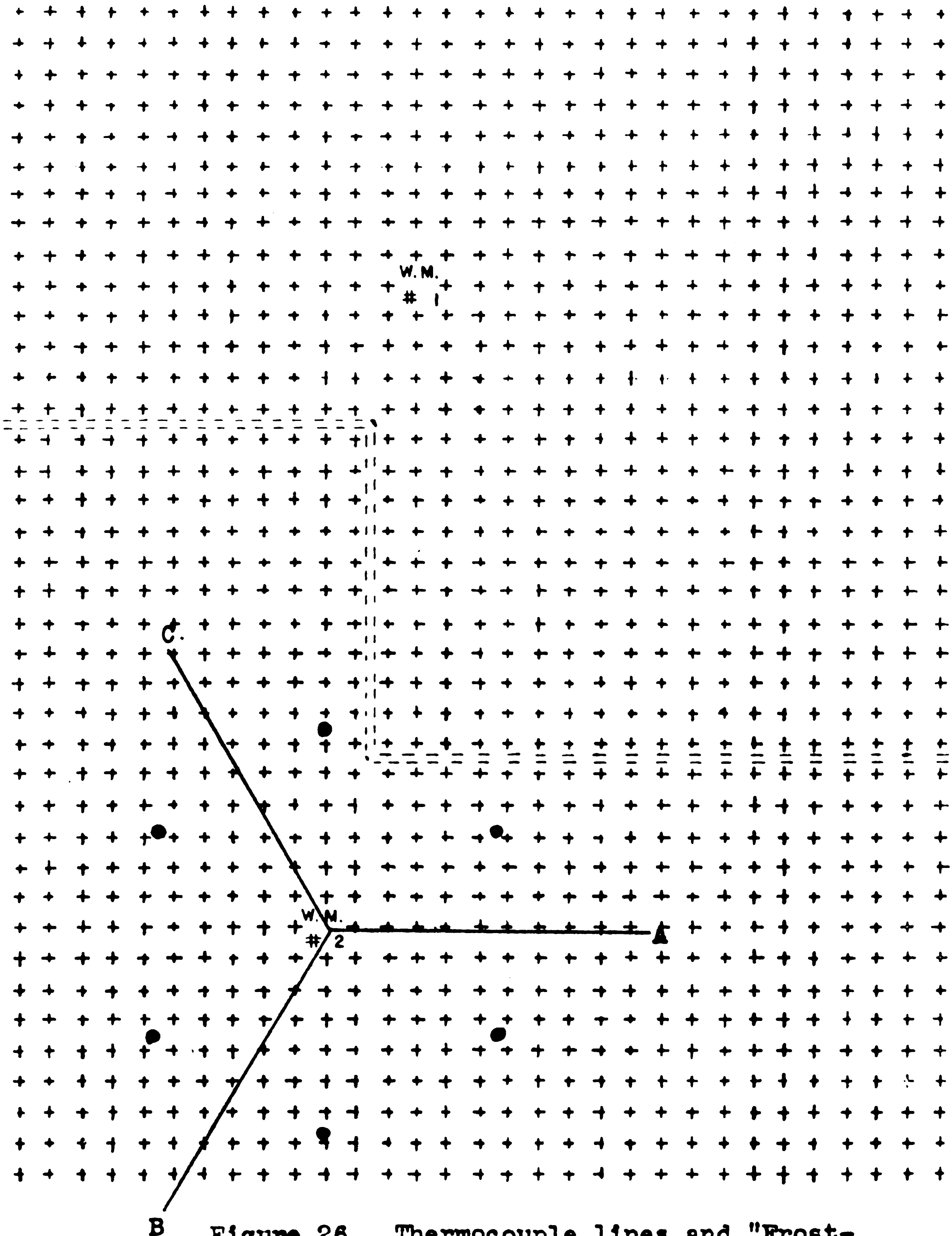

Figure 26. Thermocouple lines and "Frost-guards" - Thornhill Orchard.
● indicates "Frostguard"
A, B, C indicate Thermocouple lines

Table VII

AIR TEMPERATURE MEASUREMENTS IN THORNHILL ORCHARD WITH THE "FROSTGUARDS" AND WIND MACHINE OPERATING
3:00 A.M., SEPTEMBER 30, 1952

Distance from Wind Machine (Feet)	Average of Three Thermocouple Readings (Degrees Fahrenheit)
40	38.4
60	38.1
80	37.4
100	36.6
120	34.4
140	33.0
160	33.2
180	32.7
200	33.2
220	32.7
260	32.5
300	33.0
340	32.7
380	32.7

The temperatures given in Table VII show the effect of the wind machine when operated in conjunction with the "Frostguard" units.

The differences in the amount of temperature inversion before and after the wind machine was started were due to an increase in the temperature at the ground level. The vertical thermocouple line was anchored within the effective area of the wind machine.

C. Yield and Frost Occurrence - 30-Acre Portion of Thornhill Apple Orchard, 1947-1952

Table VIII shows the yield and number of killing frosts that occurred in a 30-acre portion of Thornhill Orchard from 1947 to 1951. This information was furnished by Wright Stone and Sons, owners of the orchard.

Table VIII

YIELD AND FROST OCCURRENCE IN A 30-ACRE PORTION OF THORNHILL ORCHARD, 1947 - 1951

Year	Bushels Produced	Number of Killing Frosts	Comments
1947	8000	0	No damaging frosts
1948	2100	4	First attempt to save the crop by the use of 400 orchard heaters
1949	0	6	A partial crop until June 8 when an unexpected freeze occurred that killed the fruit
1950	7000	2	Operational plan furnished by Agricultural Engineering Department, Michigan State College. Map made to show location of burners
1951	5000	4	Wind machine used with burners and tire fires. Temperature measurements were made by use of thermo-couples

Figure 27 shows the yield from a portion of Thornhill Apple Orchard for 1952. Every tree was not checked for yield because this would have required extra labor at picking time. The selective picking method which was used would have made this more difficult. The numbers at the left of the

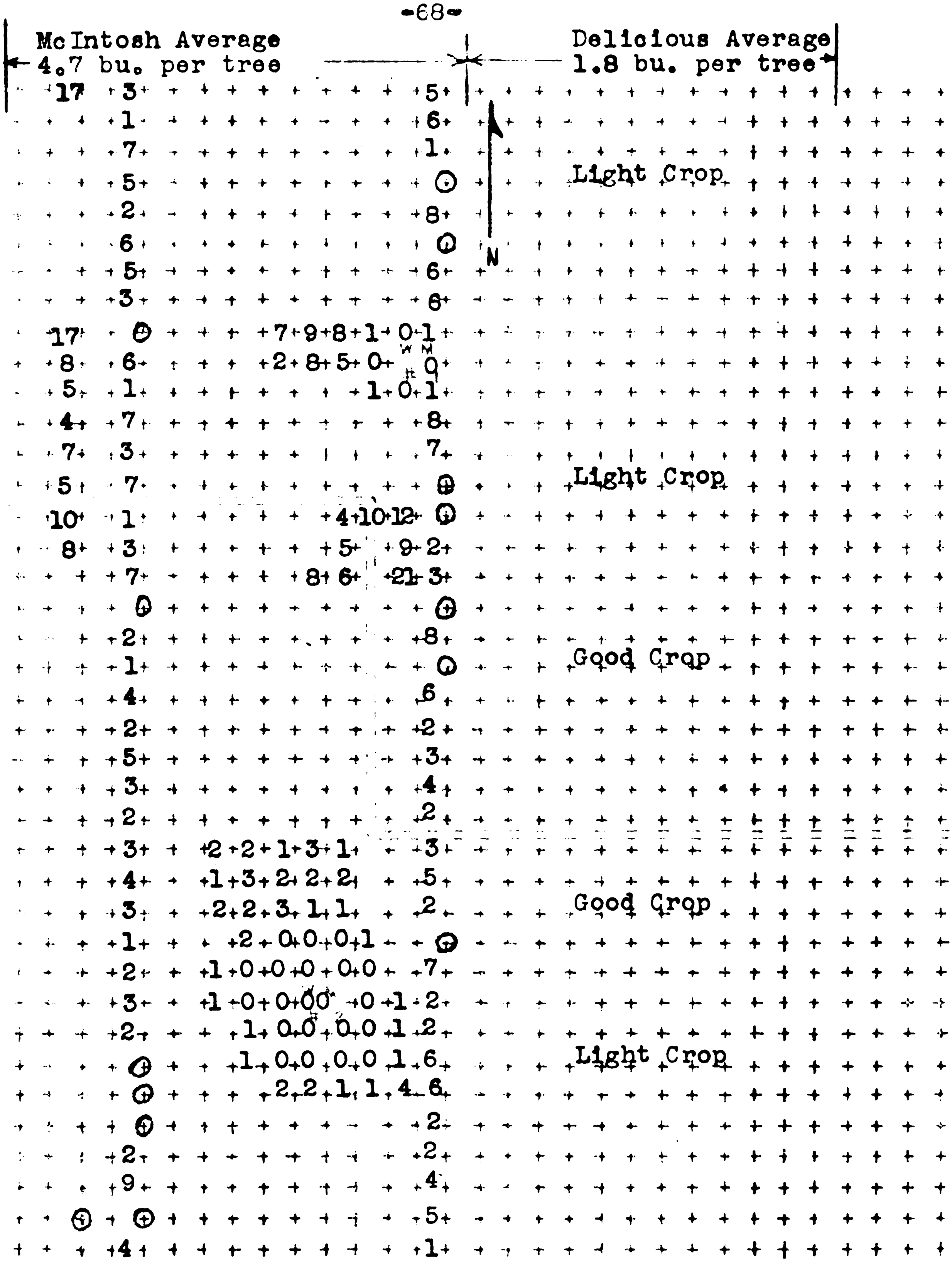

Figure 27. 1952 yield from a 30-acre portion of Thornhill Apple Orchard. Number at the left of tree cross shows yield in bushels. 0 indicates missing trees.

tree crosses in Figure 27 show the yield in bushels which ranged from 0 to 21 bushels per tree. The average McIntosh yield was 4.7 bushels per tree, and the average Delicious yield was 1.8 bushels per tree. Several factors contributed to this wide variation in the yield. Considerable damage to the 1952 crop was attributed to a hard freeze in November, 1951. The trees adjacent to both wind machines bore no fruit because the blossoms were frozen during the night of May 2. The wind machines were not started until the temperature was 26 degrees Fahrenheit. This temperature was maintained within the effective area, although the minimum temperature recorded at the check point outside the area was 18 degrees Fahrenheit. Observations made the next day indicated more frost damage to the trees surrounding the wind machines than those beyond the effective area. This observation was borne out by the absence of fruit on trees adjacent to the wind machine at picking time. This indicated that the 18-degree Fahrenheit temperature without the air movement caused less blossom damage than the 26-degree Fahrenheit temperature and movement from the wind machines. Apparently the air movement had a tendency to break down the air film thermal barrier surrounding the blossoms. The apple crop was further diminished by the June drop.

D. Wind Machine Number One and "Frostguard" Units
Michigan State College Orchard

Figure 28 shows the lateral air temperatures in the Michigan State College Orchard on October 17, 1952. These temperatures were measured at the time indicated in the figure and before either wind machine or the "Frostguards" were started. Table IX gives the time during which the "Frostguards" were operated and the fuel consumption of each.

Table IX

TIME DURING WHICH "FROSTGUARDS" WERE OPERATED, CUMULATIVE OPERATING TIME AND KEROSENE CONSUMPTION IN MICHIGAN STATE COLLEGE ORCHARD, OCTOBER 17, 18, 1952

"Frostguard" Number	Start (P.M.)	Stop (A.M.)	Time Operated	Kerosene Consumption (Gallons)
1	8:55	4:00	7 hrs. 5 min.	105
2	9:05	4:30	7 25	110
*3	9:12	4:35	6 38	90
4	9:20	4:55	7 35	103
5	9:27	4:35	7 8	100
6	9:33	4:40	7 7	102

* "Frostguard" Number Three was not burning from 12:20 A.M. to 1:05 A.M.

Figure 29 shows the lateral air temperature at the times indicated for each thermocouple line. The six "Frostguard" units were operating; the wind machine had not yet been started.

Figure 30 shows the maximum and minimum lateral temperatures measured on the night of October 17 between

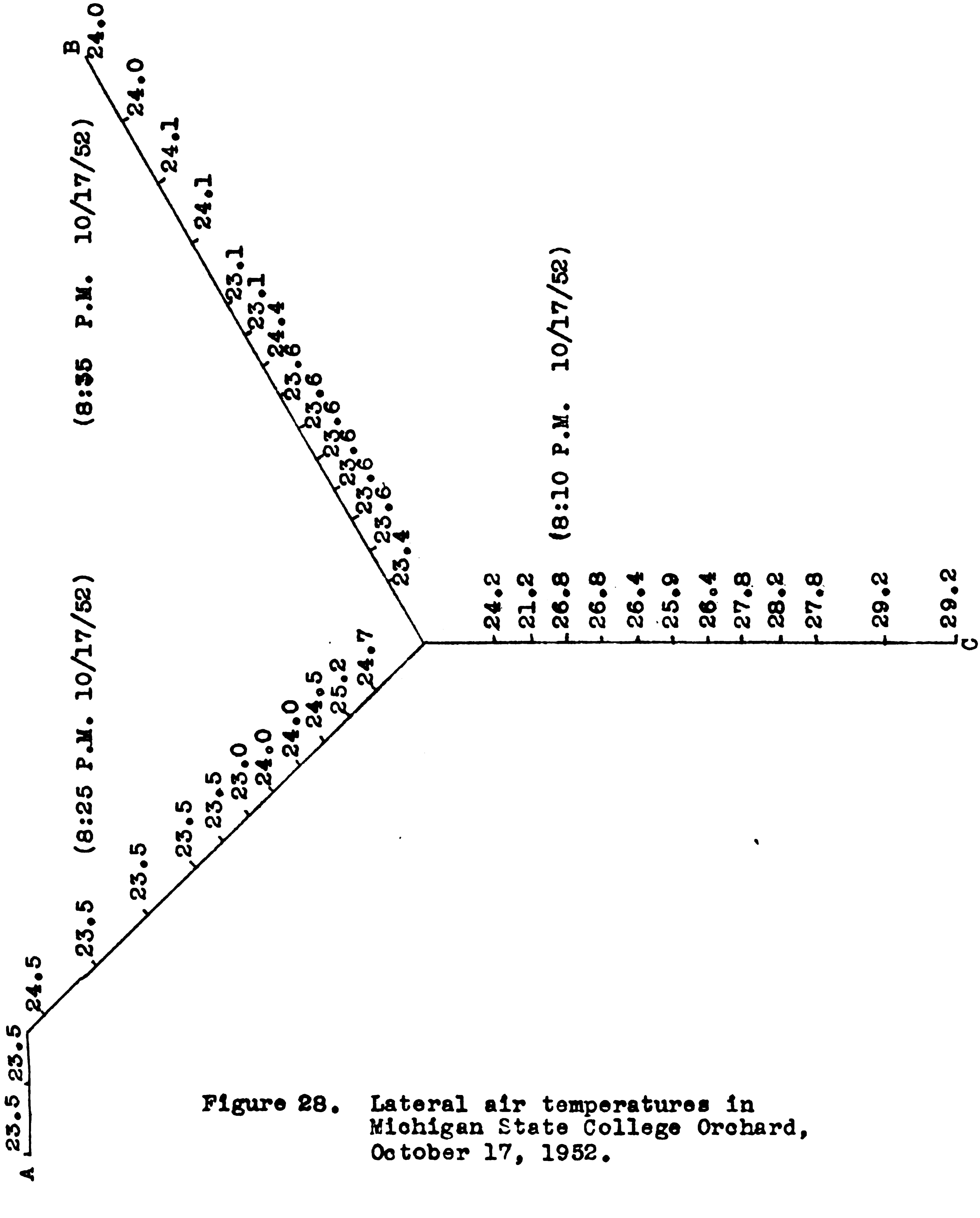

Figure 28. Lateral air temperatures in Michigan State College Orchard, October 17, 1952.

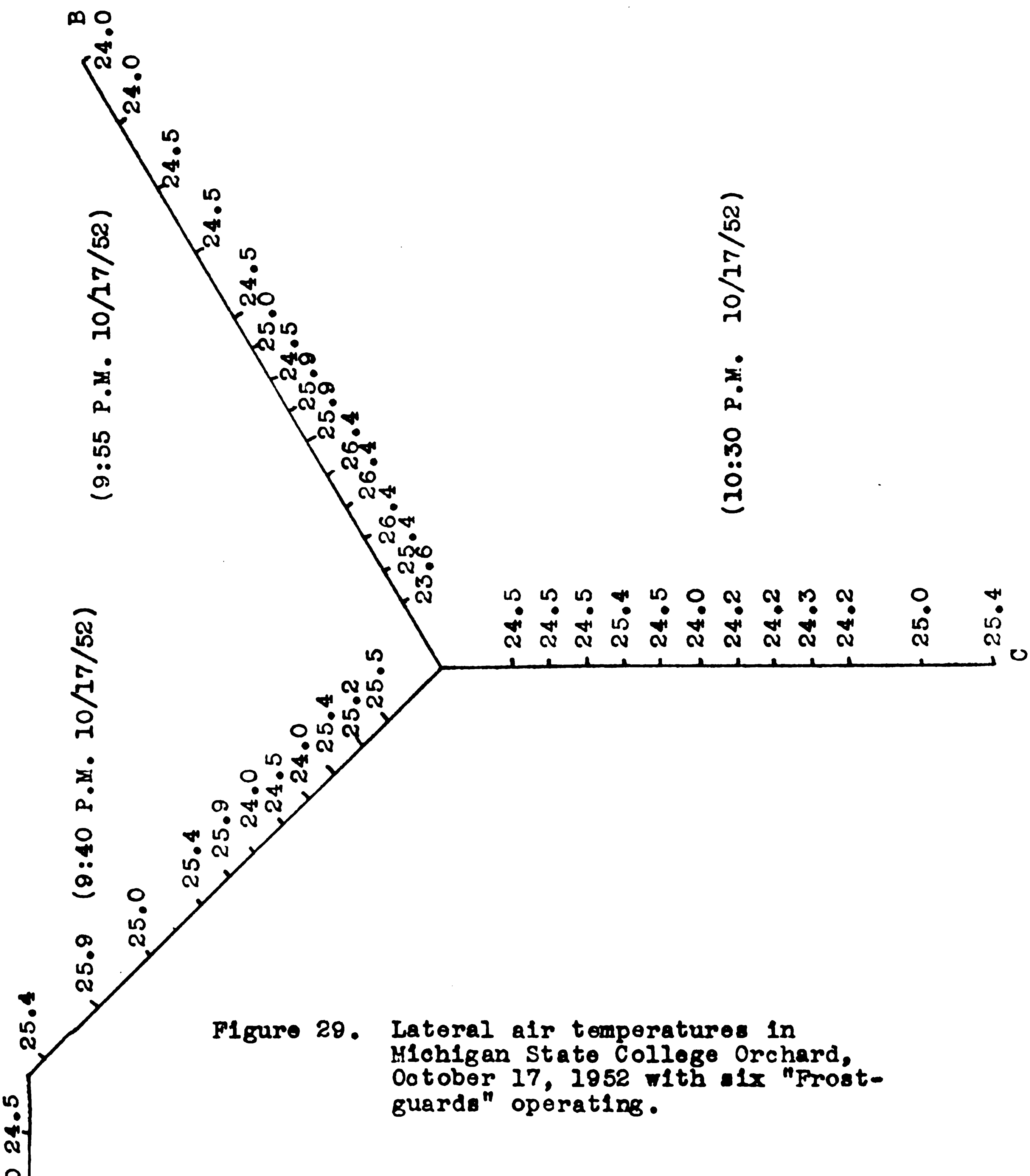

Figure 29. Lateral air temperatures in Michigan State College Orchard, October 17, 1952 with six "Frost-guards" operating.

8:50 P.M. and 4:40 A.M. The wind machine and six "Frostguards" were operating during this time.

Figure 31 shows the lateral temperatures measured at the hour indicated. The wind machine and "Frostguards" were operating at this time. Temperatures read from the mercurial thermometers were also indicated in Figure 31.

The curves in Figures 32, 33 and 34 show a more complete record of the temperatures between "Frostguards" Number Four and Five. These curves indicate that no effect of the wind machine could be measured at this distance.

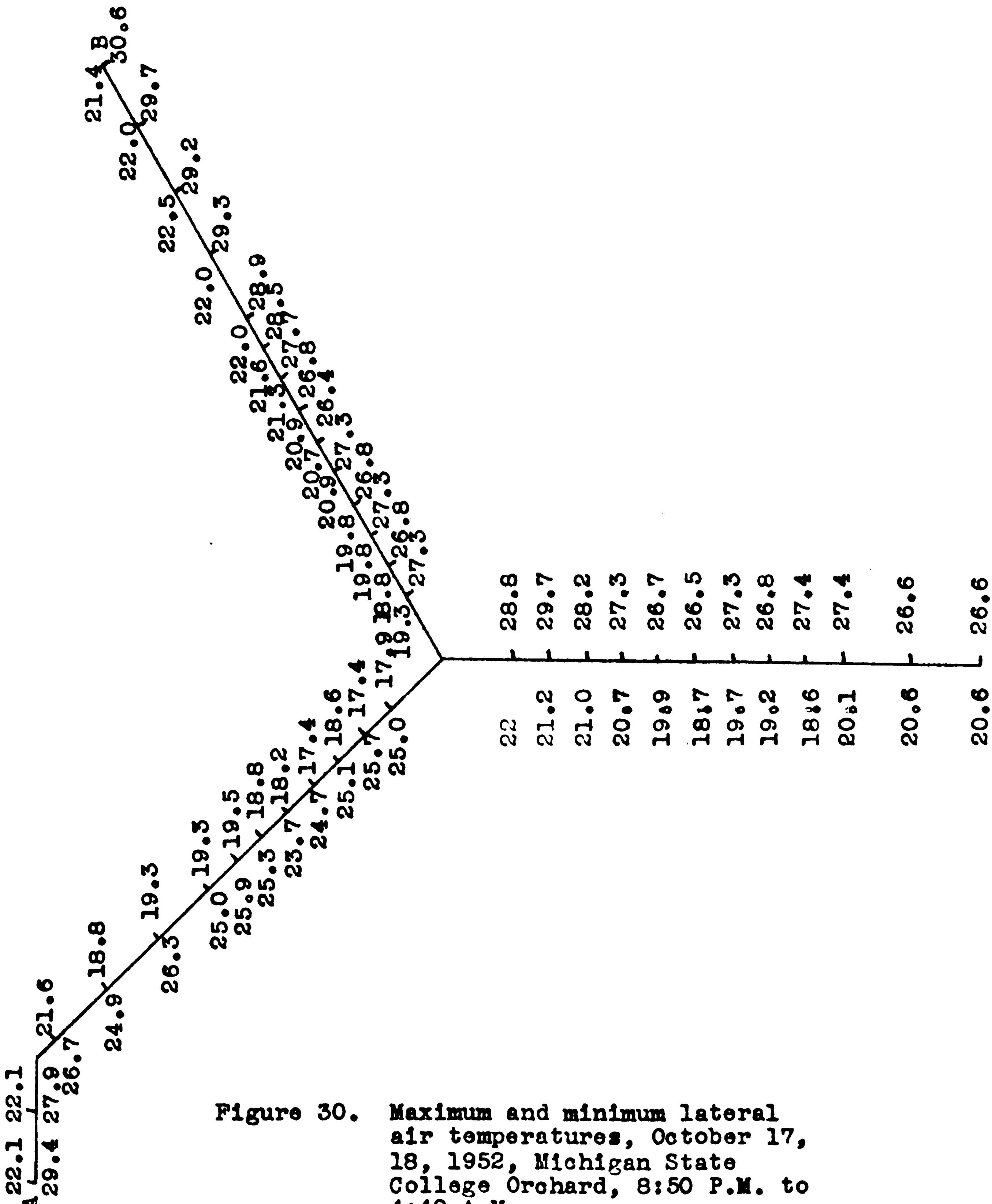

Figure 30. Maximum and minimum lateral air temperatures, October 17, 18, 1952, Michigan State College Orchard, 8:50 P.M. to 4:40 A.M.

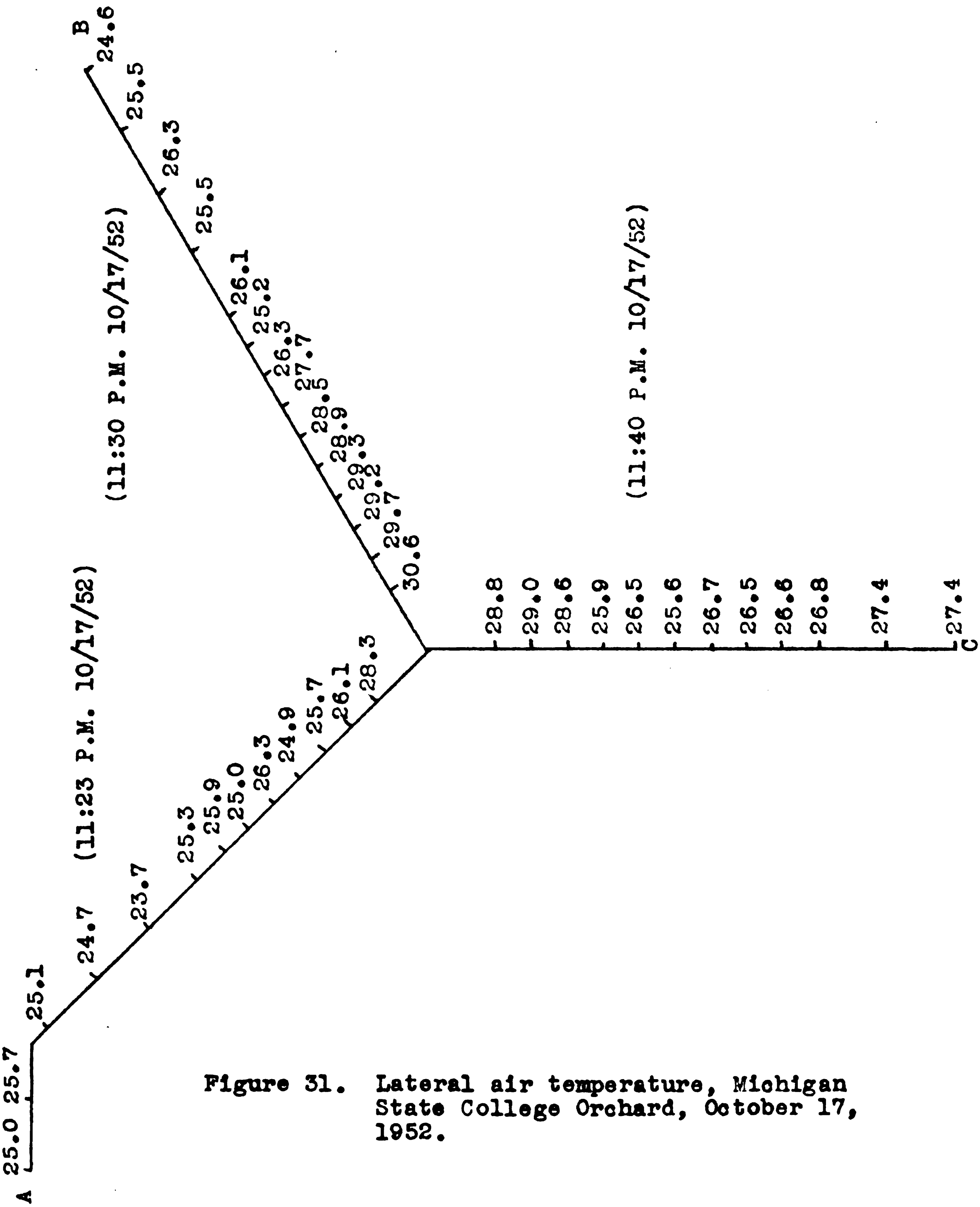

Figure 31. Lateral air temperature, Michigan State College Orchard, October 17, 1952.

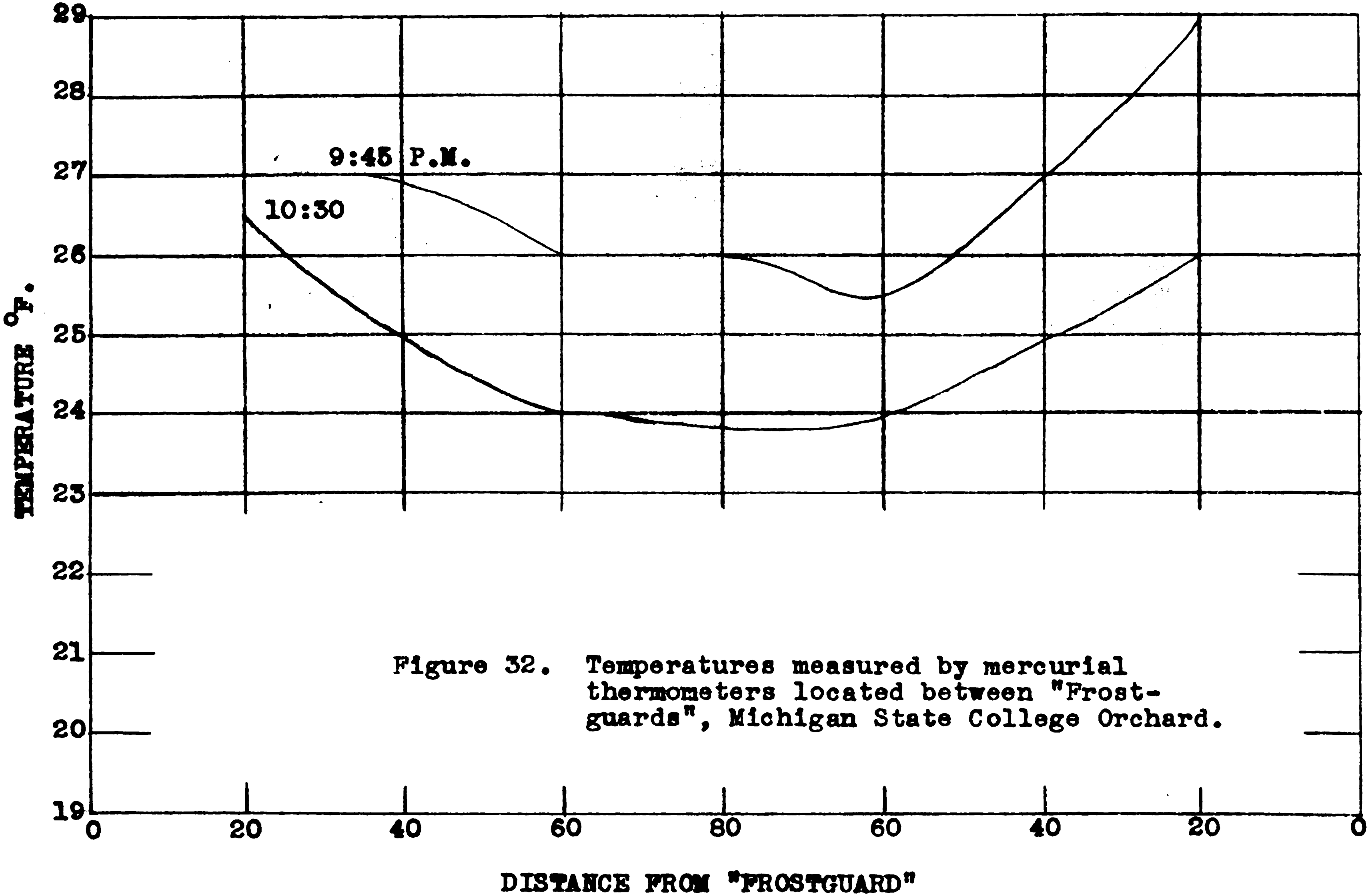

Figure 32. Temperatures measured by mercurial thermometers located between "Frost-guards", Michigan State College Orchard.

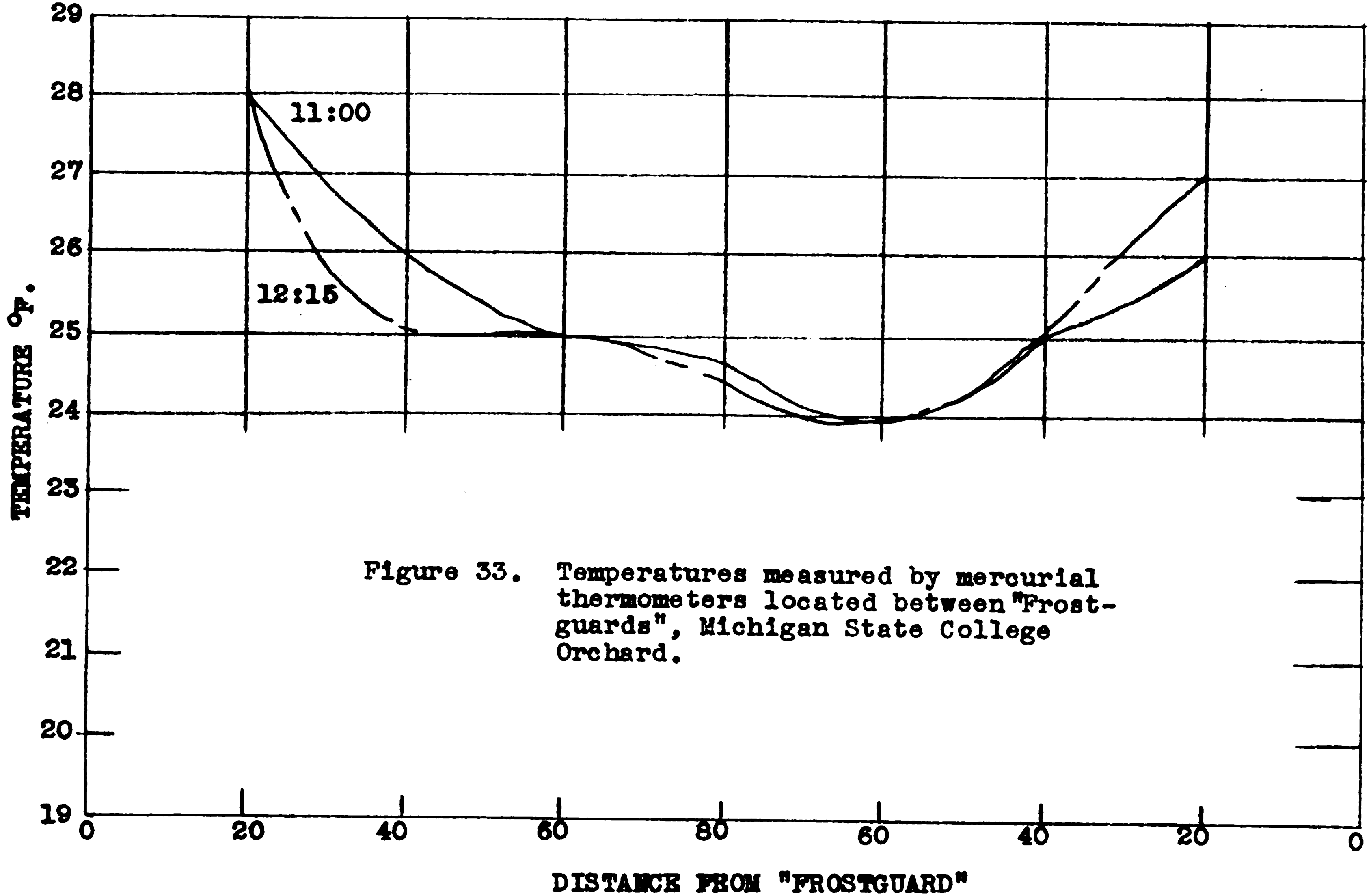

Figure 33. Temperatures measured by mercurial thermometers located between "Frostguards", Michigan State College Orchard.

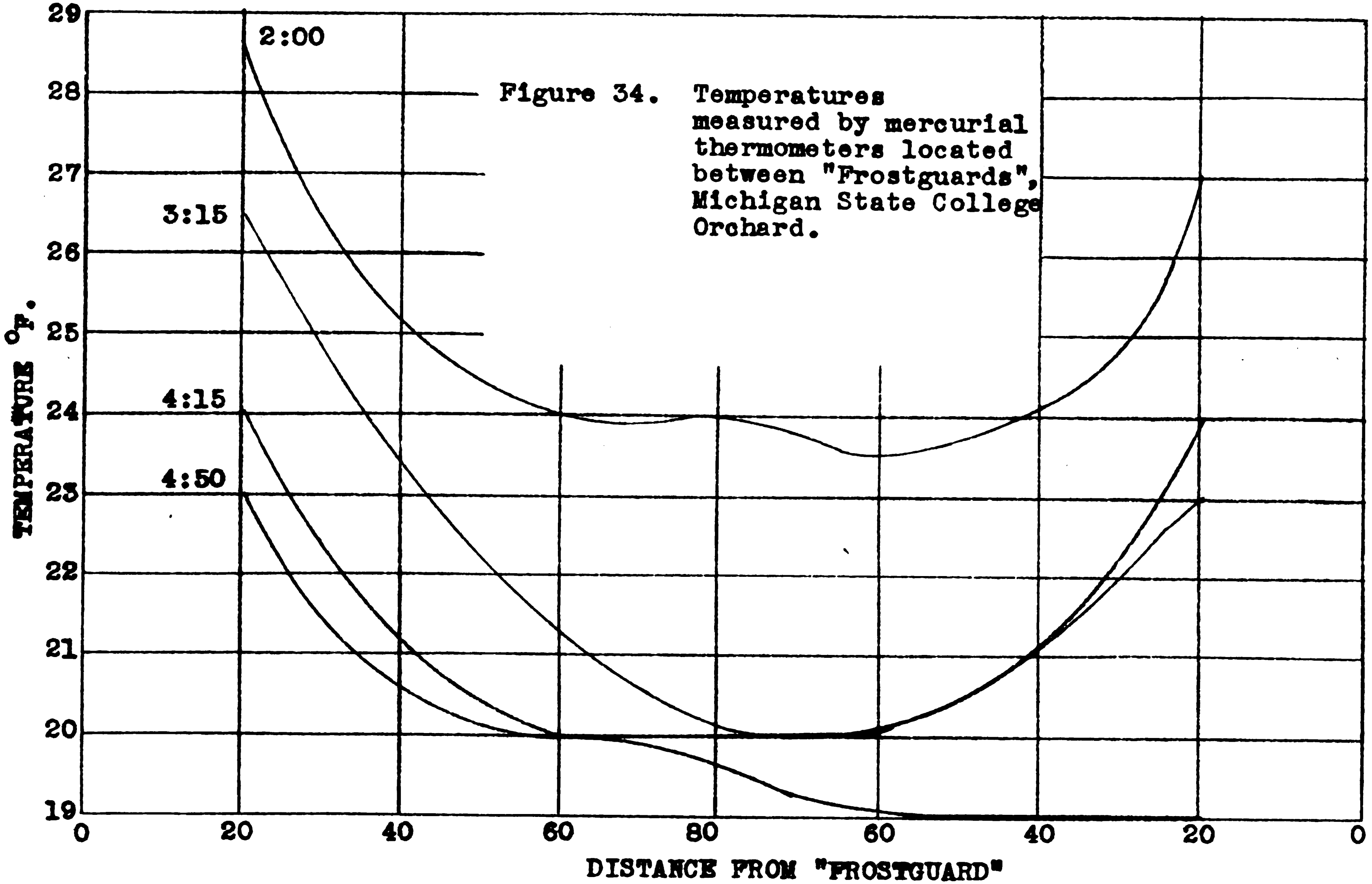

Figure 34. Temperatures measured by mercurial thermometers located between "Frostguards", Michigan State College Orchard.

Table X

AIR TEMPERATURES IN DEGREES FAHRENHEIT MEASURED BY THE THREE MERCURIAL THERMOMETERS LOCATED OUTSIDE THE RING OF "FROSTGUARDS" AND ON A RADIUS FROM THE WIND MACHINE TO "FROSTGUARD" NUMBER FIVE

Distance from "Frostguard" (Feet)	Time							
	9:45 P.M.	10:30 P.M.	11:00 P.M.	12:15 A.M.	2:00 A.M.	3:15 A.M.	4:15 A.M.	4:50 A.M.
20	29.0	28.5	29.0	29.0	28.5	24.0	25.0	19.0
40	26.0	24.0	23.5	24.0	24.0	21.0	20.0	19.0
60	26.0	24.0	23.0	23.5	23.0	21.0	20.0	19.0

These temperatures show that the effect of the wind machine did not extend past the line of "Frostguards."

Records taken by the United States Weather Bureau at the Lansing Airport show that the wind velocity at the recording station varied from calm to five miles per hour between 5:00 P.M., October 17 and 6:00 A.M., October 18, 1952. These records were taken at 52 feet above the ground level. The wind direction was from the east from 6:00 to 8:00 P.M., west or southwest from 8:00 to 12:00 P.M., northwest from 12:00 to 2:00 A.M. and southwest from 2:00 to 6:00 A.M.

Figure 35 shows the temperature inversion curves from 8:00 P.M., September 17, to 6:00 A.M., September 18.

Figure 36 shows the temperature recorded at the check point during this test.

The "Frostguards" were moved to a radius of 120 feet from the wind machine for the tests conducted on the night of October 20. The wind machine was started at 6:00 P.M. on October 20.

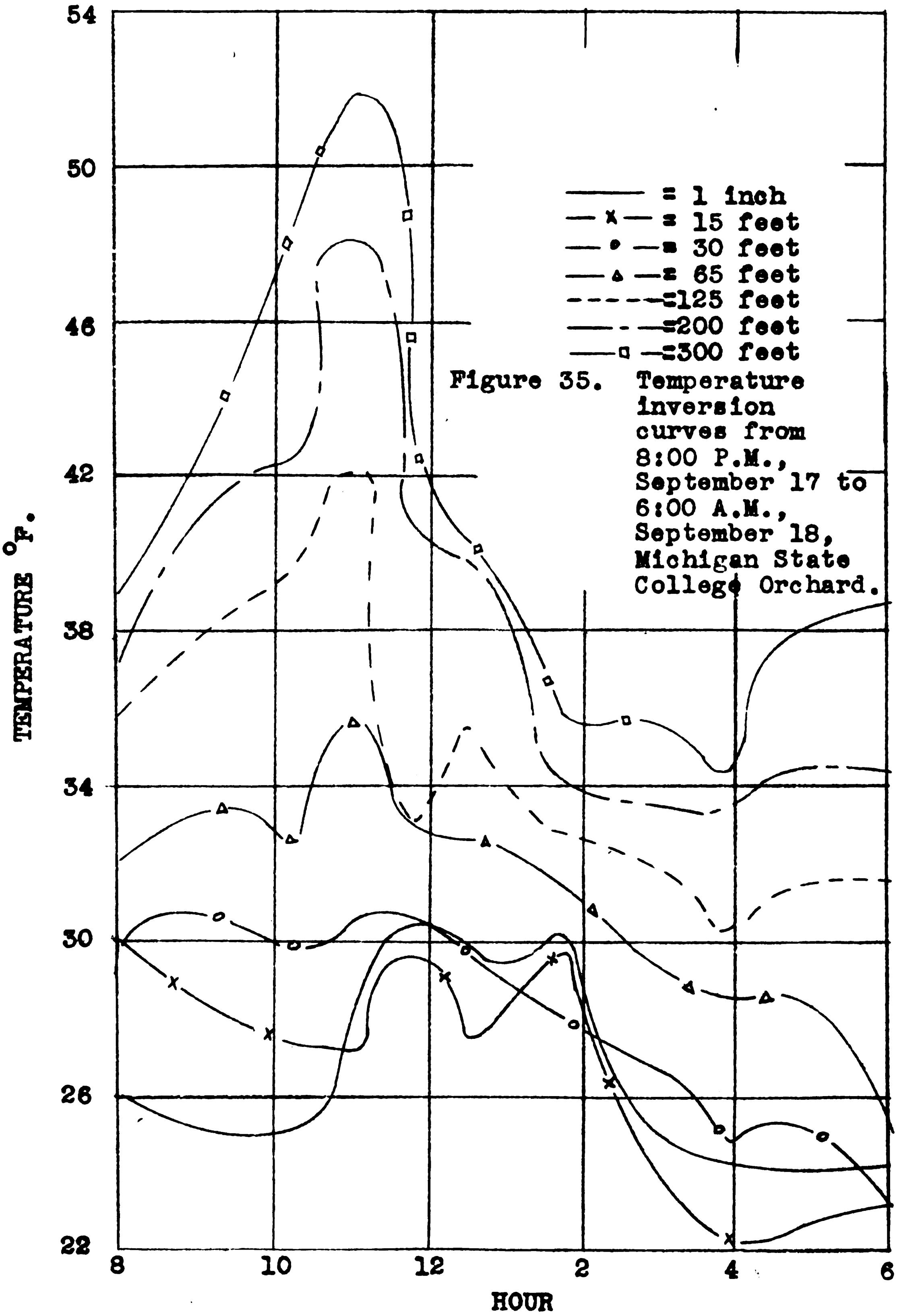

Figure 35. Temperature inversion curves from 8:00 P.M., September 17 to 6:00 A.M., September 18, Michigan State College Orchard.

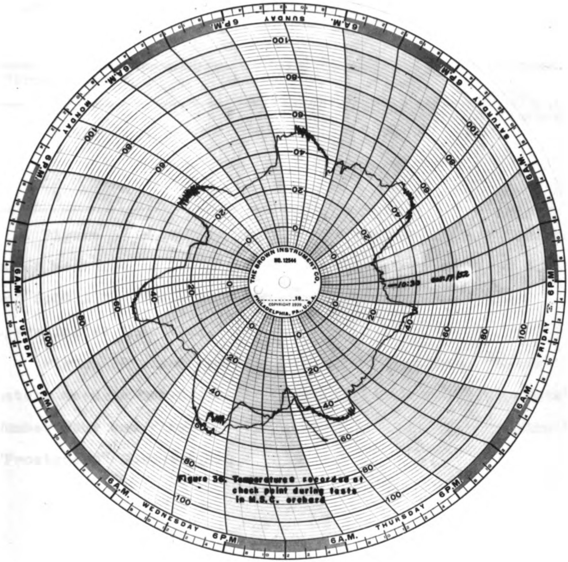

Figure 36. Temperatures recorded at check point during tests in Michigan State College Orchard.

Table XI

TIME DURING WHICH "FROSTGUARDS" WERE OPERATED AND HOURS OF CONTINUOUS OPERATION IN MICHIGAN STATE COLLEGE ORCHARD, OCTOBER 20, 21, 1952

"Frostguard" Number	Start (P.M.)	Stop (A.M.)	Time Operated
1	6:15	7:15	13 hours 0 minutes
2	6:20	6:40	12 20
3	6:25	6:20	12 0
4	6:30	6:20	12 0
5	6:35	7:05	12 30
6	6:40	7:10	12 30

Figure 37 shows the maximum and minimum lateral temperatures measured on the night of October 20 between 7:00 P.M. and 5:30 A.M. The wind machine and "Frostguards" were operating at this time.

Figure 38 shows the location of the mercurial thermometers used to measure the temperature between "Frostguards" Number Four and Five and on a radius from the wind machine to "Frostguard" Number Five.

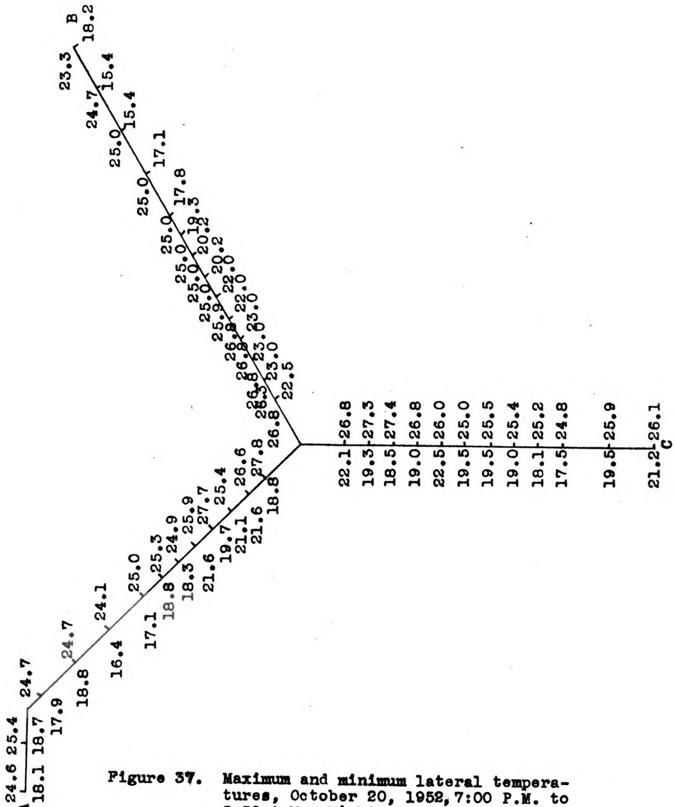

Figure 37. Maximum and minimum lateral temperatures, October 20, 1952, 7:00 P.M. to 5:30 A.M., Michigan State College Orchard.

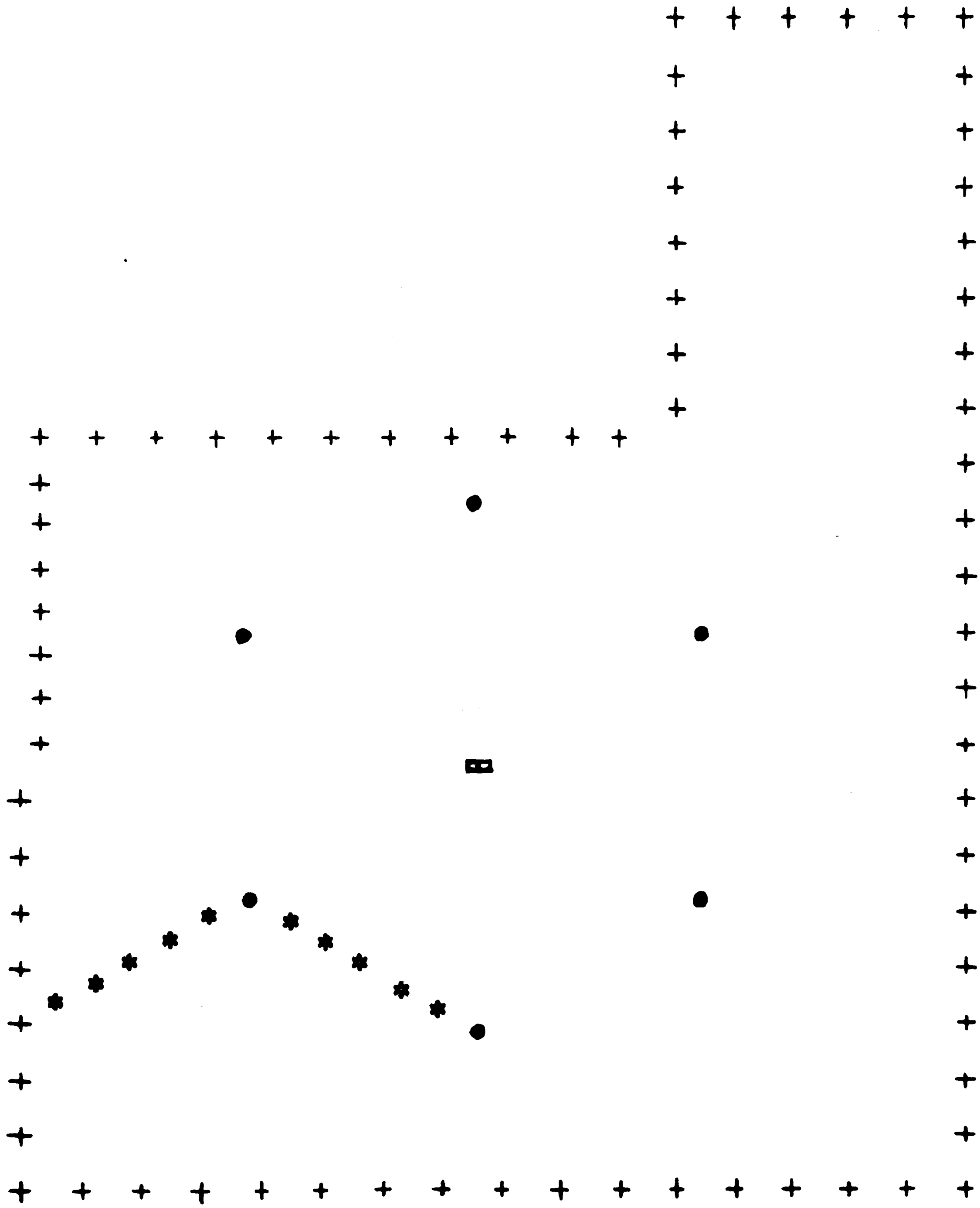

Figure 38. Location of mercurial thermometers, Michigan State College Orchard, October 29, 1952.

● indicates "Frostguard"
* indicates thermometers
▬ indicates wind machine

Table XII

TEMPERATURES IN DEGREES FAHRENHEIT MEASURED BY MERCURIAL THERMOMETERS INDICATED IN FIGURE 38. OCTOBER 20, 1952, 6:50 P.M. TO 5:25 A.M.

Thermometer Number	Distance from "Frostguard" (Feet)	Time 6:50	8:30	12:20	1:30	2:10	3:10	5:25
1	20	31.0	26.0	29.0	28.5	28.0	27.5	27.0
2	40	28.0	22.0	26.0	26.5	26.0	25.0	25.5
3	60	29.0	22.5	25.0	26.0	25.5	24.0	25.0
4	40	28.0	23.5	25.0	26.0	25.5	24.0	25.0
5	20	31.5	29.0	27.0	27.0	27.0	25.5	27.0
6	20	29.0	25.5	28.0	27.0	27.0	26.0	26.0
7	40	24.0	21.0	25.0	25.0	25.0	24.0	25.0
8	60	23.5	20.0	25.0	25.0	24.5	24.0	25.0
9	80	22.0	19.0	24.0	24.0	23.5	23.0	24.0
10	100	21.5	19.0	24.0	25.0	24.0	23.5	24.0

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The temperatures given in Table XII show that the effect of the wind machine did not extend beyond the line of "Frost-guards."

Table XIII

TEMPERATURE INVERSION TO 300 FEET DURING THE NIGHT OF OCTOBER 20, 1952, MICHIGAN STATE COLLEGE ORCHARD

Time	Inversion (Degrees) (Fahrenheit)
9:15 P.M.	9
9:50 P.M.	4.7
11:10 P.M.	3.3
11:30 P.M.	2.2
12:20 A.M.	2.1
1:20 A.M.	0

Table XIV

WIND VELOCITIES REPORTED BY THE EAST LANSING OFFICE OF THE UNITED STATES WEATHER BUREAU OCTOBER 20, 21, 1952

Direction: Southwest Throughout The Night

Time	Wind Velocity (Miles Per Hour)
7 to 10 P.M.	Calm
10 to 12	4
12 to 1 A.M.	4
1 to 2	3
2 to 3	4
3 to 4	4
4 to 5	6
5 to 6	8
6 to 7	8
7 to 8	7

The 3-mile per hour wind that occurred around one o'clock was sufficient to destroy the temperature inversion.

Figure 36 shows the temperature recorded at the check point during this test.

Figure 39 shows the outline of the frost line on the ground when "Frostguards" were turned off on October 21, 1952.

Figure 40 shows the distribution of leaves on a peach tree 30 feet from a "Frostguard." The photograph was taken three days after the October 20 test was conducted.

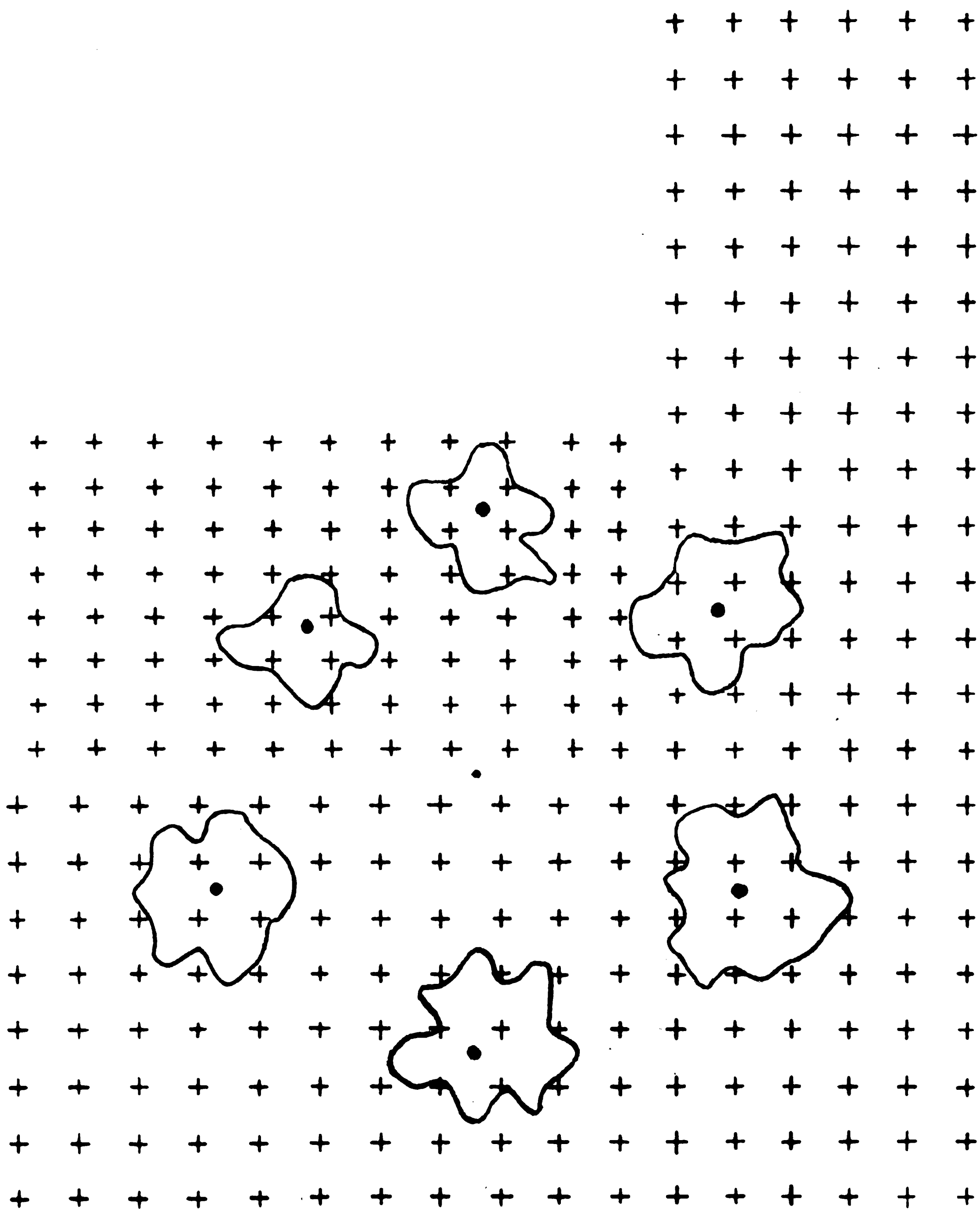

Figure 39. Outline of frost line on ground when "Frostguards" were turned off, October 21, 1952.

Figure 40. Leaf distribution on a tree 30 feet from a "Frost-guard" three days after test. The leaves remained on the side protected.

E. Studies to Determine the Practicability of the Propane Burner

1. Heat Balance Study

On August 22, 1952 a heat balance study was conducted on the propane burner, as shown in Figure 21. This study to determine the radiation pattern was conducted in the Agricultural Engineering research laboratory with the test stand shown in Figure 41. This arrangement made it possible to measure the radiation intensity in a vertical plane around the burner. The measurements were made at 10-degree intervals.

Figure 41. Test stand for determining the radiation pattern of a propane burner

Five Orsat exhaust gas analyses were made and the averages of the results are shown in Table XV.

Table XV

AVERAGE OF FIVE ORSAT EXHAUST GAS ANALYSES ON THE PROPANE BURNER

Gas	Percentage
CO_2	13.7
O_2	0.46
CO	0
N_2	85.84

The room air temperature at the time the Orsat exhaust gas samples were taken was 83.5 degrees Fahrenheit dry bulb and 67 degrees Fahrenheit wet bulb. This gave a relative humidity of 41 percent, or an absolute humidity of 73 grains of water vapor per pound of dry air.

The air-fuel ratio is expressed as pounds of air supplied per pound of fuel burned. This calculation involves the application of a nitrogen balance to find the air supplied, and a carbon and hydrogen balance to determine the weight of fuel burned.

2. Calculation of the Air-Fuel Ratio

It was assumed that the propane fuel consisted entirely of carbon and hydrogen, and that combustion took place without the formation of free carbon. The basis of calculation was 100 pound moles of exhaust gas (37).

Table I in the Appendix shows the results of the Orsat analysis when converted to pound moles of carbon and oxygen. This was used as a basis for the calculation of the heat balance.

3. Calculation of the Theoretical Air Needed

The theoretical air is the amount of air that must be supplied to completely oxidize the fuel constituents. That is, all of the carbon must be used to form carbon dioxide, and the available hydrogen used to form water, and the sulfur to form sulfur dioxide. Any air supplied in addition to the theoretical air is called excess air. The percent of excess air is then defined as:

$$\%\text{ excess air} = \frac{\text{Actual air supplied} - \text{Theoretical air required}}{\text{Theoretical air required}}$$

The calculations for the excess air are included in the Appendix.

4. Calculation of the Heat Disposition of the Fuel And Air Used in the Combustion Process

Calculations were made to determine the following: total heat liberated by the combustion of the fuel, the losses through flue gases and moisture in the air supply, the losses by convection, and the amount and distribution of the heat given off by radiation. These calculations are also included in the Appendix. Figure 42 shows the radiation pattern from the propane burner for this particular test.

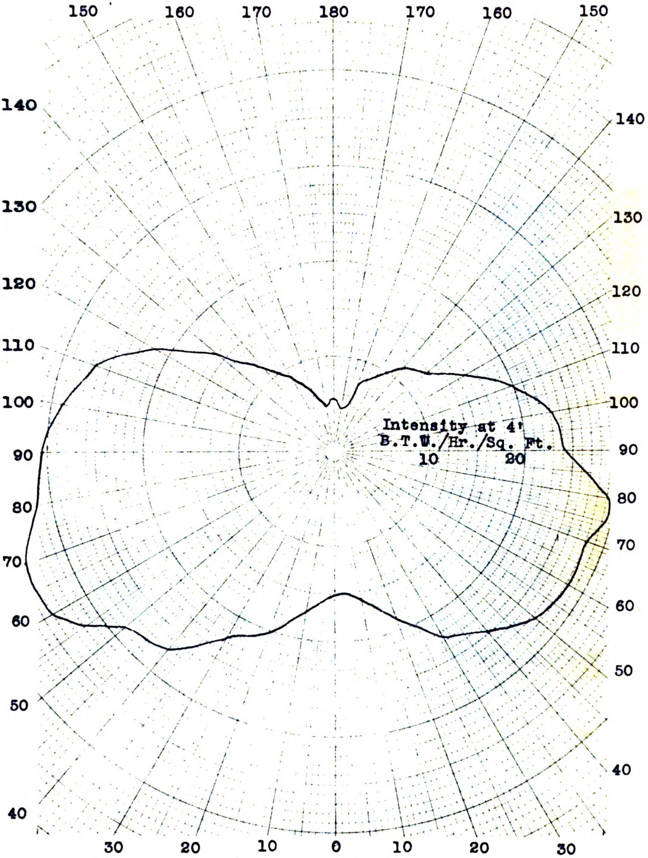

Figure 42. Radiation pattern from experimental propane heater.

SUMMARY, CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

Two helicopter type wind machines were tested in the Thornhill Apple Orchard, Beulah, Michigan, and one of the two wind machines was tested in the Michigan State College Cherry Orchard at East Lansing, Michigan. One of these machines, which has been referred to as Wind Machine Number One, used a 22-foot rotor mounted on a tower 20 feet high and was driven at 140 revolutions per minute. Wind Machine Number Two used a 32-foot rotor mounted on a tower 25 feet high and was driven at 93 revolutions per minute. Both wind machines were driven through the power-take-off of farm tractors.

Both wind machines were definitely limited in the extent of the area over which they could provide frost protection. Helicopter type rotors mounted in a horizontal plane do not force air in the plane of rotation.

When orchard heaters are used in conjunction with a wind machine, the heaters should be arranged radially from the wind machine rather than closely placed in concentric circles around it. The heat from the orchard heaters causes convection currents which act as a barrier to the lateral movement of the air from the wind machine.

Wind Machine Number One increased the temperature 3.5 degrees Fahrenheit over an area which included 20 apple trees or approximately 0.60 acre when the temperature inversion was 11 degrees Fahrenheit. The increase beyond this area was not uniform, and no effect could be measured outside an area of 42 trees or approximately 1.25 acres. When used in conjunction with 34 open pot type heaters per acre and an 8 degrees Fahrenheit natural inversion, a 3.5 degree rise was measured within an area of 27 trees or approximately 0.80 acre. When used in conjunction with six "Frostguard" units spaced at equal intervals on a circle having a 165-foot radius from the machine, a 3.5 degree Fahrenheit rise was measured within an area of .55 acre. A temperature increase of 3 degrees Fahrenheit was measured over an area of 1.6 acres after the "Frostguards" had been moved to a radius of 120 feet.

Wind Machine Number Two increased the temperature 5 degrees Fahrenheit within an area of 47 trees, or approximately 1.4 acres, when the temperature inversion was 10 degrees Fahrenheit. No temperature increase could be detected outside an area of 3.75 acres or 127 trees.

The apple yields indicate that the wind machine should not be operated unless the temperature can be maintained above freezing. When the wind machines maintained a temperature of 26 degrees Fahrenheit, more frost damage occurred to blossoms on trees within 100 feet of the wind machines than to those in other parts of the orchard. This greater damage occurred even though the temperature decreased to 18 degrees Fahrenheit outside the area affected by the wind machines

Early models of the "Frostguard" units had proven to be erratic in their operation, but the improved units gave uninterrupted service and after 30 hours of burning showed no signs of failure. It was possible to increase the temperature inversion from 11 degrees Fahrenheit to 24 degrees by using six "Frostguards" spaced at equal intervals on a circle having a 165-foot radius.

Frost prevention equipment must be selected to meet the requirements of the situation. Limited areas in orchards can be protected by the helicopter type wind machines when a temperature inversion of 10 degrees Fahrenheit or more is present. If the natural inversion is not great enough, supplemental heat must be added from either small orchard heaters or from large units such as the "Frostguard." For some low growing, high value crops "Frostguard" units give economical frost protection while on other low growing crops and on favorable soil types, water application is most practical.

It is suggested that studies be conducted on the use of a small, 15 to 20 horsepower, vertical rotor type wind machine when used alone or in conjunction with "Frostguard"

units. It is recommended that additional studies be conducted to develop economical, low pressure, burners designed to burn gas or liquid petroleum.

APPENDIX

Calculation of the Air Fuel Ratio

Table 1

RESULTS OF ORSAT ANALYSIS EXPRESSED AS POUND MOLES OF CARBON AND OXYGEN IN 100-POUND MOLES OF EXHAUST GAS

Gas	Pound Moles	Pound Atoms C	Pound Moles O_2
CO_2	13.7	13.7	13.7
CO	0	0	0
O_2	0.46	----	0.46
N_2	85.84	----	-----
Totals	100	13.7	14.16

The carbon in 100-pound moles of exhaust = 13.7 atoms

The carbon in the fuel burned to form 100-pound moles of exhaust = 13.7 atoms

The pounds of carbon in fuel burned = (13.7) (12) = 164.4

The dry air supplied = $\frac{85.84}{0.79}$ = 108.6 pound moles

The dry air supplied = (108.6)(28.8) = 3127.7 pounds

The oxygen supplied with the dry air = (.21)(108.6) = 22.81 pound moles

The total oxygen in the exhaust gas = 14.16 pound moles

Since 14.16 pound moles of oxygen appeared in the exhaust, 22.81 pounds - 14.16 pounds = 8.65 pound moles of oxygen that must have combined with the hydrogen in the fuel to form water.

Since $2H_2O + O_2 = 2H_2O$

H_2O formed = (2)(8.65) = 17.30 pound moles of water

H_2 in fuel = 17.30 pound moles

H_2 in fuel burned = (2)(17.30) = 34.6 pounds

The total weight of fuel burned = 164.4 + 34.6 = 199 pounds

The air fuel ratio = $\frac{\text{pounds of air}}{\text{pounds of fuel}} = \frac{3127.7}{199} = 15.70$

Calculation of the Theoretical Air Needed

The chemical formula for propane is C_3H_8

$C_3H_8 + 5O_2 + N_2 = 4H_2O + 3CO_2 + N_2$

Relative weight (3)(12) + (8)(1) + (5)(32) =

(8)(1) + (4)(16) + (3)(12) + (3)(32)

Per pound fuel 1 + 3.64 = 1.64 + 3

Theoretical air needed = (4.33)(3.64) = 15.78 pounds of air per pound of fuel

15.78 pounds of air required per pound of fuel - 14.96 pounds of air used per pound of fuel = 0.08 pound of air deficient per pound of fuel

$\frac{0.08}{15.78}$ = 0.506 percent deficient

Calculation of the Weight of Dry Gases Formed Per Pound of Fuel Burned

Propane is 81.8 percent carbon and 18.2 percent hydrogen by weight.

$$W_g = \frac{(4)\, CO_2 + O_2 + 700}{3\,(CO_2 + CO)}\; C_f$$

$CO_2 = 13.7$

$O_2 = .46$

$CO = 0$

$$W_g = \frac{(4)(13.7) + 0.46 + 700}{3\,(13.7)}\; .818$$

C_f = pounds of carbon per pound of fuel = .818

W_g = weight of dry gas formed per pound of fuel

W_g = 15.03 pounds of dry gas formed per pound of fuel burned

Calculation of Heat Loss Due to Dry Flue Gases

$$H_2 = W_{dg} C_p\, (t_g - t_a)$$

H_2 = B.T.U. loss per pound of fuel as fired

W_{dg} = Wgt. dry gas, pound per pound of fuel as fired = 15.03

C_p = Mean specific heat of dry flue gas = 0.24

t_g = Temperature of flue gas = 1500°F.

t_a = Temperature of the air supplied = 83.5°F.

$H_2 = (15.03)(.24)(1500 - 83.5)$

H_2 = 5,110 B.T.U. per pound of fuel

Heat loss per hour = (5,110)(5.53) = 28,258 B.T.U. per hour

Calculation of the Heat Loss Due to the Moisture in the Air Supplied

$H_1 = (W_v)(0.46)(t_g - t_a)$

H = B.T.U. loss per pound of fuel as fired

t_a = Temperature of the air supplied

t_g = Temperature of the flue gas = 1500°F.

W_v = Relative humidity expressed decimally times the weight of water vapor to saturate one pound of dry air at t_a times the weight of dry air used per pound of fuel as fired

$W_v = (.41)(.025)(15.03) = .154$

$H_1 = (0.154)\ (.046)(1500 - 83.5)$

H_1 = 100.3 B.T.U. per pound of fuel

Heat loss per hour = (5.53 pounds per hour)(100.3) =

555 B.T.U. per hour

Calculations for Amount of Heat That
Is Being Radiated Per Hour

Angle=θ c.c.w.	M.V. at 4'x10^{-2}	Btu/Hr/Ft^2 at 4'	Intensity@Source I=(Btu/Hr/Ft^2)D^2	Sin θ	I(Sin θ)
0	13.0	147.0	2,352	0	0
10	14.0	158.2	2,531	.17365	439
20	16.5	186.5	2,984	.34202	1,021
30	20.0	226.2	3,619	.50000	1,809
40	21.75	246.0	3,936	.64279	2,530
50	24.0	271.5	4,344	.76604	3,328
60	25.0	282.5	4,520	.86603	3,914
70	25.0	281.5	4,504	.93969	4,232
80	25.75	291.0	4,656	.98481	4,585
90	21.50	243.0	3,888	1.00000	3,888
100	20.50	232.0	3,712	.98481	3,656
110	17.5	198.0	3,168	.93969	2,977
120	14.0	158.5	2,536	.86603	2,196
130	11.25	126.5	2,024	.76604	1,550
140	10.30	116.4	1,862	.64279	1,197
150	8.0	90.5	1,488	.50000	744
160	6.50	73.5	1,176	.34202	402
170	4.0	45.2	723	.17365	126
180	5.0	56.5	904	0	0
c.w.					
0	14.0	158.2	2,531	0	0
10	15.0	170.0	2,720	.17365	472
20	18.0	202.5	3,240	.34202	1,108
30	20.0	226.2	3,619	.50000	1,809
40	24.0	271.5	4,344	.64279	2,792
50	25.5	286.0	4,576	.76604	3,505
60	30.0	340.0	5,440	.86603	4,711
70	30.0	340.0	5,440	.93969	5,112
80	28.0	317.0	5,072	.98481	4,995
90	27.0	305.0	4,880	1.00000	4,880
100	25.5	288.0	4,608	.98481	4,538
110	24.0	265.0	4,240	.93969	3,984
120	19.0	214.5	3,432	.86603	2,972
130	14.0	158.0	2,528	.76604	1,937
140	10.50	118.7	1,899	.64279	1,221
150	8.0	90.5	1,488	.50000	744
160	6.0	67.8	1,085	.34202	371
170	4.0	45.2	723	.17365	126
180	5.0	56.5	904	0	0

Average total radiation clockwise and counter clockwise

$= 41,935$ B.T.U. per hour

Average radiation above horizontal $= 14,370$ B.T.U. per hour

$$E_{total} = \frac{2\pi^2}{N} \sum_{0}^{\pi} I \text{ Sin} \qquad N = 17 \text{ zones}$$

$$\frac{2\pi^2}{17} = 1.16 = \text{a constant}$$

$E = (1.16)(41,935) = 48,645$ B.T.U. per hour

$E_{above\ horizontal} = (1.16)(14,370) = 16,669$ B.T.U. per hour

Percentage above horizontal $= \frac{16,669}{48,645} = 34.3$ per cent

Calculation to Determine The Heat Loss by Convection

The convected heat is estimated by the difference between input and calculated output, thus completing the heat balance for the unit.

Input = (heating value of fuel)(pounds burned per hour)

= (21,654)(5.53) = 119,747 B.T.U. per hour

Output

Heat loss to dry flue gas = 28,258 B.T.U. per hour

Heat loss to moisture in air supply = 555 B.T.U. per hour

Heat given off by radiation = 48,645 B.T.U. per hour

Total = 77,458 B.T.U. per hour

Convected heat = Input - Output = heat loss by convection

= 119,747 - 77,458 = 42,289 B.T.U. per hour

Summary of Data Obtained from Heat Balance

Total heat liberated by combustion of fuel = 119,747 B.T.U. per hour

Loss through flue gases and moisture in the air supply = 28,813 B.T.U. per hour = 24.2 percent of heat liberated

Loss by convection = 42,289 = 35.3 percent of heat liberated

Heat given off by radiation = 48,645 B.T.U. per hour = 40.5 percent of heat liberated

Heat radiated above horizontal 90 to 180 degrees = 16,669 B.T.U. per hour = 13.92 percent of heat liberated = 34.3 percent of heat radiated

Heat radiated below horizontal 0 to 90 degrees = 31,976 B.T.U. per hour = 26.7 percent of heat liberated = 65.7 percent of heat radiated

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