UTILIZATION OF RADIANT HEAT FOR THE PROTECTION OF VEGETATION FROM FROST DAMAGE

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Francis Jefferson Hassler

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This is to certify that the

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Utilization of Radiant Heat
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A. W. Farrall
Major professor

Date May 27, 1948

UTILIZATION OF RADIANT HEAT FOR THE PROTECTION OF VEGETATION FROM FROST DAMAGE

By

Francis Jefferson Hassler

A THESIS

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

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Department of Agricultural Engineering

1948

THESIS

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The funds for the project were made available through the Agricultural Experiment Station under the direction of V.R. Gardner. The Research Board of the Detroit Chamber of Commerce aided in solving commercial problems.

It would be impossible to mention specifically all the numerous people who gave valuable assistance to this project, but it is the wish of the writer to especially thank Mr. George Gibson and Professor Clarence Hansen for many days and nights of hard work, and Mr. J.M. Klock for the arrangement and correction of the manuscript.

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I. INTRODUCTION

A. Nature of the Problem

One of the main hazards to fruit and truck crops is radiation-type frost damage. This damage includes late maturity of crops, poor quality and quantity, and in some instances a total loss of produce.[1] In the United States, losses due to frost damage are more pronounced in states such as Florida and California where the citrus crop makes up intensive or highly-valued agriculture. The same is true for states that grow truck crops and fruit orchards extensively. Michigan represents this type of agriculture and the annual frost damage in the State of Michigan is estimated to range from ten to twenty million dollars.[2]

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1 Footnotes are on pages 100-102

B. Radiation-Type Frost

The earth receives its heat from the sun in the form of radiant energy. This energy is absorbed by plants and transformed into sensible heat. At the same time that heat is being received, plants are radiating a part of this heat back toward the sky. However, there is a net gain on the part of the plants during a twenty-four hour period. This condition is brought about by the blanketing effect of the atmosphere on the earth, for the energy of the sun is emitted in short wave length radiation which penetrates the atmosphere of the earth with little loss, while the plants, having absorbed this energy, emit it in long wave length radiation which is readily absorbed by the atmosphere and thereby results in heat being added to the atmosphere. Thus the atmosphere acts as a trap whereby the earth retains sufficient heat to carry it through the night.

The condition of the atmosphere, then, will greatly influence the net amount of heat gained by plants in any one period of time. For example, the absorbing

characteristics of the air become more pronounced as the absolute humidity increases. Conversely, if there is little humidity in the air, as on a clear night, the plants rapidly lose their heat.

Radiation-type frost is common during the early and late parts of the growing season. To set the stage for this type of freeze it is required that there be a preliminary influx of cool to cold air, followed by a calm, clear night. Since the plants under these conditions are radiating heat to the outer space, the net heat transmission is away from the plants. The air will become cooled by conduction to these plants.[3] As the air becomes cooled, gravity pulls it down to settle close to the ground. When the plants have lost sufficient heat by radiation and have cooled the surrounding air to a low temperature, their temperatures will approach the freezing point. If the plant temperature falls below the dew point of the surrounding air, moisture will condense on the vegetation, and when subsequently frozen to ice, will give the familiar frost appearance.

Not all freezing however, is visible. One example is when the wind velocity is in the magnitude of five miles per hour and the condensate is carried off the vegetation, leaving no moisture to form visible frost. Another condition is when the dew point is lower than the minimum plant temperature for that freeze.[4] This freezing without visible frost is commonly known as "black frost."

Except for extremely cold conditions, a four mile per hour wind will cause sufficient turbulence to prevent the air from collecting in strata.[5] The moving air also convects heat to the plants, keeping their temperatures above the freezing point. When the preliminary influx of air is relatively cold, freezing is likely to occur even if there is a brisk wind, because this cold air cannot convect enough heat to the plants to offset the heat that is lost by radiation.

C. Methods Used for the Protection of Vegetation From Frost Damage

The basic principle involved in the problem of keeping vegetation from freezing is to maintain the temperature of the vegetation safely above its freezing point. The three approaches to this problem are: (1) conserve the existing heat possessed by the plants and the ground; (2) utilize the heat in the surrounding air through stirring; (3) add artificial heat.

Numerous attempts have been made to gain these three objectives, but the methods tried have either been too expensive or not entirely successful. For example, glass coverings, or a covering of cloth and lath screens, are excellent protection, but far too expensive for the average crop. Irrigation has been used successfully, but it, too, is expensive to install.[6] Flooding is effective, but often causes water damage. Efforts to make artificial clouds have not been successful.[7] Large motor-driven propellors have been used to stir the air, which in turn convects heat to plants, but there is not agreement on the success of this method.[8]

The most widely-used and successful means of combating frost damage has been the use of orchard heaters in the citrus groves. The original idea was to blanket the area with dense smoke in order to cut down radiation loss. From this practice, the burners came to be called "smudge pots." The individual units cost little, but one per tree, or two hundred per acre, are required to be effective. The damage from the smoke and the nuisance they cause have led urban communities to pass ordinances restricting the use of this type of heater.

A larger orchard heater was then designed to heat the groves by convection. While these units are more expensive, only about fifty per acre are required. This heater takes advantage of the fact that on a clear calm night there is a thin layer of cold air near the ground, while the air temperature increases with elevation to a certain point, above which the temperature again decreases. This phenomenon is called temperature inversion. The purpose of these heaters is to warm the air under the inversion point to the necessary degree. Conditions limit the effectiveness of this method. It is most effective if the day temperature has been high and therefore it is necessary to heat less air.

These heaters are generally effective for the control of radiation-type frost, but give little protection during cold fronts that are accompanied by cold winds. These units are also expensive, not only because of the initial cost and the fuel cost, but because much labor is required for installation and maintenance. These facts have caused the citrus industry to look for better means for preventing frost damage.

D. Preliminary Tests Made at Michigan State College

The farmers of Michigan realize the need for protection against frost damage, as a large part of their agricultural industry is devoted to truck gardening and fruit growing. The problem of frost damage, while always important, became more so during World War II when the crop values increased.

By 1945 this problem had become so acute that the Michigan Agricultural Experiment Station, a part of Michigan State College, was asked to develop a practical means for controlling frost formation. The problem was subsequently referred to the Agricultural Engineering Department.

As a first step, an intensive study was made to determine the relative advantages and disadvantages of all known attempts to control frost. Methods that appeared to be practical were given careful consideration, and some of these methods were tested by the Agricultural Engineering Department. In one instance the United States Army Air Forces sent a helicopter to the college to be used in circulating the air by flying at low altitudes over the areas to be protected.

It was concluded that while some of these practices are effective under selected conditions, they would be impractical for the conditions surrounding Michigan agriculture.

Careful study showed that convected heat is of limited value because its success depends on the atmospheric conditions. In the fall of 1945, A. W. Farrall, Head of the Department of Agricultural Engineering, at Michigan State College, proposed radiant heating as a practical method of solving the problem. Professor Farrall, pointed out that by this method energy can be directed onto the objects to be heated without directly heating the intervening air.

In order to test this method, an electrically-powered radiant-type unit was designed and constructed at Michigan State College in the spring of 1946 with the cooperation of the Research Committee of the Detroit Board of Commerce. Information was needed as to the effectiveness of radiant heat in preventing frost damage, the radiation intensity required per unit surface area, and the cost of constructing and operating a practical unit.

This unit was designed to cover a plot forty feet square. The heating unit consisted of rod-type chromolox elements with an imput of twenty K.W. With the use of standard reflector design techniques, this unit was so constructed that practically all of the heat being radiated was uniformly distributed over the designated area.

Tests were made during natural radiation-type frosts.[9] Although actual temperatures of the vegetation and the surrounding air were not recorded, the tests indicated that a radiation intensity of three watts per square foot would adequately protect vegetation from frost under the conditions most likely to occur during the spring and early fall.[10] Although this electrically heated unit was excellent for testing purposes, and supplied the necessary basic data, it would be too costly to be commercially feasible. Furthermore, present lines are of insufficient capacity to provide protection for appreciable areas. The next step was to develop a radiant heat source that would be practical.

Two factors led to the use of oil-burning equipment.

First, on a BTU basis oil is inexpensive; second it was felt that oil-heated radiation units could be constructed at a reasonable cost.

The average net heat loss from the surface of the earth by radiation at night has been found to be at the rate of approximately one million BTU per hour per acre.[11] Using this as a basis from which to start, an oil-burning unit was constructed that would burn fuel at the rate of approximately seven gallons per hour. The radiating surface was made of three steel oil drums welded end to end. Aluminum reflectors were positioned around the barrels in an attempt to direct the radiation downward. A commercial-type pressure vaporizing burner was used. This unit was tested during the fall of 1946 under natural frosting conditions. The results were conclusive in establishing the effectiveness of the principle of frost control through the use of radiant heat. The area covered was greatly expanded and the originial figure of three watts per square foot was found to be the average intensity requirements for protection against normal frosting conditions during the fall.

The object of this study was to collect detailed information regarding the application of radiant heat to large areas, and to determine principles of design which could be incorporated into a practical commercial unit.

II. DESIGNING AN EFFECTIVE, PRACTICAL OIL-BURNING INFRARED RADIANT HEATER FOR LARGE AREA FROST PROTECTION.

A. Objectives

1) To analyze and summarize that part of radiation theory which pertains to infrared radiant energy;
2) To study the radiating and reflecting characteristics of materials to determine which are the most practical;
3) To determine the shapes of both reflectors and radiating surfaces which are the most effective and practical;
4) To study the relative positioning of reflectors and radiating surfaces to determine the most effective combinations;
5) To design and construct test units;
6) To analyze the performance of test units to determine their effectiveness for frost control and their practicality for commercial manufacture.

B. The Theory of Radiation

The discussion of radiation in this paper will be limited to radiant heat. The term "radiant heat" names that part of the electromagnetic spectrum which imparts heat to material objects. This interval of the spectrum is commonly referred to as the "infrared" range. Radiant heat and infrared, even though used interchangeably, must be used only when illustrating the range of wave length from visible light to radio waves. From Figure 1 it is noted that this range includes the wave lengths from 7800 Angstrom Units to approximately 5,000,000 Angstrom Units.

There is much published information concerning laws pertaining to radiation. Here, however, only those fundamental laws which will give the reader a working knowledge of the application of radiant heat will be outlined.

The theory of radiation states that energy is being transferred by vibrating waves in a medium of "ether." These waves have varying lengths and amplitudes, as is also illustrated in Figure 1. It has been established that all wave lengths traverse equal distances in the

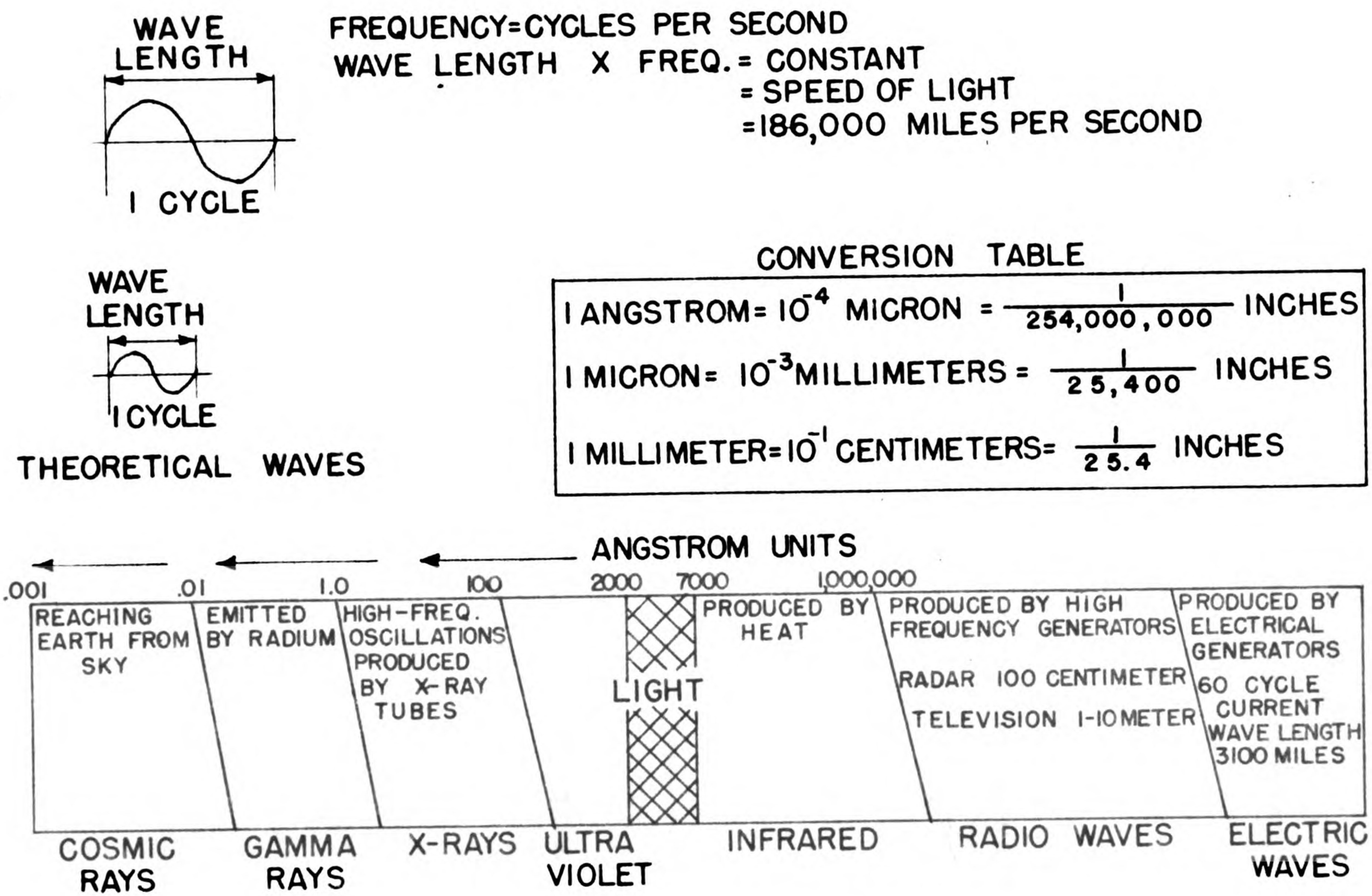


FIGURE 1. THE RADIANT ENERGY SPECTRUM.

same interval of time. This brings out the physical relationship that wave length times frequency equals a constant which is the speed of light, or approximately 186,000 miles per second. To satisfy this relationship means that the wave length varies inversely as the frequency.

The Stefan-Boltzman Law gives the total net energy for all wave lengths radiated by a solid in the following equation:[12]

$$E = k(T^4 - T_o^4)\ e_t$$

Where,

E = net energy radiated in BTU per hour per square foot of radiating surface

k = constant 0.173 times 10^{-8} BTU per square foot per hour per degree Rankine^4

T = absolute temperature of the radiating body, in degrees Rankine

T_o = absolute temperature of the surrounding surface, in degrees Rankine

e_t = total emissivity

The total emissivity, e_t, is a surface characteristic and varies with the temperature of the radiating body. A blackbody radiator is called the standard radiator and is considered to have a total emissivity of unity. All other materials or objects have radiating characteristics which give them a total emissivity of a fractional part of unity. These values are given in tables in most books dealing with heat transfer.[13]

The Stefan-Boltzman Law gives the rate or power of radiation as proportional to the fourth power of the absolute temperatures (see Figure 2). This is an important factor when considering the application of radiant heat. In addition heat will be given off by conduction and convection, but the means by which the greatest rate of heat transmission is obtained usually names the system or principle employed.

The heat that is being radiated does not leave the heated body in any single wave length. Nor does the heat being radiated change to different wave lengths as the body changes temperature. The heat will always be given off in the longest wave lengths, but the temperature of the heated body determines the shortest

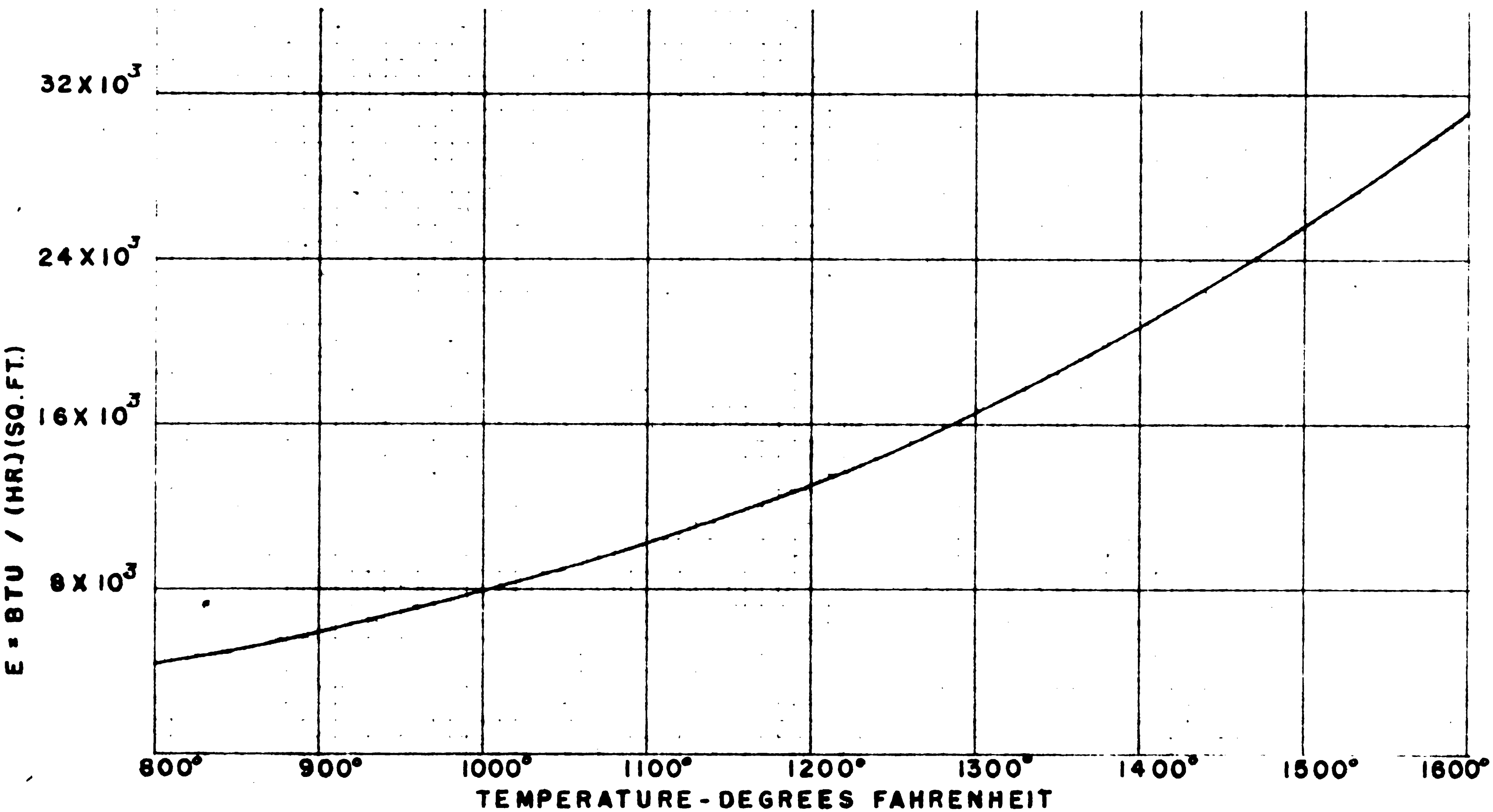


FIGURE 2. ENERGY RADIATED BY A BLACKBODY AS A FUNCTION OF TEMPERATURE.

wave length. This is illustrated by the visible light or incandescence of a body as its temperature increases; this visible light that is given off progresses from dull red, which is at the long wave length end of the visible spectrum, to yellow light of shorter wave length.

Although the Stefan-Boltzman law gives the total amount of energy radiated at a given temperature for a body at that temperature, it does not yield any information regarding the distribution of the energy over the various wave lengths. This phase is referred to as spectral distribution and can be calculated by Planck's Distribution Law:[14]

$$E_\lambda d\lambda = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1}$$

Where

$E_\lambda d\lambda$ = energy radiated in wave length intervals $d\lambda$, in BTU per hour per square foot per micron or cm.

λ = wave length in cm.

T = absolute temperature in degrees Rankine

C_1 = 1.18×10^{-8} BTU per square foot per hour times $cm.^4$

C_2 = 2.58 x cm. x degrees Rankine

e = Napierian base of logarithms which is numerically equal to 2.718

This law is represented by the temperature curves of Figure 3, which are for a blackbody radiator. These curves give the relation between energy radiated and wave length. The ordinate represent the rates of radiation or radiant intensity per unit area of emitting surface per element $d\lambda$ of wave length interval at the wave length λ. The abscissas are wave length intervals at the wave length λ given in microns. The energy radiated at any wave length interval, $d\lambda$, is the area of the vertical strip under the curve or the product of the ordinate and the wave length interval. For greater wave length intervals, when the ordinate approximation would introduce appreciable error, a planimeter can be used to determine the area under the curve.

The total area is found by summing up the intervals

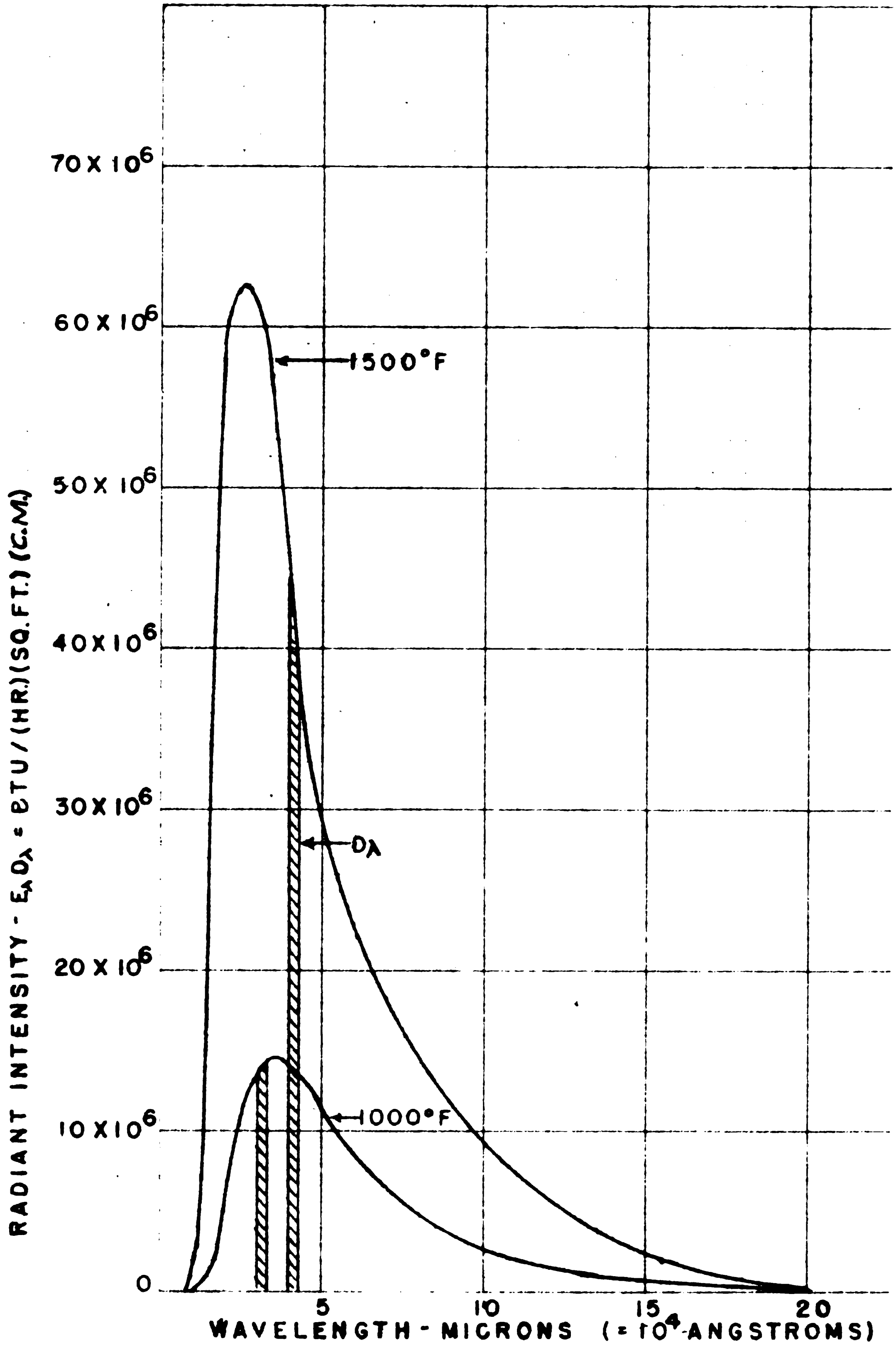


FIGURE 3. SPECTRAL DISTRIBUTION OF THE RADIATION FROM A BLACKBODY AT TEMPERATURES OF 1000°F. AND 1500°F. THE CROSS-HATCH PART SHOWS THE INTENSITY FOR A WAVELENGTH INTERVAL EQUAL TO Dλ.

of wave lengths from 0 to ∞ . This is:

$$E_\lambda = \int_0^\infty \frac{C_1 \lambda^{-5}}{\epsilon^{C_2/\lambda T} - 1} d_\lambda$$

which after integration gives Stefan-Boltzman Law for a black body:

$$E = kT^4$$

The curves in Figure 3 illustrate that the energy passes through a maximum. The wave length at which maximum radiation occurs shifts towards the shorter wave lengths as the temperature of a body increases. The maximum is at 3.5 microns for a temperature of 1100° F., while at 1500° F. it is 27 microns. The relation between the wave length at which the maximum energy is radiated and the temperature is given by Wien's Displacement Law:

$$\lambda_{max} T = 0.5193$$

λ = wave length in cm.

T = the absolute temperature in degrees Rankine

A further point of theorectical interest is Lambert's Cosine Law of Incidence, which states that the radiation intensity on a surface is equal to the incident radiation times the sine of the angle which the radiation makes with that surface. This is illustrated by Figure 4. A point of more than theoretical interest for this problem is the Inverse Square Law. Briefly, energy radiating from a point source will have an intensity that varies inversely as the square of the distance, or $E = I/D^2$. See Figure 5. The reflectors on the finished units are used to converge the energy in order to offset this effect, and the laboratory investigations were made mainly to find out how to so arrange the reflectors as to best accomplish this end.

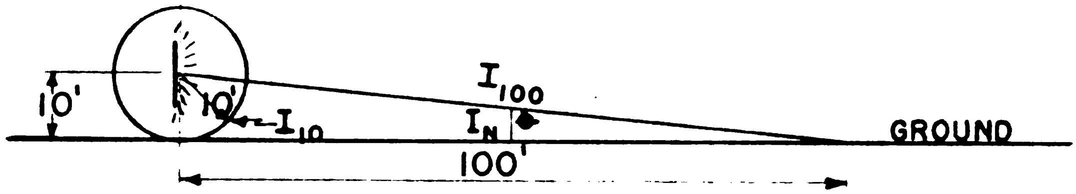


FIGURE 4. THE APPLICATION OF LAMBERT'S COSINE LAW OF INCIDENCE. IN THIS FIGURE THE RADIATION INTENSITY ON THE HORIZONTAL SURFACE AT 100 FEET, I_n, IS EQUAL TO I_{100} TIMES COSINE θ.

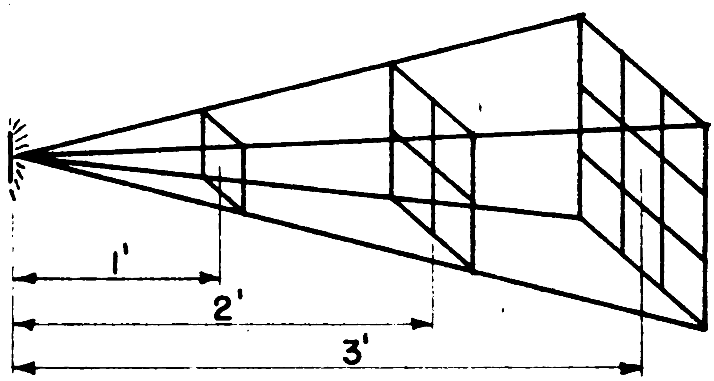


FIGURE 5. THE OPERATION OF THE INVERSE SQUARE LAW.

C. Laboratory Testing

The purposes of the laboratory tests were:

1) To select materials for the radiating surface that would be comparatively cheap in cost, available, easy to shape, and that would have a relatively high coefficient of emissivity;

2) To select materials for the reflectors that would be cheap, available, flexible, and have a high coefficient of reflectivity. The surfaces would have to be of an inert nature to prevent excessive oxidation;

3) To so position and shape the radiating surface and the reflectors as to offset the inverse square law.

It was not the purpose of this work to find out only the theoretically best, but also to arrive at a design that would be commercially feasible.

1. Materials

Rolled sheet steel satisfies the requirements for the radiating surface. After oxidation through excessive heating it has an emissivity factor of approximately .80.

Sheet aluminum with an anodized surface meets the requirements for the reflectors.

2. Instruments

Three instruments were used in the laboratory experiments. They were later used for gathering information once the units were constructed. These instruments were:

1) Leeds and Northrup potentiometer for measuring temperatures with thermocouples;
2) Leeds and Northrup optical pyrometer for measuring the temperature of the radiating surface;
3) Eppley Radiation Meter, which is illustrated by Figure 6. This instrument consists of a thermopile to expose to the radiation. The thermopile is electrically connected to a potentiometer for measuring the EMF, which, by the proper conversion factor of 35.6 microwatts per square cm. per microvolt, gives the radiation intensity.

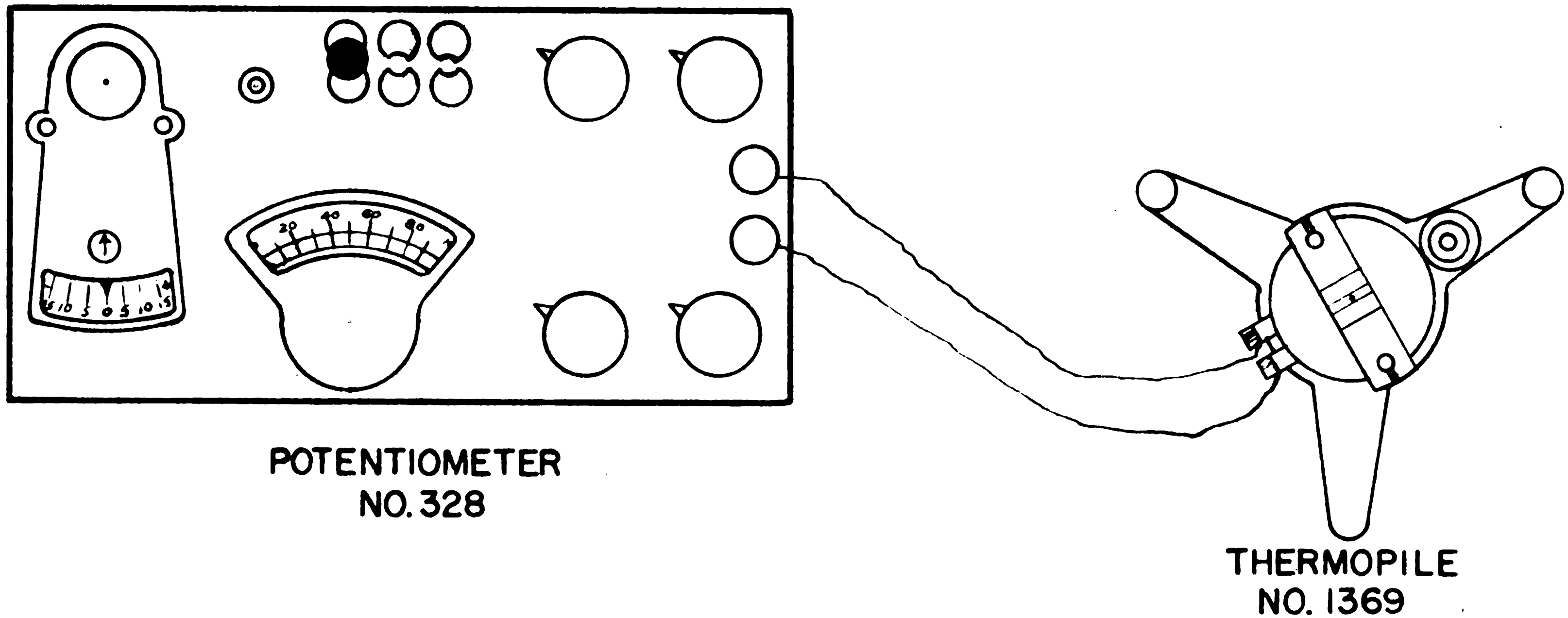


FIGURE 6. LEEDS AND NORTHRUP INFRARED RADIATION METER.

3. The First Laboratory Investigation

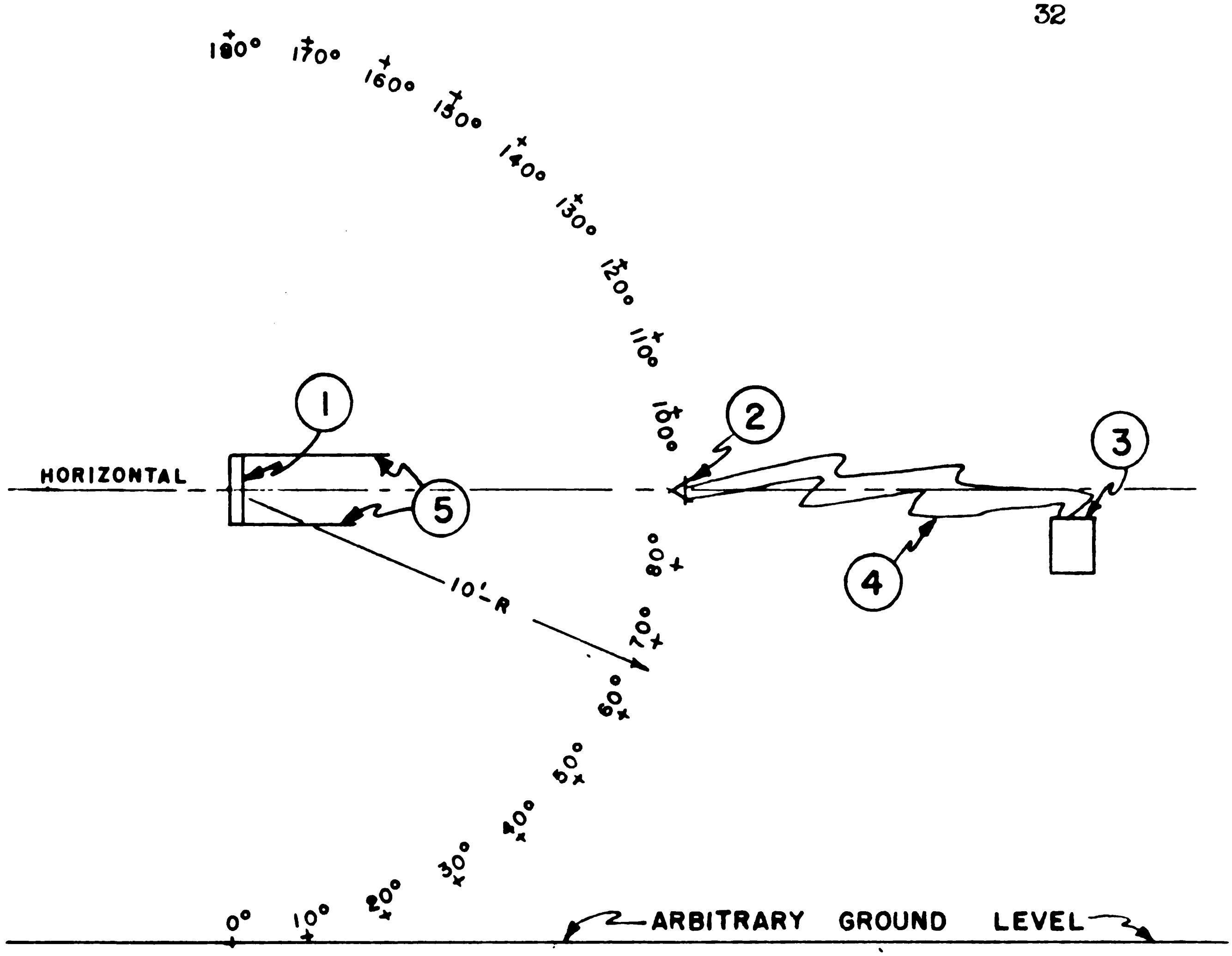
This preliminary investigation was made to study the distribution of radiant heat from a flat radiating surface. Figures 7 and 8 illustrate the apparatus for the first laboratory experiments.

The radiating surface consisted of a six-inch commercial strip heater with an imput of 110 volts, 400 watts. It was so mounted that the angle it made with the so-called horizontal could be changed.

The reflectors were made of sheet aluminum with an anodized surface which gave them a specular finish. In this experiment they are left straight, but their length and their position relative to the radiating surface could be changed.

Radiation intensities could then be measured with the radiating surface at various angles to the so-called horizontal, and with the reflectors at various positions in relation to the radiating surface. This was done at 10^{o} intervals on a ten-foot radius from the radiating surface.

Figures 9 through 13 show the typical results obtained from these tests. On each figure, the position-



(1) ELECTRICALLY HEATED RADIATING SURFACE

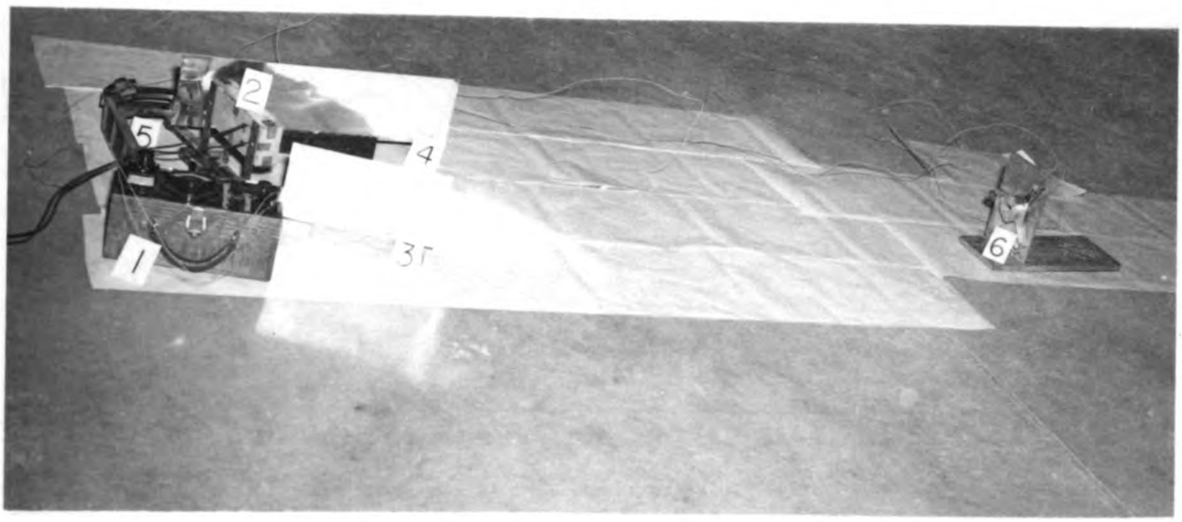
(2) THERMOPILE (PLACED AT 10° INTERVALS ON 10' RADIUS FROM RADIATING SURFACE)

(3) POTENTIOMETER

(4) COPPER WIRES CONNECTING THERMOPILE AND POTENTIOMETER

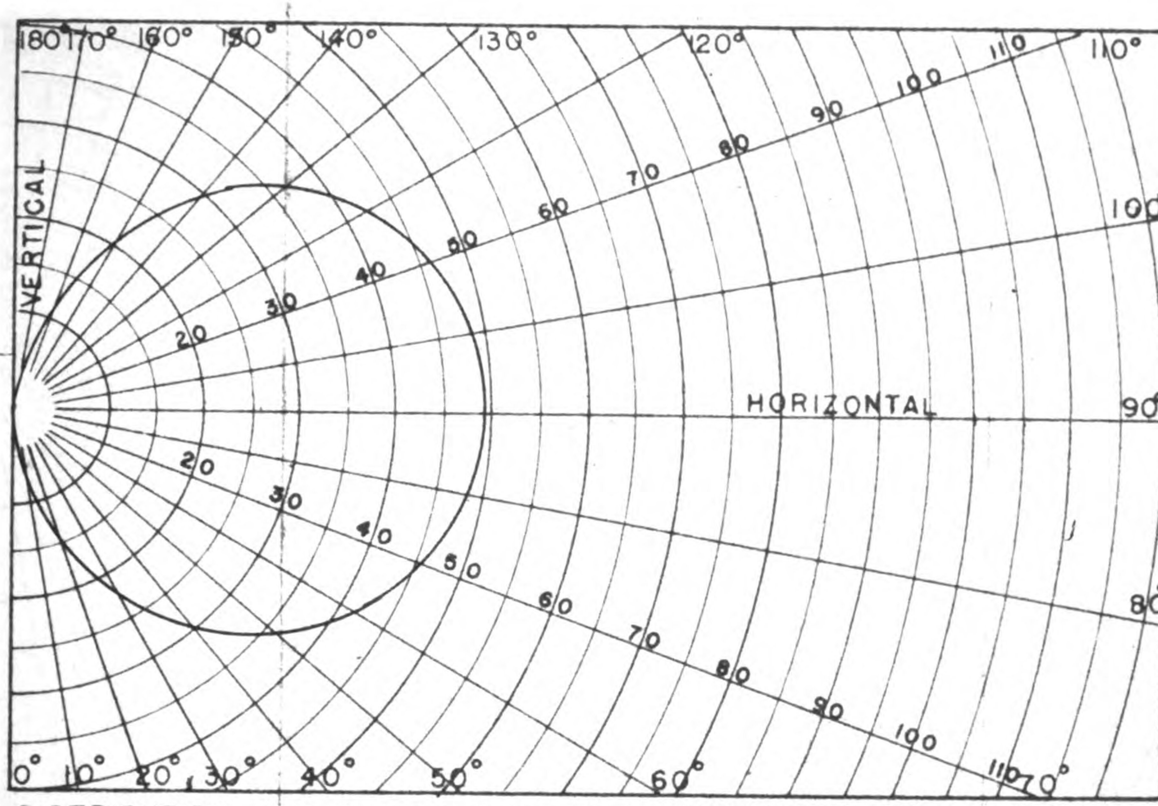
(5) REFLECTORS OF VARYING LENGTH AND POSITION

FIGURE 7. APPARATUS AND SET-UP FOR THE FIRST LABORATORY INVESTIGATION.



1) Potentiometer.
2) Radiating Surface.
3) Lower Reflector.
4) Upper Reflector.
5) Mounting for Measuring Angles of the Radiating Surface.
6) Thermopile.

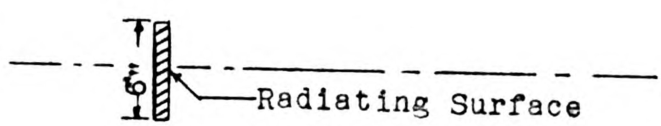
FIGURE 8. APPARATUS USED IN THE FIRST LABORATORY INVESTIGATION.



DISTRIBUTION CURVE FOR RADIATION INTENSITY AT 10 FEET

ANGLE FROM VERTICAL	Intensity (Mv)*
Temp.-1250F.	
0	
10	5
20	15
30	23
40	30
50	36
60	41
70	45
80	48
90	49
100	48
110	47
120	43
130	37
140	30
150	20
160	12
170	5
180	

DATA

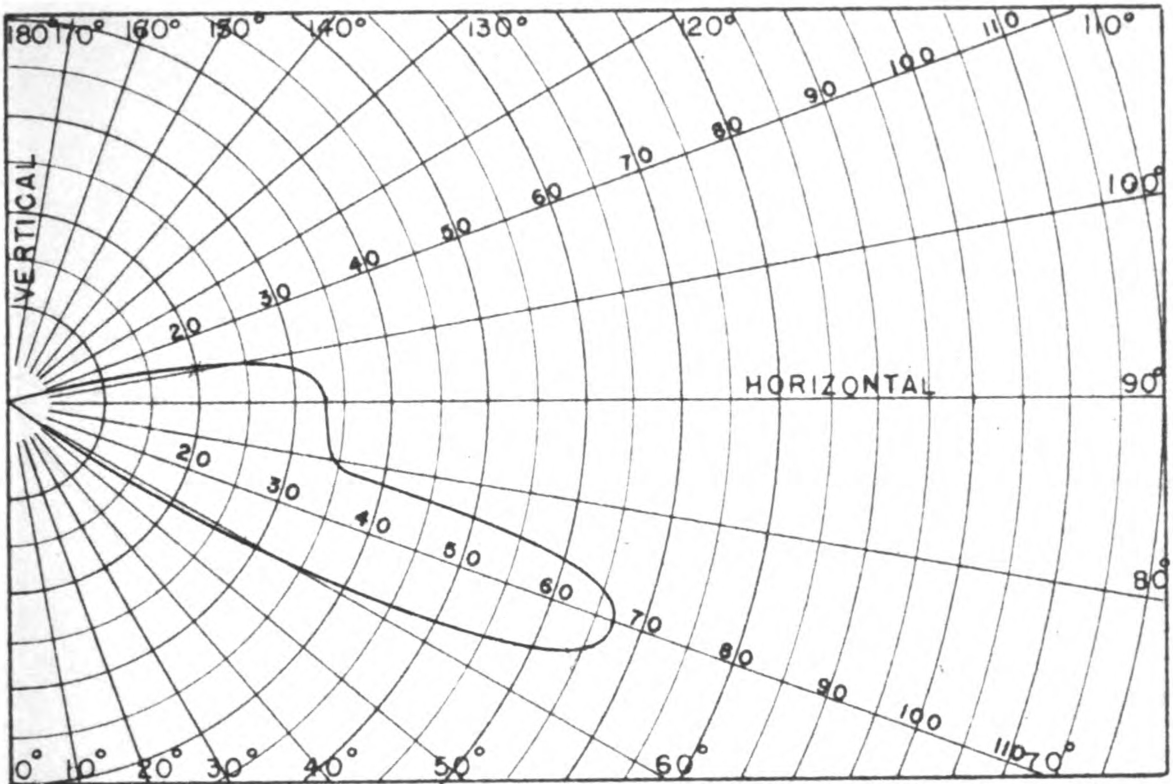


Scale 1"= 1'

DIAGRAM OF TEST SET-UP

* 1 Microvolt =35.6 Microwatts per sq.cm.

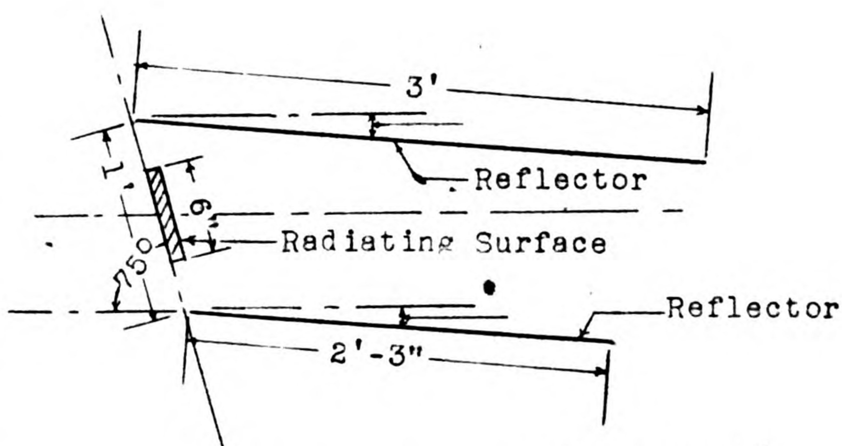
FIGURE 9



DISTRIBUTION CURVE FOR RADIATION INTENSITY AT 10 FEET

ANGLE FROM VERTICAL	Intensity (Mv)*
Temp.- 1250F	
0	
10	
20	
30	
40	
50	0
60	28
70	67
80	34
90	33
100	20
110	0
120	
130	
140	
150	
160	
170	
180	

DATA

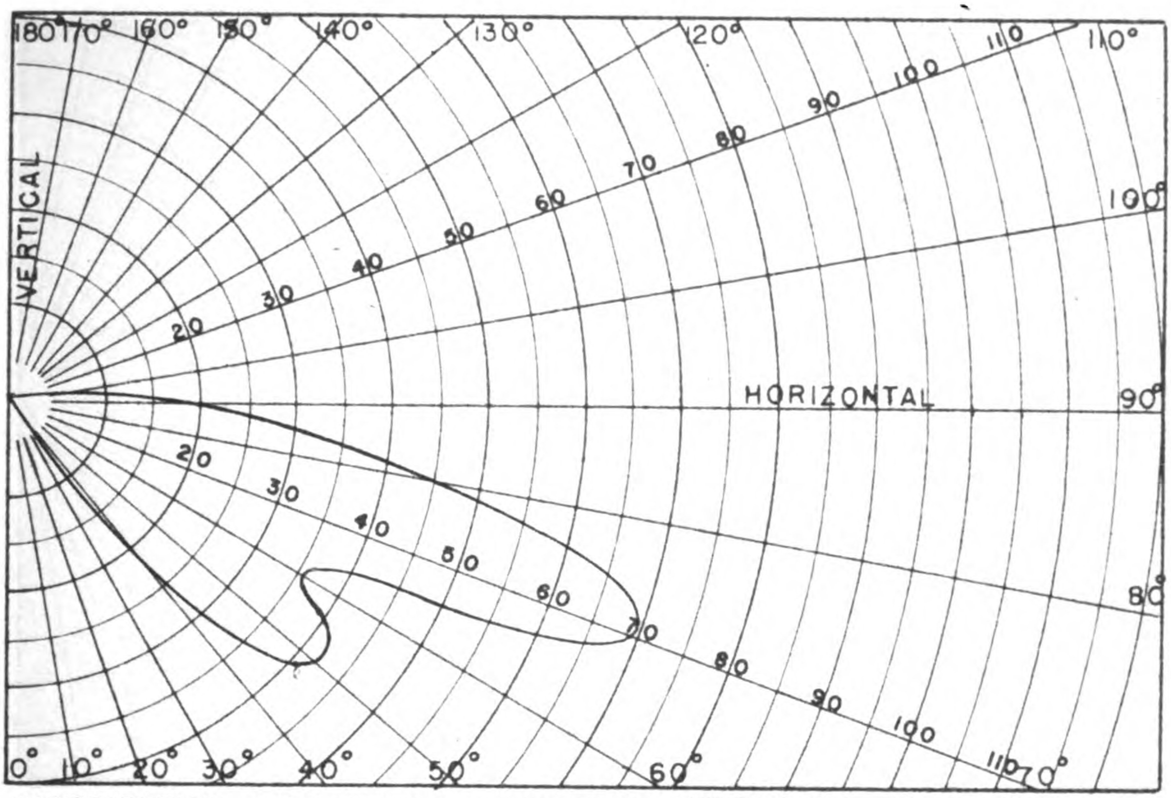


Scale 1"= 1'

DIAGRAM OF TEST SET-UP

* 1 Microvolt = 35.6 Microwatts per sq.cm.

FIGURE 10



DISTRIBUTION CURVE FOR RADIATION INTENSITY AT 10 FEET

ANGLE FROM VERTICAL	Intensity (Mv)*
Temp.-1250F.	
0	
10	
20	
30	
40	20
50	42
60	36
70	69
80	44
90	20
100	5
110	
120	
130	
140	
150	
160	
170	
180	

DATA

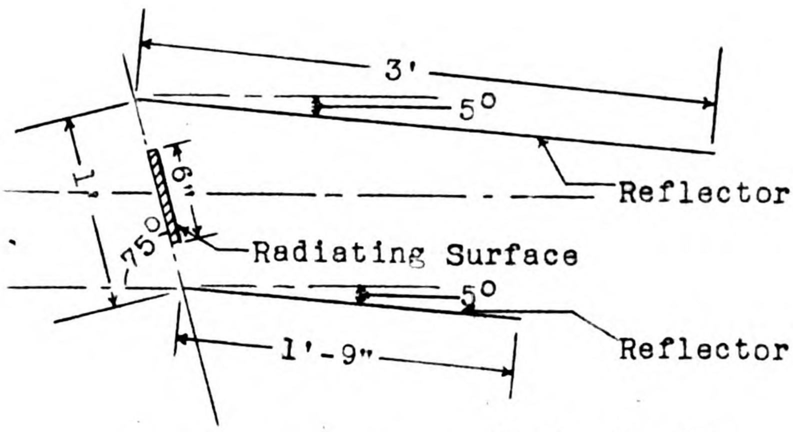
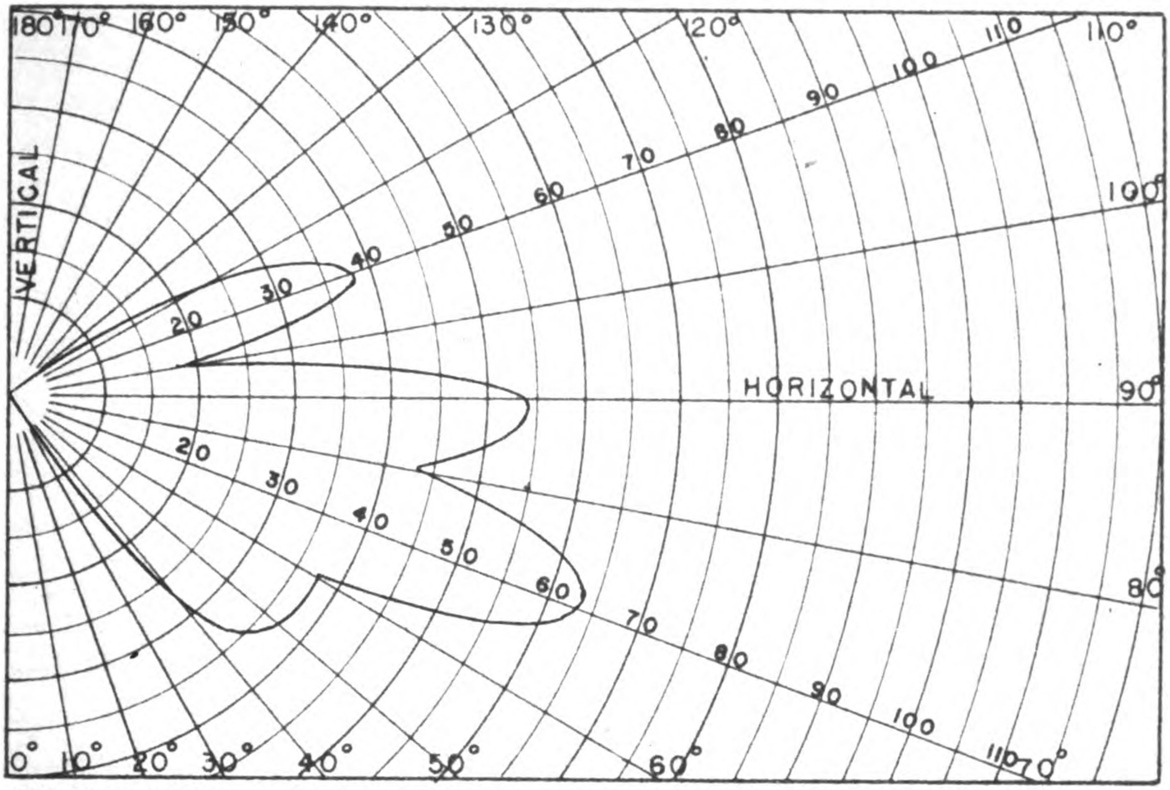


DIAGRAM OF TEST SET-UP

* 1 Microvolt = 35.6 Microwatts per sq.cm.

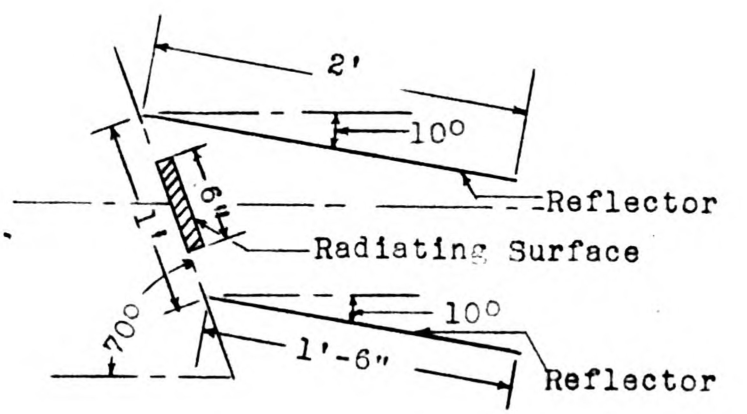
FIGURE 11.



DISTRIBUTION CURVE FOR RADIATION INTENSITY AT 10 FEET

ANGLE FROM VERTICAL	Intensity (Mv)*
Temp.-1250F.	
0	
10	
20	
30	5
40	27
50	37
60	37
70	63
80	43
90	54
100	20
110	38
120	23
130	5
140	
150	
160	
170	
180	

DATA

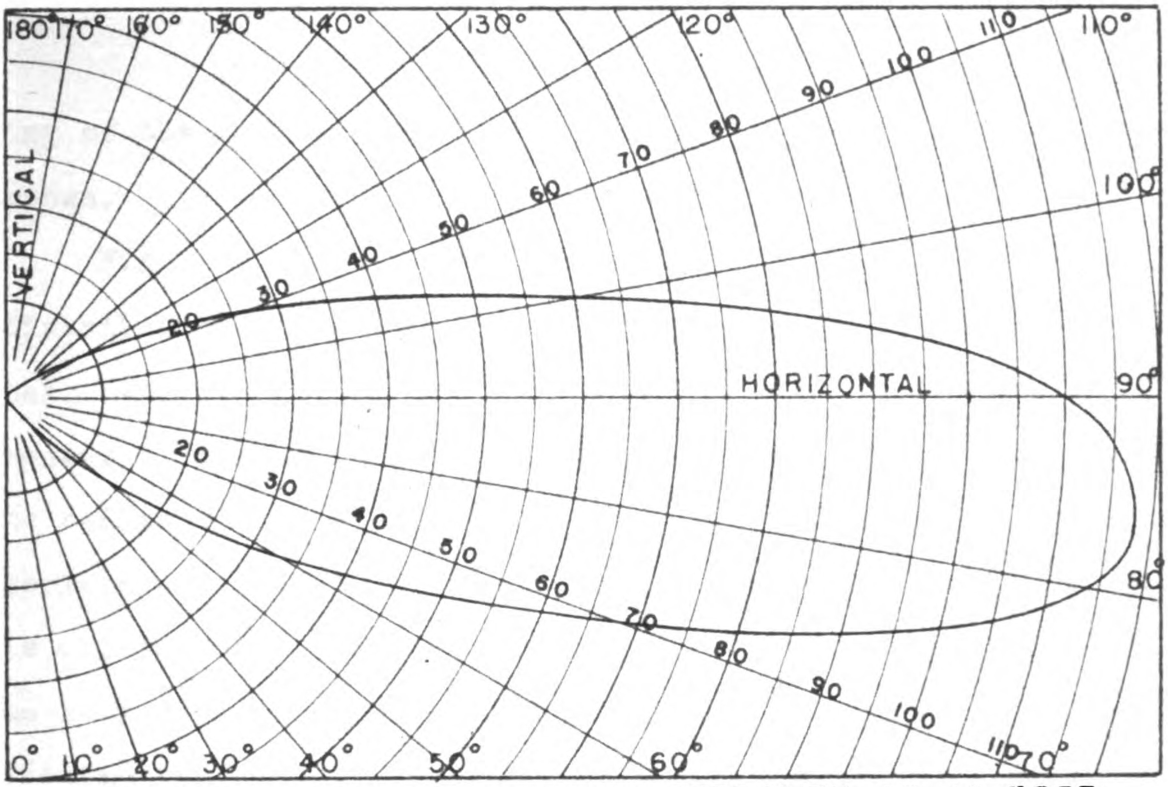


Scale 1"= 1'

DIAGRAM OF TEST SET-UP

* 1 Microvolt = 35.6 Microwatts per sq.cm.

FIGURE 12.



DISTRIBUTION CURVE FOR RADIATION INTENSITY AT 10 FEET

ANGLE FROM VERTICAL	Intensity (Mv)*
Temp.-1250 F.	
0	
10	
20	
30	
40	
50	16
60	35
70	68
80	120
90	110
100	60
110	24
120	8
130	
140	
150	
160	
170	
180	

DATA

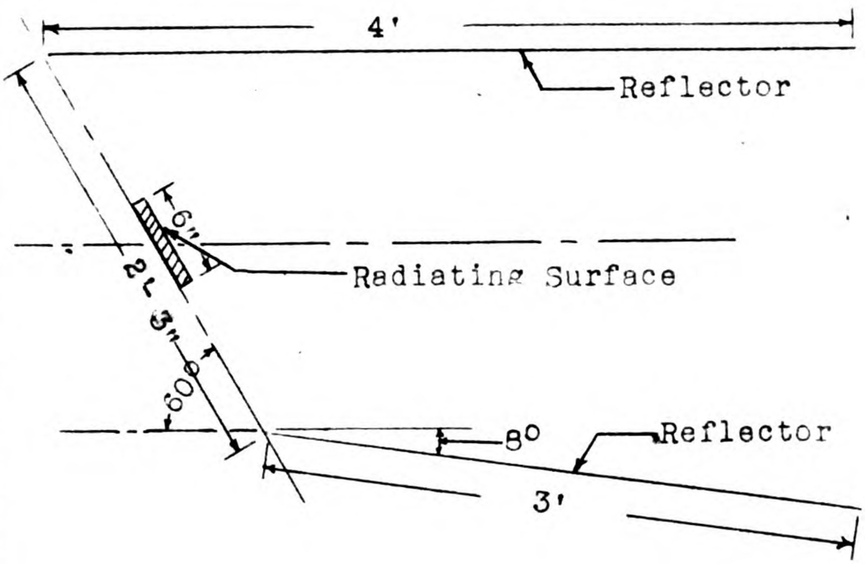


DIAGRAM OF TEST SET-UP

* 1 Microvolt = 35.6 Microwatts per sq.cm.

FIGURE 13.

ing of the radiating surface and the reflectors is shown.

Figure 9 shows a symmetrical curve, with an equal distribution of intensity above and below the horizontal. The strongest point of intensity was at the horizontal or normal to the radiating surface. There were no reflectors to divert the energy from above the horizontal, and all of the energy above the horizontal is considered to be lost. Therefore, the problem was to so position reflectors of adequate length in relation to the radiating surface that the radiation would be converged below the horizontal.

Figures 10 through 13 show other typical results from the various positionings. Figure 13 was especially interesting, as the results showed most of the radiation converged within a narrow angle interval.

From this experiment it was concluded that the inverse square law could be offset.

4. The Second Laboratory Investigation

The first laboratory investigation demonstrated that the inverse square law could be offset; the second laboratory investigation was made to get further information. The effort in this experiment was to see if the energy could be converged like a beam towards the vegetation to be protected.

In this experiment the radiating surface was an eighteen-inch commercial electrical strip heater, which was expected to give more effective results than did the six-inch surface. It was shaped three ways on a hydraulic press with jig: straight, slightly curved, and curved on a small radius of curvature. The radiating surface was mounted so that its angle with the so-called horizontal could be changed.

Figure 14 shows the apparatus for this investigation. The reflectors consisted of chrome-plated stainless steel, so they would be affected by magnets. A labelled grid was drawn up, and the shape of the reflectors was changed by changing the position of the magnets on this grid, which made it easy to record the reflector shape in each case. It will also be noticed

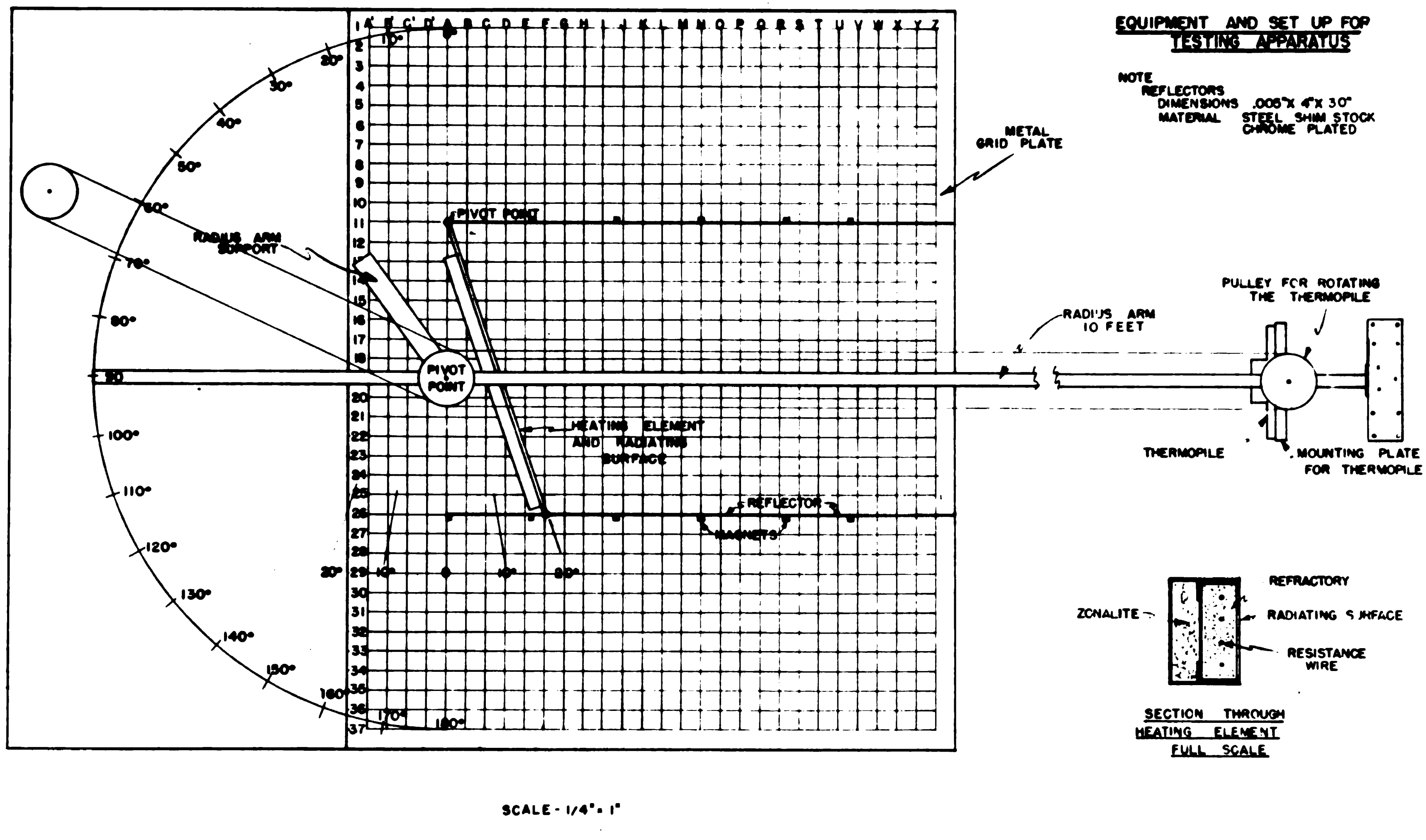
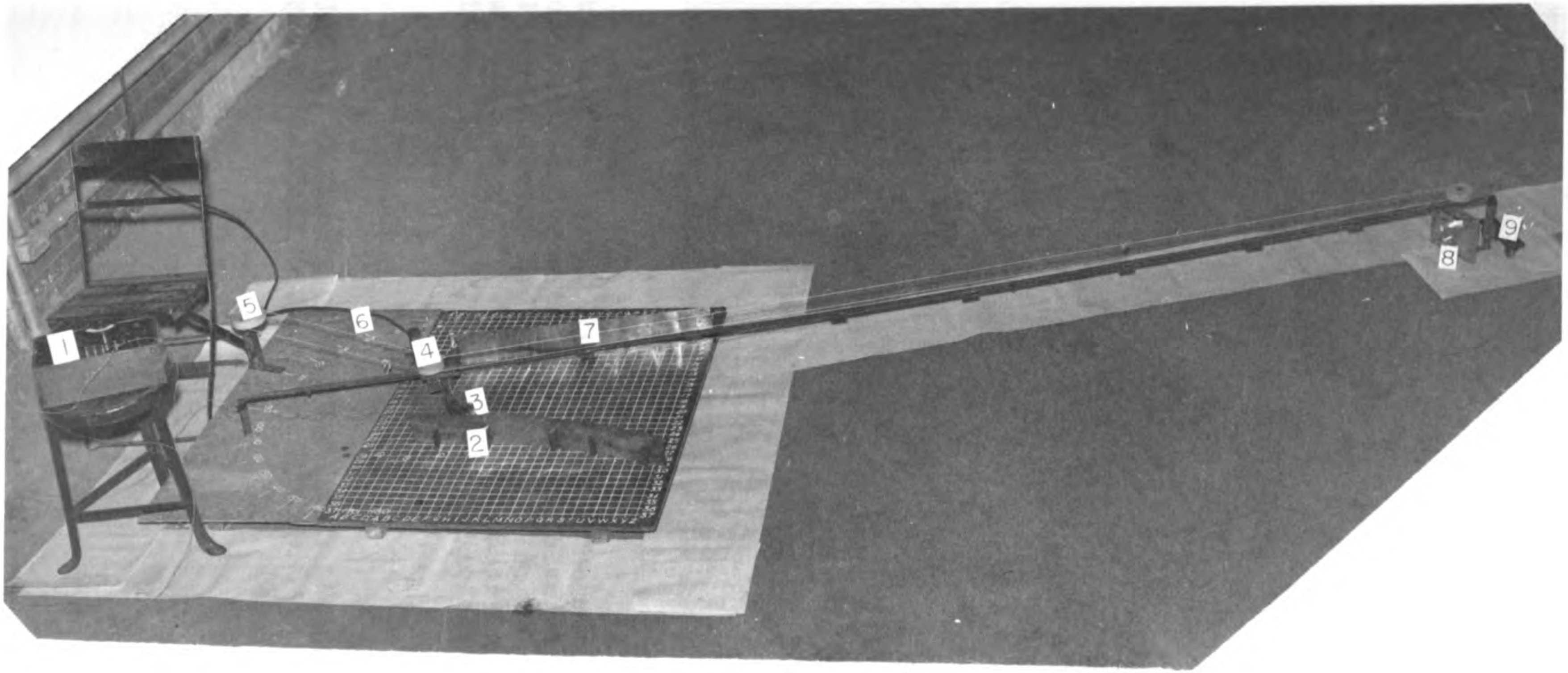


FIGURE 14. APPARATUS AND SET-UP FOR THE SECOND LABORATORY INVESTIGATION.

that the thermopile was so mounted that it could be rotated by a pulley arrangement, and therefore one man could make the investigation. A photograph of the entire apparatus is shown in Figure 15. Figure 16 illustrates how the reflectors were bent by the magnets. Figure 17 shows the pulley arrangement whereby the thermopile could be rotated at the ten-foot radius from which the readings were taken.

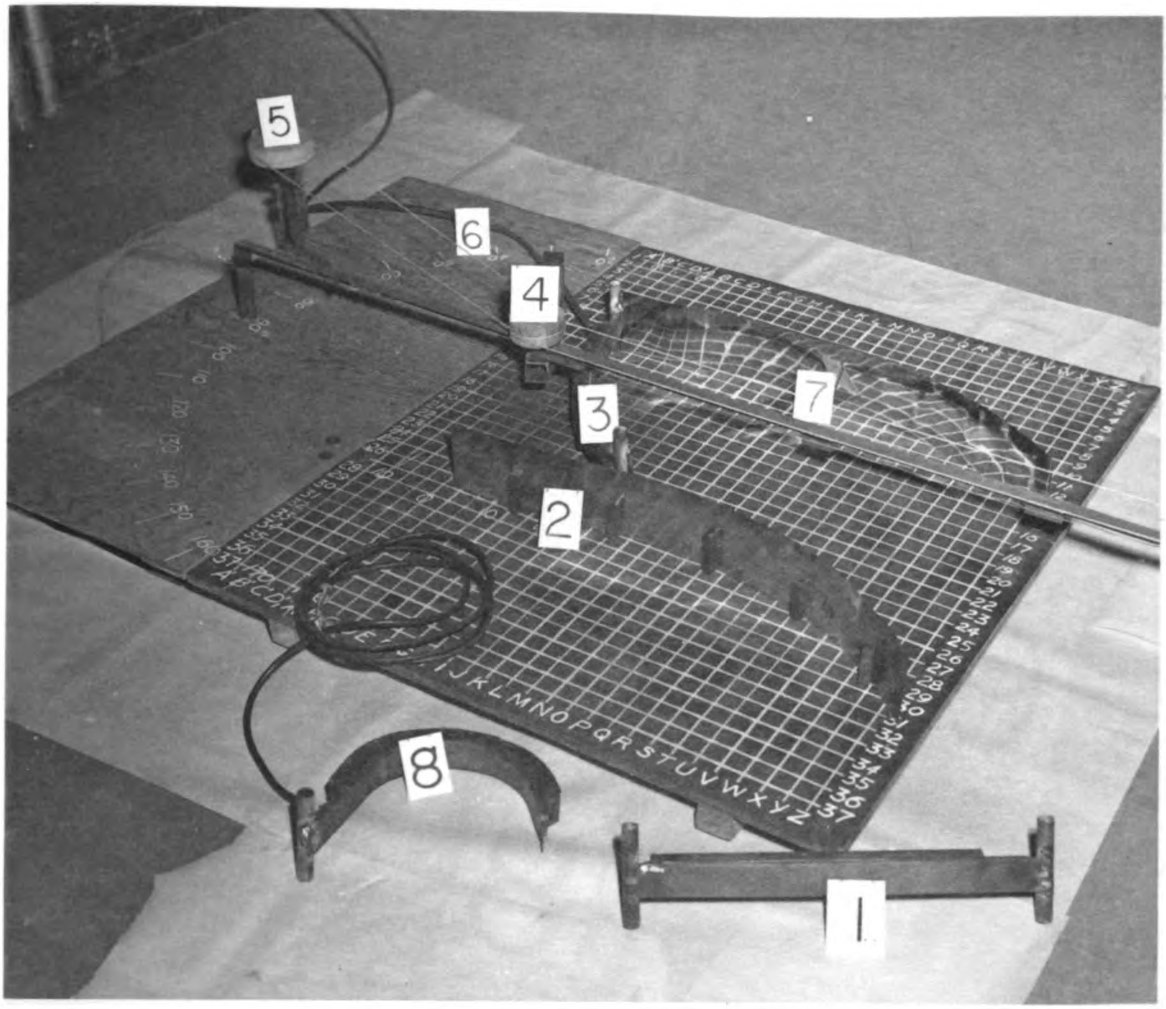
Figures 18 through 23 show the typical results obtained in this investigation. Figure 19 shows an energy distribution curve for the slightly-curved radiating surface when no reflectors are used. It will be noted that a complete and symmetrical curve does not result, and furthermore, there is slight "beaming" effect from the curving of the radiating surface. Figure 20 shows that curving the radiating surface to a small radius of curvature does give a noticeable beaming; however, in comparison with Figures 9, 18, and 19, a reduced radiation intensity is indicated.

Figures 21 through 23 show typical results obtained with various shapes and positionings of both the



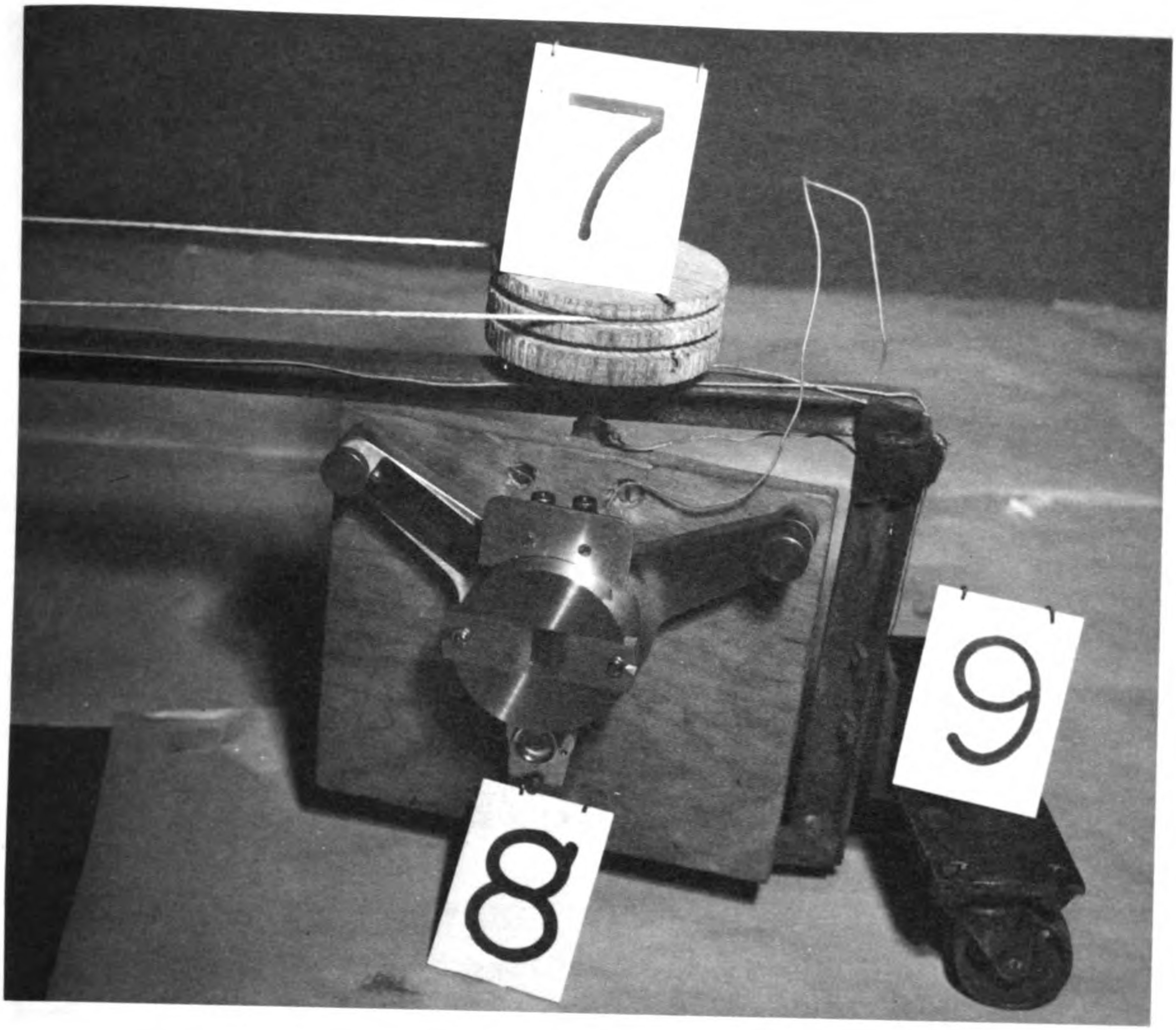
1) Potentiometer.
2) Lower Reflector with Magnets.
3) Radiating Surface.
4) Pivot.
5) Thermopile Positioner.
6) Electric Cords.
7) Reflector.
8) Thermopile.
9) Caster.

FIGURE 15. APPARATUS USED IN THE SECOND LABORATORY INVERSTIGATION.



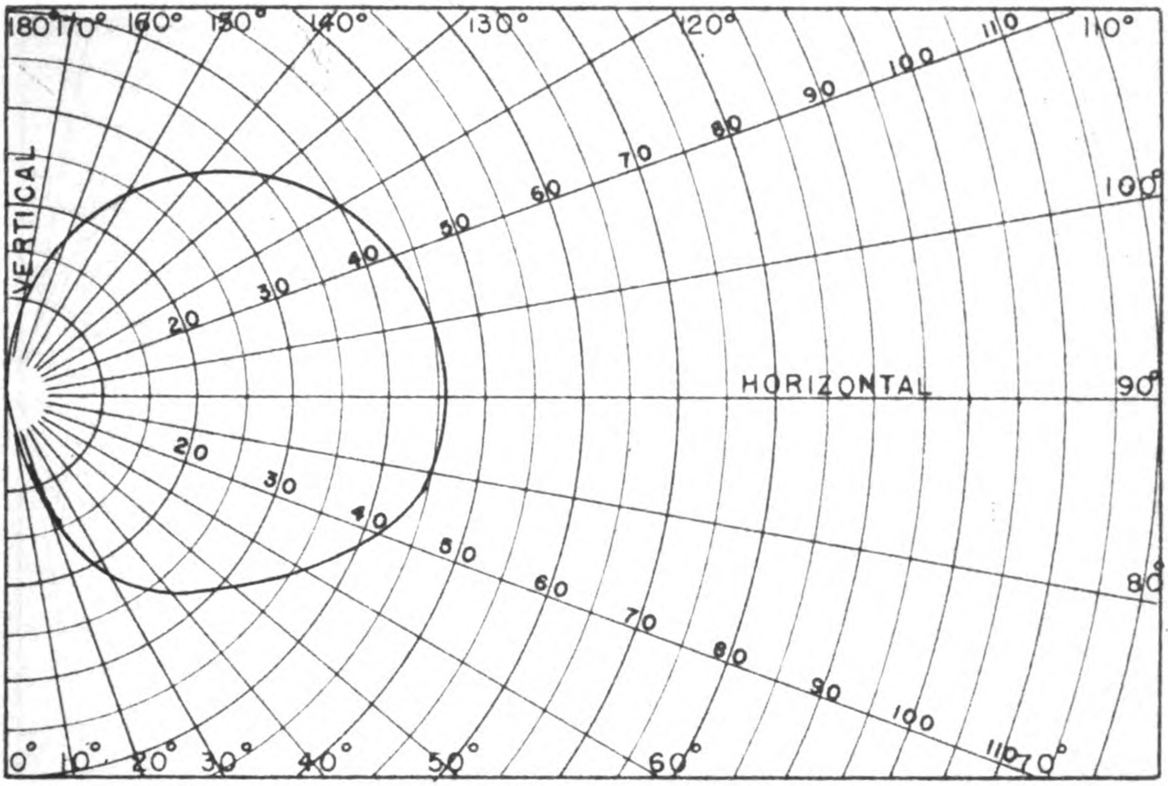
1) Straight Radiating Surface.
2) Lower Reflector with Magnets.
3) Slightly Curved Radiating Surface.
4) Pivot.
5) Thermopile Positioner.
6) Electric Cord.
7) Top Relfector.
8) Sharply Curved Radiating Surface.

FIGURE 16. CLOSE-UP OF THE LABELLED GRID WITH THE THREE SHAPES OF RADIATING SURFACES TESTED.



7) Pivot. 8) Thermopile. 9) Caster.

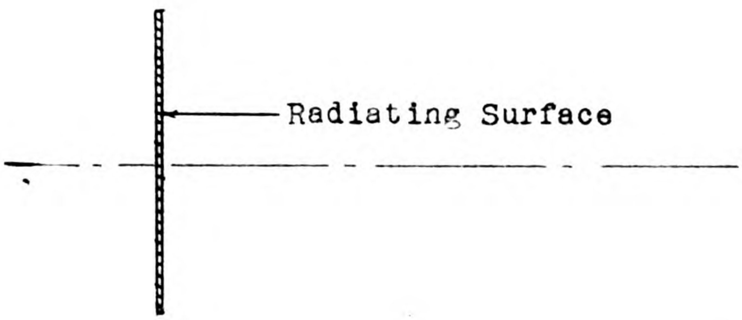
FIGURE 17. DETAIL OF THERMOPILE MOUNTING.



DISTRIBUTION CURVE FOR RADIATION INTENSITY AT 10 FEET

ANGLE FROM VERTICAL	Intensity (Mv)*
Temp.- 1	150F
0	
10	5
20	14
30	23
40	27
50	32
60	36
70	42
80	45
90	45
100	44
110	42
120	38
130	34
140	29
150	23
160	15
170	9
180	

DATA

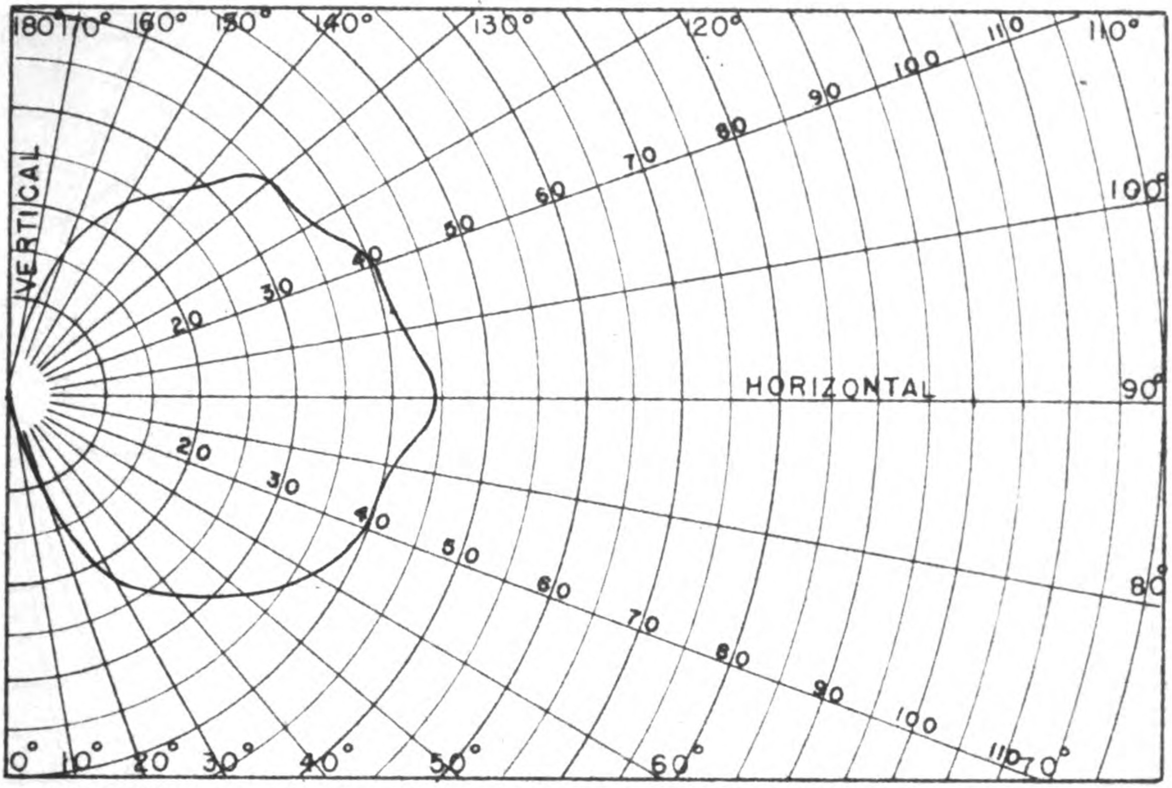


Scale 1"= 1'

DIAGRAM OF TEST SET-UP

* 1 Microvolt = 35.6 Microwatts per sq.cm.

FIGURE 18.



DISTRIBUTION CURVE FOR RADIATION INTENSITY AT 10 FEET

ANGLE FROM VERTICAL	Intensity (Mv)*
Temp.-1125 F.	
0	
10	4
20	13
30	21
40	27
50	32
60	37
70	40
80	41
90	44
100	42
110	41
120	36
130	36
140	28
150	23
160	16
170	8
180	

DATA

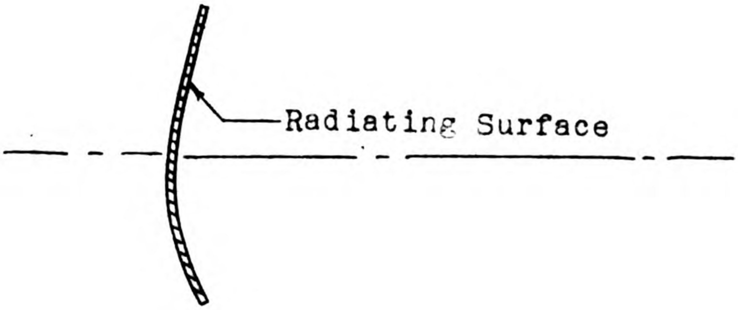
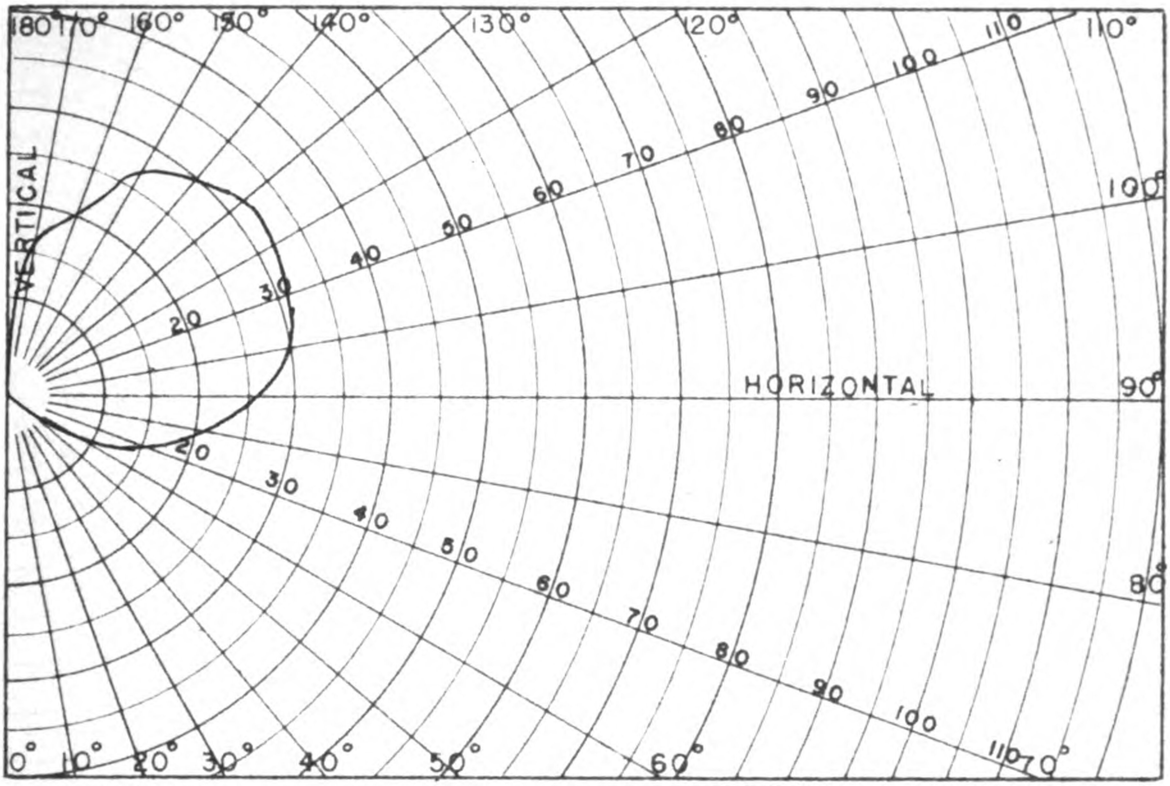


DIAGRAM OF TEST SET-UP

Scale 1"= 1'

* 1 Microvolt = 35.6 Microwatts per sq.cm.

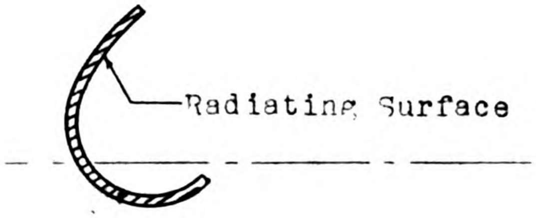
FIGURE 19.



DISTRIBUTION CURVE FOR RADIATION INTENSITY AT 10 FEET

ANGLE FROM VERTICAL	Intensity (Mv)*
Temp.-1050F.	
0	
10	
20	
30	
40	
50	
60	
70	16
80	21
90	24
100	30
110	31
120	32
130	32
140	30
150	27
160	20
170	17
180	

DATA

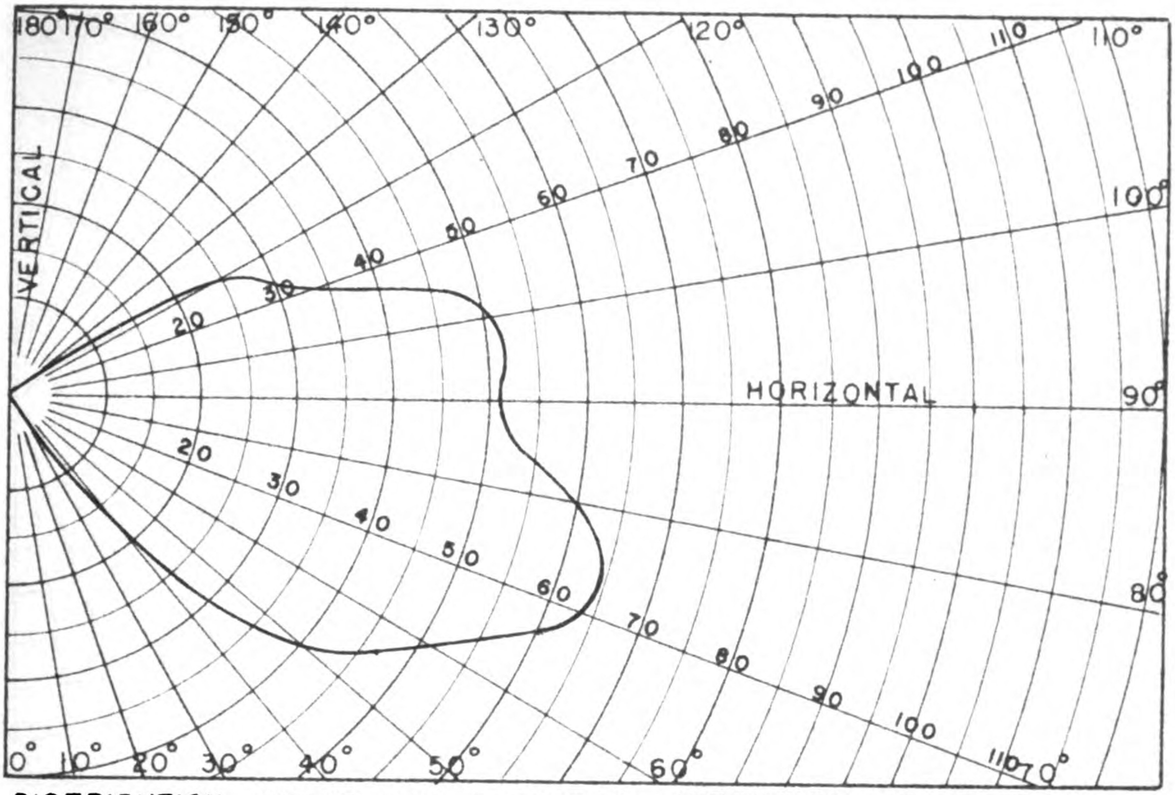


Scale 1"=1'

DIAGRAM OF TEST SET-UP

* 1 Microvolt = 35.6 Microwatts per sq.cm.

FIGURE 20.



DISTRIBUTION CURVE FOR RADIATION - INTENSITY AT 10 FEET

ANGLE FROM VERTICAL	INTENSITY MICRO-VOLTS*
Temp. - 1125 F.	
0	
10	
20	
30	4
40	15
50	39
60	50
70	63
80	61
90	51
100	51
110	33
120	25
130	8
140	
150	
160	
170	
180	

DATA

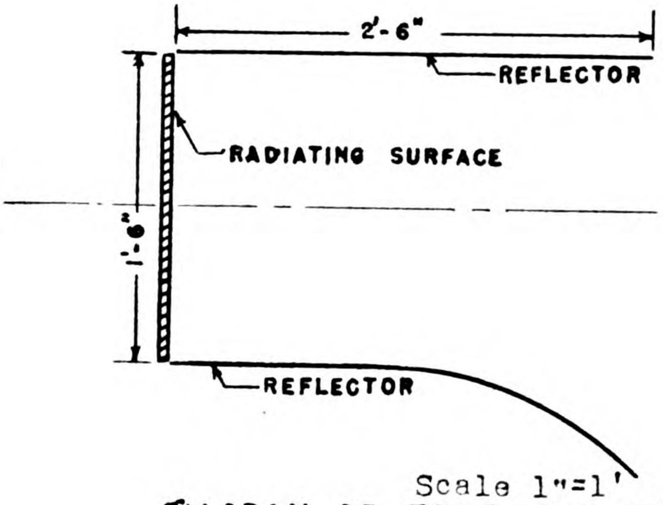
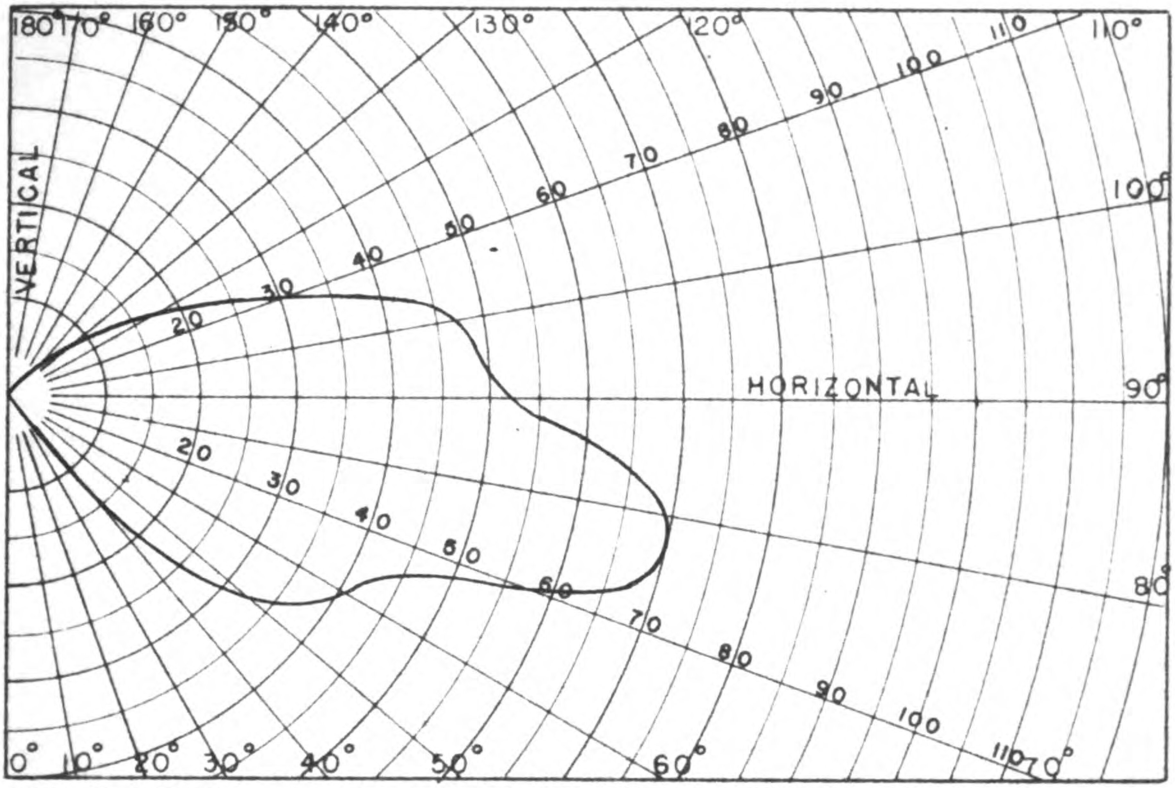


DIAGRAM OF TEST SET-UP

*1 Microvolt = 35.6 Microwatts per sq.cm.

FIGURE 21.



DISTRIBUTION CURVE FOR RADIATION INTENSITY AT 10 FEET

ANGLE FROM VERTICAL	INTENSITY MICRO-VOLTS*
Temp.-1125F.	
0	
10	
20	
30	
40	16
50	34
60	41
70	58
80	68
90	52
100	47
110	28
120	17
130	4
140	
150	
160	
170	
180	

DATA

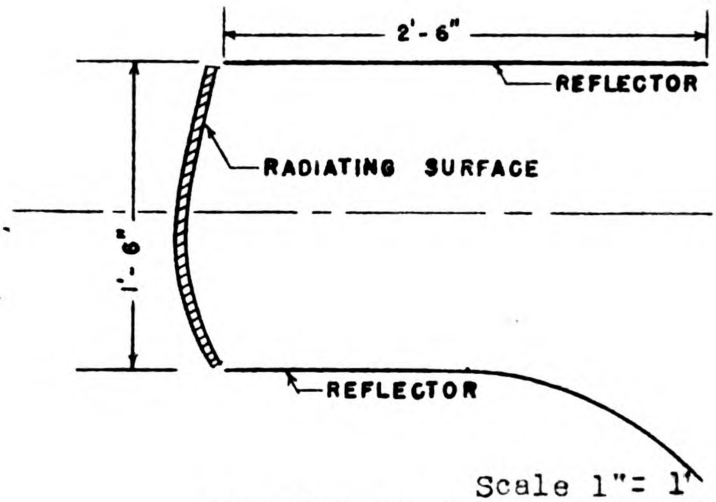
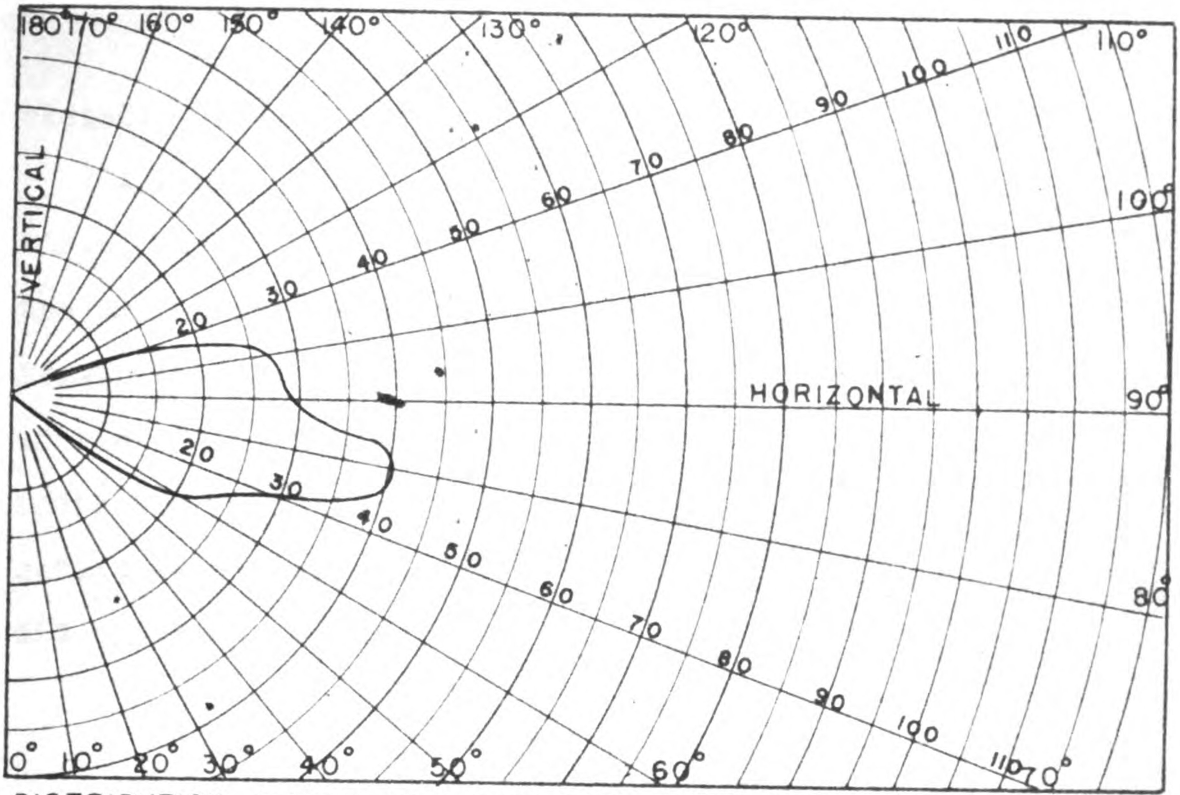


DIAGRAM OF TEST SET-UP

* 1 Microvolt = 35.6 Microwatts per sq.cm.

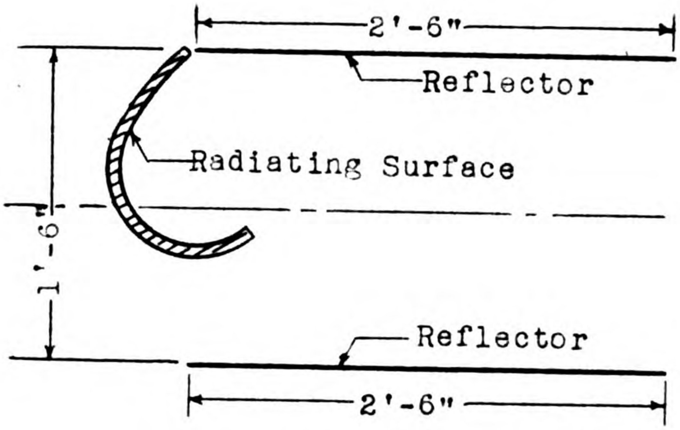
FIGURE 22.



DISTRIBUTION CURVE FOR RADIATION INTENSITY AT 10 FEET

ANGLE FROM VERTICAL	Intensity (Mv)*
Temp.-1050F.	
0	
10	
20	
30	
40	
50	3
60	21
70	29
80	40
90	28
100	27
110	11
120	
130	
140	
150	
160	
170	
180	

Data



Scale 1"= 1'

DIAGRAM OF TEST SET-UP

* 1 Microvolt = 35.6 Microwatts per sq.cm.

FIGURE 23.

radiating surfaces and the reflectors.

A study of this evidence lead to two conclusions. First, curvature of the radiating surface cut down on the amount of radiation. Probably it radiated back on itself instead of outwards and thus reduced the projected radiating surface. Second, little advantage was indicated from curving either the reflectors or the radiating surface. At least the gain in effectiveness did not seem to offset the added cost of construction.

D. Designing and Building the Units

On the basis of the laboratory investigations, four units were designed and tested. These are labelled the "A", "B", "C", and "AA". The AA unit is now being manufactured commercially by the Evans Products Company of Plymouth, Michigan, and goes under the trade name of the "Evans Frostguard."

1. Burner

An Aeroil commercial burner was used in the units, but was modified to increase the capacity by adding vaporizing coils. This modified burner is illustrated by Figure 24. The burner operates on a pressure-vaporizing principle, and the fuel is supplied under pressure with a diaphram-pump powered by a six-volt motor. Commercial kerosene was used for fuel.

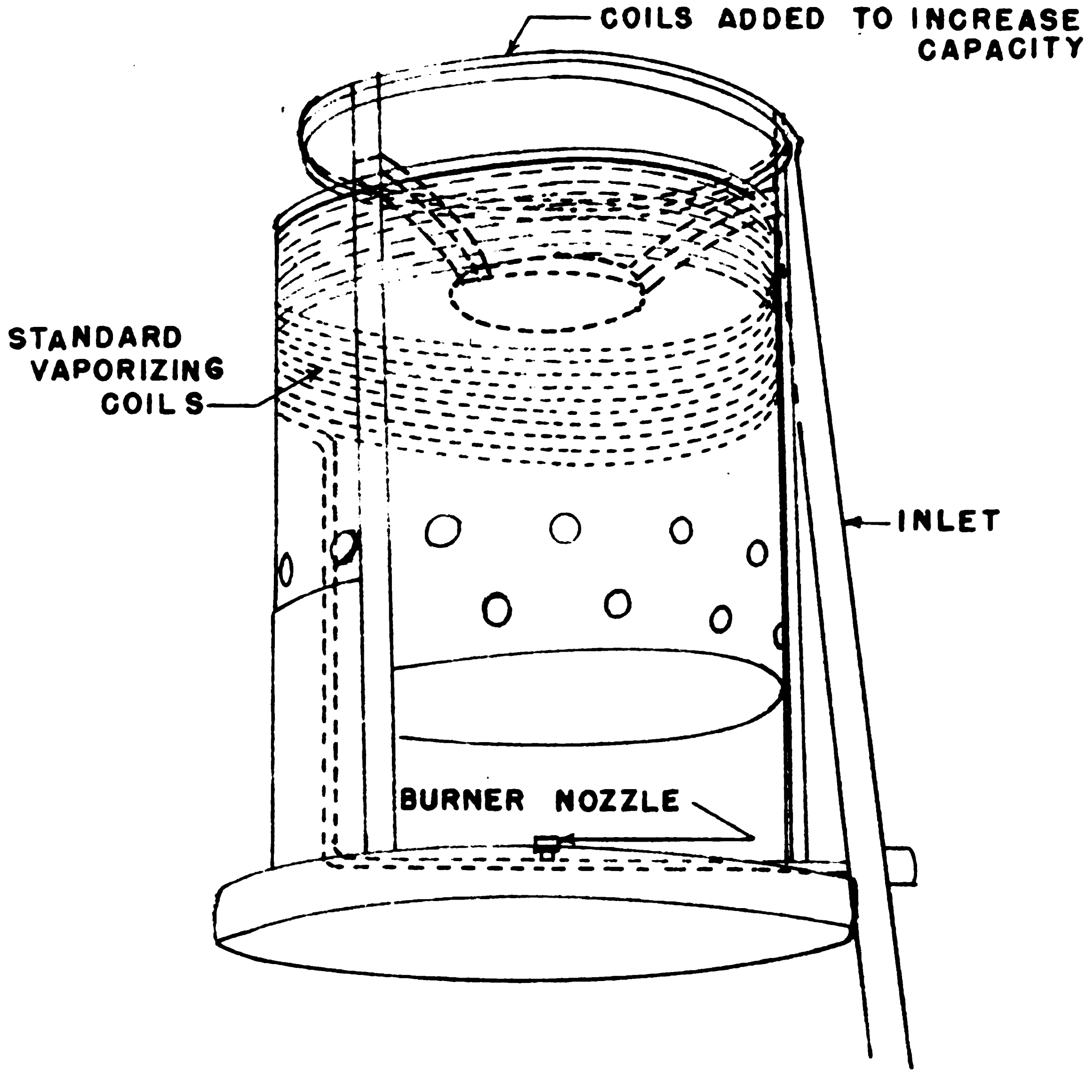


FIGURE 24. "AEROIL" BURNER WITH MODIFICATION

2. The First Design: Type A Unit

The object was to design a unit that would protect an acre of ground. In designing such a unit, the data obtained from the electrical unit described above, pp. 10-11, were used.

The electrical unit had a total of 7.86 square feet of radiating surface operating at a temperature of 800° F. This afforded protection to 1600 square feet of ground area, or 214 square feet of ground area per square foot of radiating surface.

The radiating intensity varies as the fourth power of the absolute temperature, so raising the radiation surface temperature from 800° F. to 1200° F. would result in .25 square feet of radiating surface protecting 214 square feet of ground area, or 856 square feet per square foot of radiating surface. From these figures, it can be computed that 51 square feet of radiating surface at a temperature of 1200° F. surface temperature would protect an acre. To allow for radiation loss it was decided to design the unit with a radiating surface of approximately sixty square feet.

The laboratory tests (see pp. 34 & 46 above) showed that oxidized steel radiated at the strongest intensity from rays given off normal to the surface. From this information, it was decided to design Type A unit so that the normal radiation would intercept the ground at a distance of eighty to ninety feet from the unit. This would require an inverted cone-shaped radiating shell, and there would be additional effective radiating surface when the unit was drawn back in to form a stack. This section was to have the necessary slope and relationship to reflectors to distribute most of the energy at an approximate distance of ninety feet from the unit.

For natural draft the stack outlet would require a cross-sectional area of 144 square inches, and the inlet would have to be 50% greater. This was a basis for estimating the size of inlet and outlet openings.

As most of the heat transferred from the flame to the radiating surface at the initial point of combustion would be exchanged by radiation, it was decided that a baffle would be designed to take advantage of that effect. To aid in accomplishing uniform heating of the radiating surface, the baffle was made conical-shaped to allow the top of the baffle to be closer to the radiating surface than the bottom part that is closer to the initial point of combustion.

Figure 25 is a cross-sectional drawing of this unit, and Figure 26 is a photograph of the unit. It will be noticed that the shape breaks the body of the unit into two parts; the top and bottom section. The bottom section was set 8° from the vertical to have the normal radiation intercept the ground at 85 feet. The top section was designed on the basis of the energy distribution curve of Figure 13 from the first laboratory investigation. This figure shows the radiating surface at an angle of 60° in order to get maximum radiation to eighty-five feet. The top reflector is four feet long, and the bottom one, three feet.

The unit was originally designed with three reflectors, but field test evidence, as is illustrated in Figure 27, showed that the middle reflector did not make enough difference to pay for its cost. In Figure 27, the curve (1) is with three reflectors, and the curve (2) is with two.

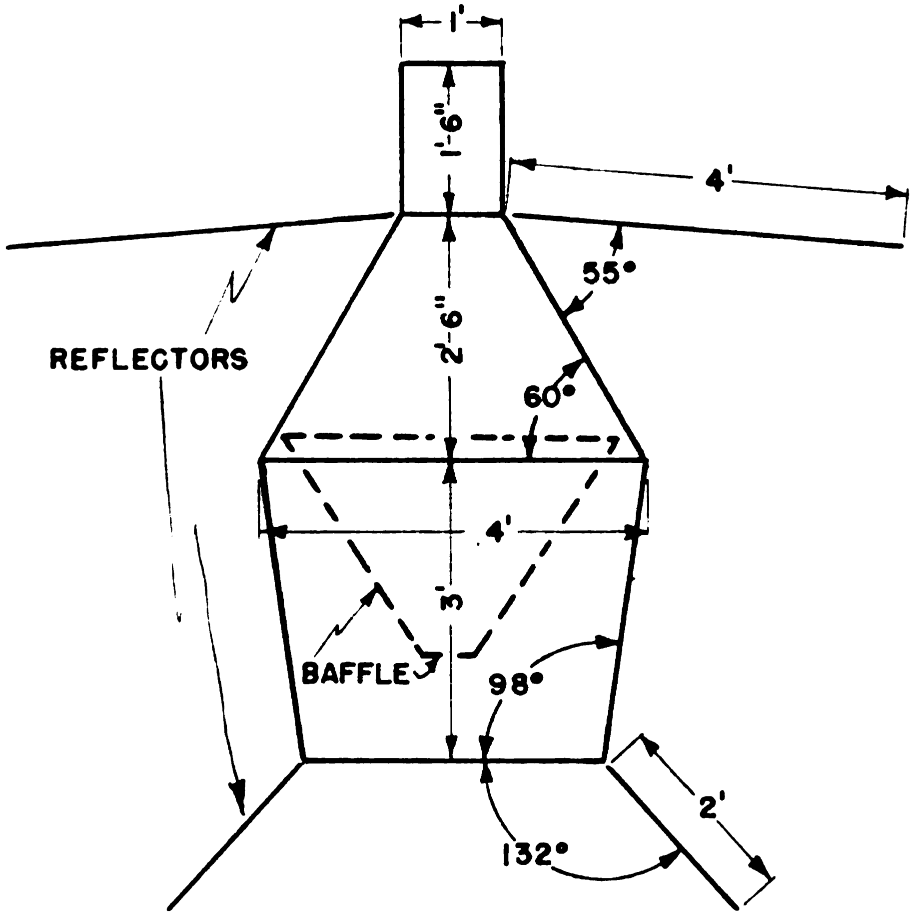


FIGURE 25. TYPE "A" FROST PREVENTION UNIT

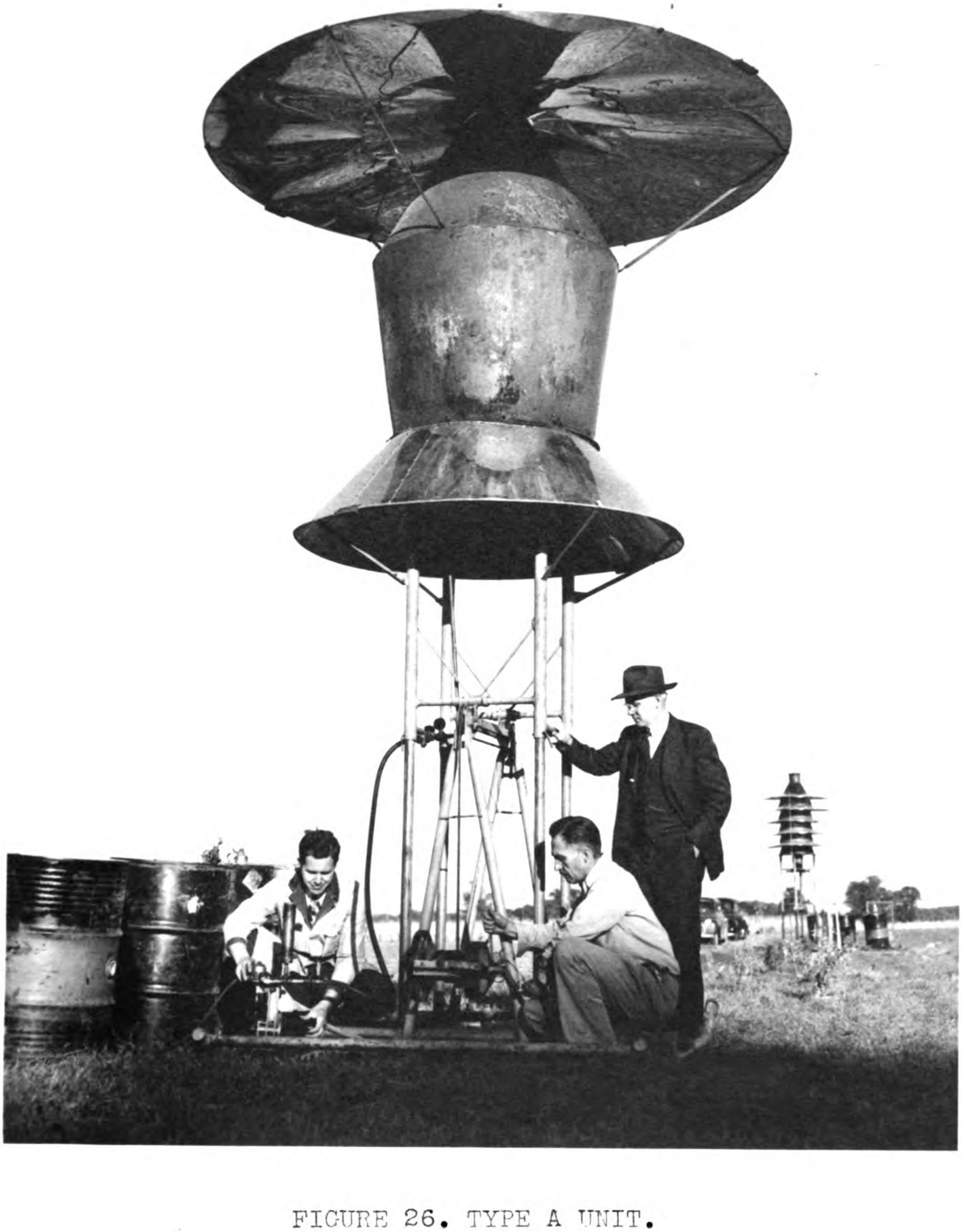


FIGURE 26. TYPE A UNIT.

3. The Field Test

Figure 27 shows the results of the field test.

The preliminary tests with the first experimental units mentioned on pages 10-12 above showed that an intensity of ninety microvolts is sufficient for frost prevention.[16] Therefore, this test denoted that one unit of this type would be effective to between fifty and sixty feet. The test also indicated that two units overlapping would be effective to eighty feet, and therefore could be placed between 140 and 160 feet apart. It should be noted that the readings were taken on the cooler, and therefore least effective, side of the unit. The curves on Figure 27 also give a complete picture of the intensity recorded out to 130 feet from the unit.

From the commercial and practical aspects, the test showed three things. First, the fuel consumption was found to be 11.36 gallons per hour. Second, one reflector was left off the unit. Third, the effective range of protection that the unit affords was indicated.

The unit was now considered ready for tests under natural frost conditions. These natural frost tests will be described later on pages 84-97 below.

TEST DATA FOR FROST PREVENTION UNITS

DATE 4-21-47 TAKEN BY HANSEN, HASSLER, PORTER

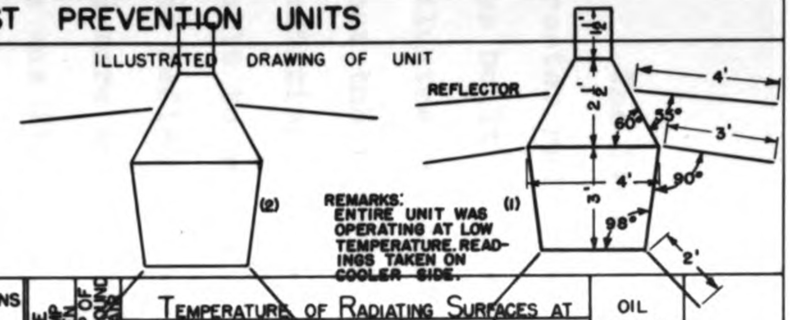
PLACE ACROSS ROAD SOUTH OF CHEMISTRY BUILDING

TYPE OF UNIT TYPE "A" TYPE OF BURNER

MODIFICATION OF UNIT (1) ALL REFLECTORS ON (2) MIDDLE REFLECTOR REMOVED

CENTER LINE HEIGHT OF UNIT

ILLUSTRATED DRAWING OF UNIT



	TIME UNIT STARTED	TIME TEST STARTED	TIME TEST ENDED	ELAPSED TIME	WEIGHT OF FUEL AT START OF TEST	WEIGHT OF FUEL AT END OF TEST	WEIGHT OF FUEL CONSUMED	POUNDS PER HOUR	GALLONS PER HOUR	TIME TEMP TAKEN	TEMP OF SURROUNDING AIR	TEMPERATURE OF RADIATING SURFACES AT					OIL PRESSURE
(1)	11:00	11:15		15.77'			20#	76	11.36	12:10	38.3						40#
(2)		11:54		15.77'			20	76	11.36								40#

RADIANT ENERGY MEASURED IN MICRO-VOLTS

	TIME	10'	20'	30'	40'	50'	60'	70'	80'	90'	100'	110'	120'	130'
(1)	11:15	1100	545	245	110	89	68	51	40	34	28	20	16	10
(2)	11:54	1350	500	250	140	110	76	56	40.5	31.5	23	20	17	12

ELEVATION ELEV.	READINGS AT 100' DIST. (1) READINGS	(2)
0	28	24
2'	28	24
4'	27	25
6'	25	25
8'	24	25
10'	24	25

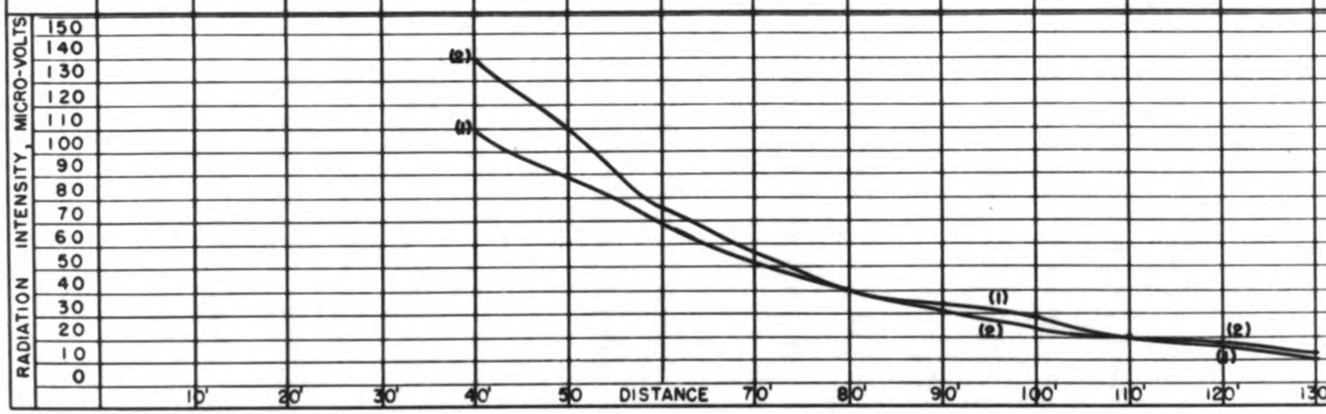


FIGURE 27. FIELD OPERATION DATA FOR TYPE A UNIT.

4. Type B Unit

The Type B unit was built to attempt to achieve greater radiation intensity at further distances. It was built on the basis of the laboratory experiment illustrated in Figure 12. This experiment indicated that the inverse square law is offset by a sloped radiating surface and two reflectors. Type B unit was built to see if a series of such radiating surfaces and reflectors would attain optimum distribution over an acre area. It was constructed of the same material as was Type A. A cross-sectional drawing of the unit is shown in Figure 28, and Figure 29 is a photograph of the unit.

Figure 30 illustrates the results of the field test with Type B. Once again the readings were taken on the coolest side of the unit.

This unit offset the inverse square law more than did the Type A unit, as radiation intensity indicated that the unit would be effective between sixty and seventy feet distance, and that two of the units would be effective if placed between 180 feet and 200 feet apart. This unit burned 10.75 gallons of fuel per hour as compared to the A, which burned 11.36 gallons per hour.

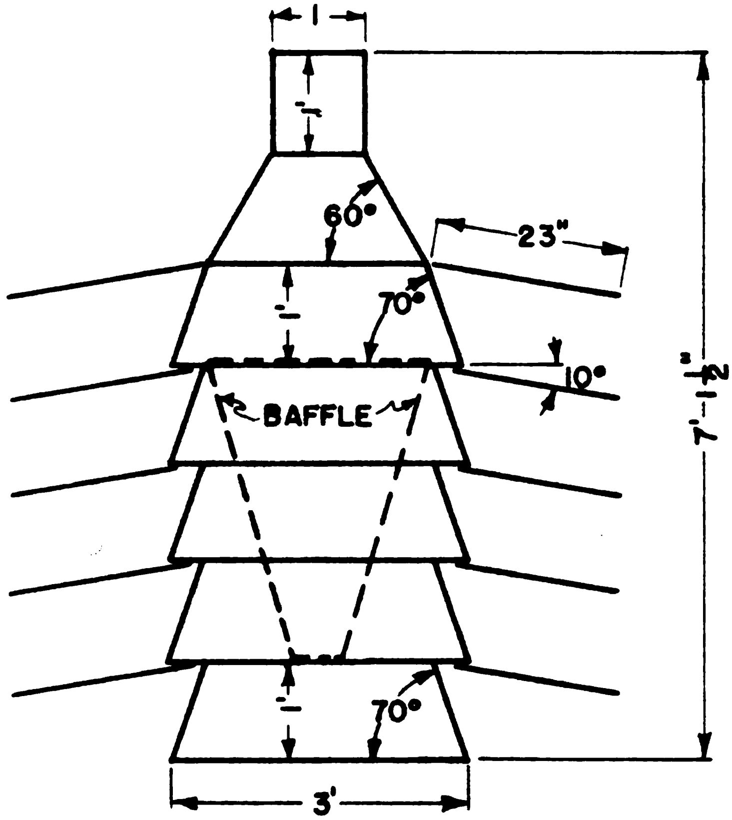


FIGURE 28. TYPE "B" FROST PREVENTION UNIT

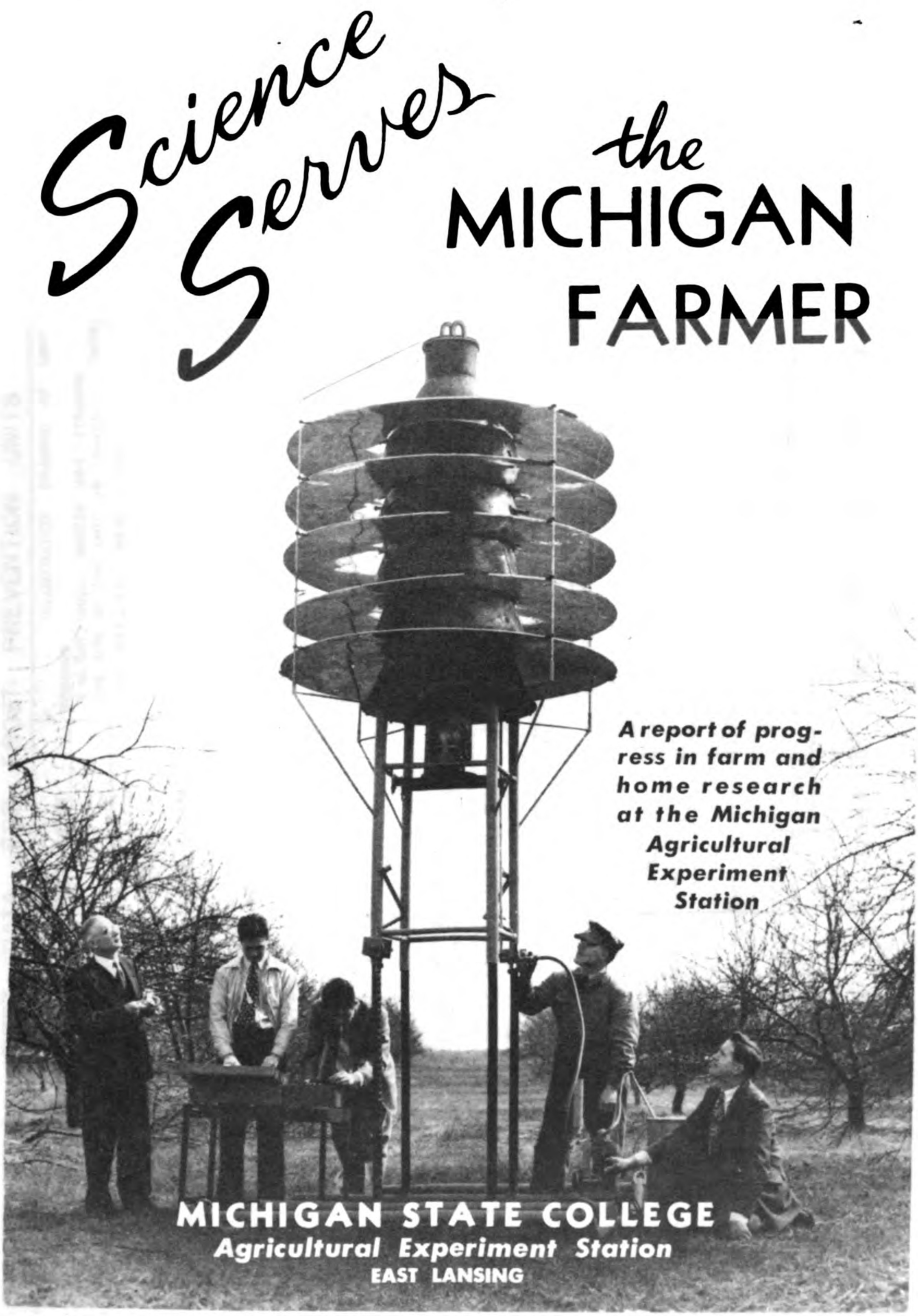


FIGURE 29. TYPE B UNIT.

TEST DATA FOR FROST PREVENTION UNITS

DATE 4-21-47 TAKEN BY FARRALL, HANSEN, HASSLER, PORTER

PLACE ACROSS ROAD SOUTH OF CHEMISTRY BLDG.

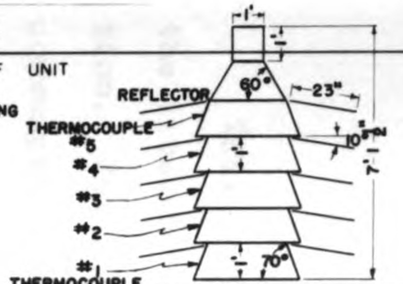
TYPE OF UNIT TYPE "B" TYPE OF BURNER MODIFIED AEROIL

MODIFICATION OF UNIT 1" DIST. BETWEEN BAFFLE & INSIDE SURFACE

CENTER LINE HEIGHT OF UNIT 12½'

ILLUSTRATED DRAWING OF UNIT

REMARKS:
A SLIGHT, CHILLY BREEZE WAS STRIKING THE SIDE OF THE UNIT ON WHICH THE READINGS WERE TAKEN.



TIME UNIT STARTED	TIME TEST STARTED	TIME TEST ENDED	ELAPSED TIME	WEIGHT OF FUEL AT START OF TEST	WEIGHT OF FUEL AT END OF TEST	WEIGHT OF FUEL CONSUMED	POUNDS PER HOUR	GALLONS PER HOUR	TIME TEMP TAKEN	TEMP OF SURROUNDING AIR	TEMPERATURE OF RADIATING SURFACES AT THERMOCOUPLE #1	#2	#3	#4	#5	OIL PRESSURE
8:20	8:32		4.166'			5#	72.1	10.75	8:48	57°	903	1213	1228	1184	1153	34
			8.32'			10#	72.1	10.75	9:05	38.3°	900	1213	1213	1168	1134	
									9:35	37.4						

RADIANT ENERGY MEASURED IN MICRO-VOLTS

TIME	10'	20'	30'	40'	50'	60'	70'	80'	90'	100'	110'	120'	130'
8:34 #1	870	630	350	200	146	110	84	73.7	62.5	55.2	48	44.5	41
8:57 #2	862	640	362	190	130	90	69	53	43	35	31	28	25

ELEVATION READINGS AT 100' DIST.

ELEV.	READINGS
0	37
2'	37
4'	37
6'	37
8'	37
10'	37

FIGURE 30. FIELD OPERATION DATA FOR TYPE B UNIT.

5. Heat Balance For the Type B

This test was run to determine the percentage of the liberated heat that is utilized for frost prevention. The first step was to measure the rate of fuel consumption, and then calculate the net BTU's liberated per hour. The next step was to calculate the BTU's radiated per hour from the unit by plotting a distribution curve for the unit. The third step was to analyze the flue gases with an orsat, and calculate the heat loss through the flue gasses. Finally, the loss by convection could be calculated by subtracting known flue gas losses and the heat radiated from the net heat liberated.

It was determined that the net heating value of the fuel was 18,640 BTU's per pound, and as fifty pounds per hour were being consumed, the net BTU's liberated per hour were 932,000.[17]

By use of an orsat, the flue-gas analysis was determined, which was:

CO_2	O_2	CO	N_2
12.7%	3.7%	0%	83.6%

Calculations[18] showed that the loss of heat from

from flue gases was 258,380 BTU's per hour, with 90, 674 BTU's per hour being lost because of excess air.

The intensity was measured and the distribution curve plotted with the results shown in Figure 31. This curve, it will be noted, is very similar to the curve obtained in the laboratory, shown in Figure 12, which was used as a basis for the design of this unit. The total radiation was then calculated[19] and determined to be 330,200 BTU's per hour, of which 156,000 fall into the effective range of 0°-85°.

The loss due to flue gases, 258,380 BTU's per hour, plus the amount of energy radiated, 330,200 BTU's per hour, total 588,580 BTU's per hour of known heat given off from the fuel. Subtract this from 932,000 BTU's per hour, the known total energy liberated, and the difference, 343,420 BTU's per hour, represents the heat loss by convection.

The summary of the results found from the heat balance are tabulated on pp. 71 & 72.

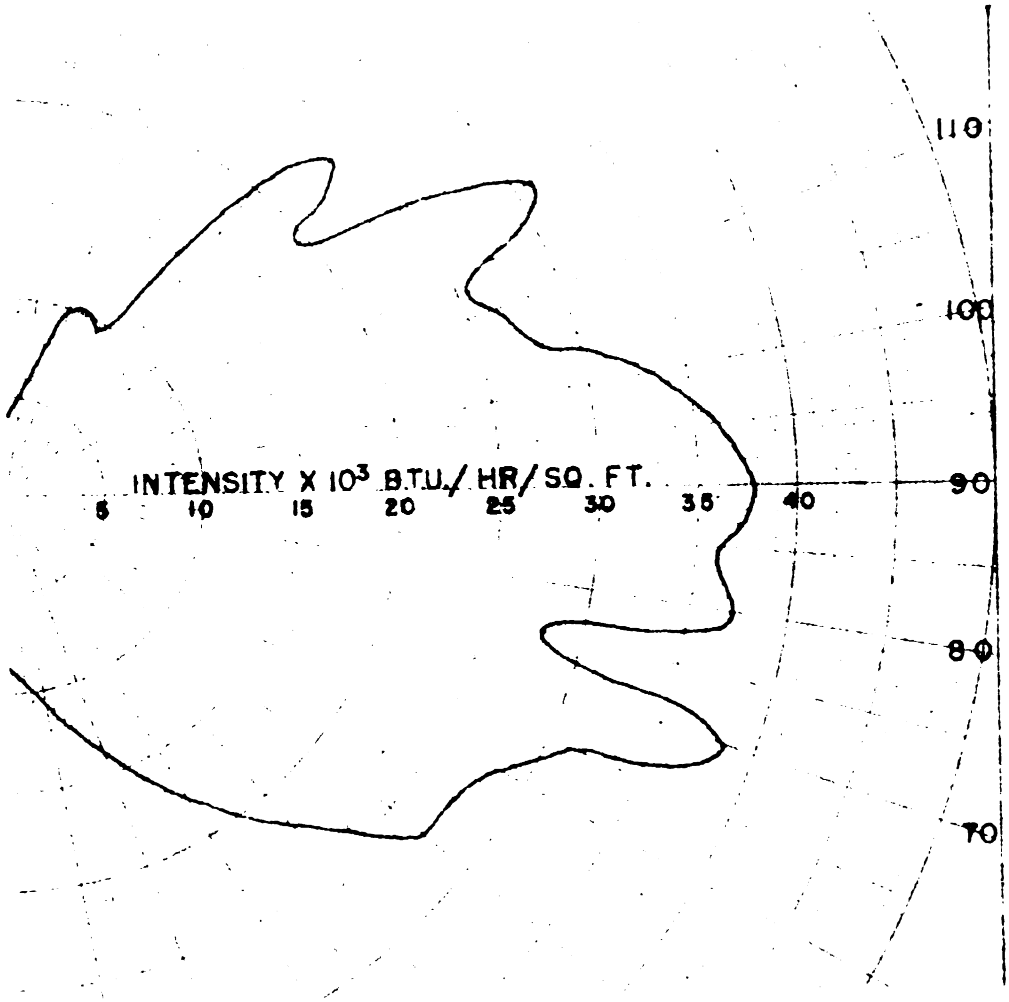


FIGURE 31. ENERGY DISTRIBUTION CURVE FOR TYPE B UNIT. CALCULATIONS BASED ON THIS CURVE DETERMINED THE PERCENTAGE OF THE TOTAL HEAT RADIATED.

Tabulated Results of Heat Balance

For Type B Unit

I Total heat liberated by combustion 932,000 Btu/Hr.

II Loss to flue gases and moisture in air supply 258,380 Btu/Hr.

Percent of heat liberated $\frac{258,380}{932,000} \times 100$ 27.7%

(Loss due to excess 90,674 Btu/Hr.

Percent of heat liberated $\frac{90,674}{932,000} \times 100$ 9.7%

III Loss by convection 343,420 Btu/Hr.

Percent of heat liberated $\frac{343,420}{932,000} \times 100$ 36.8%

IV Heat given off by radiation 330,200 Btu/Hr.

Percent of heat liberated $\frac{330,200}{932,000} \times 100$ 35.4%

A. Heat radiated above horizontal (90 to 180 degrees) 153,300 Btu/Hr.

Percent of heat liberated $\frac{153,300}{932,000} \times 100$ 16.5%

Percent of heat radiated $\frac{153,500}{330,200} \times 100$ 46.5%

B. Heat radiated below horizontal (0 to 90 degrees) 176,700 Btu/Hr.

Percent of heat liberated $\frac{176,700}{932,000} \times 100$

19%

Percent of heat radiated $\frac{176,700}{330,200} \times 100$

53.5%

C. Heat radiated from 0 to 85 degrees

156,000 Btu/Hr.

Percent of heat liberated $\frac{156,000}{932,000} \times 100$

16.75%

Percent of heat radiated $\frac{156,000}{330,200} \times 100$

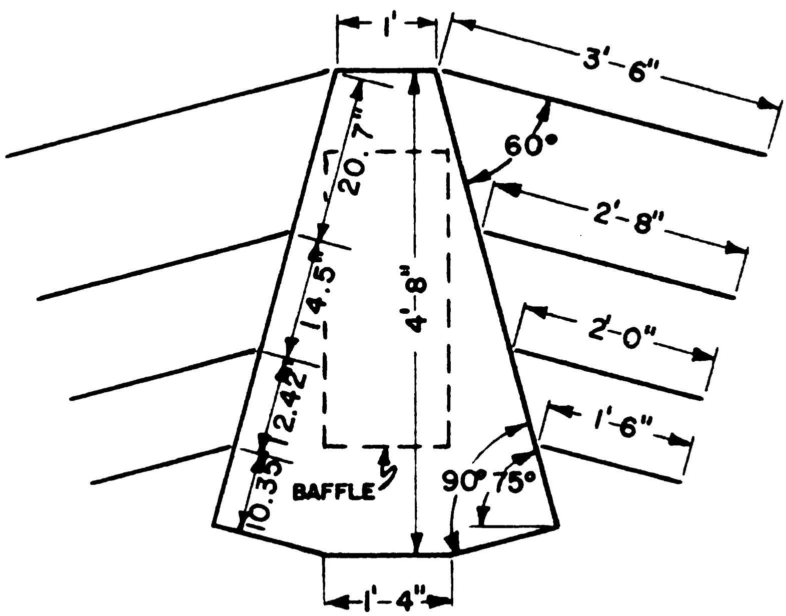
47.3%

6. Type C Unit

Type C was made from the same materials as Type A. While Type B was effective in distributing energy, it was not practical from the standpoint of commercial construction because it would be difficult and therefore expensive, to construct. It was also found that the radiating surfaces did not heat uniformly. Type C was built in an attempt to obtain the desired energy distribution with a simplified design.

Type C was designed on the basis of the laboratory curve shown in Figure 11. Figure 32 shows the cross-section of the design, and the unit is pictured in Figure 33. One of the main features of the design is a cone-shaped burner, which leads to uniform heating, for the further away from the initial point of combustion that the radiating surface is, the smaller the area to be heated.

Figure 34 shows the results of the field test. The fuel consumption of this unit, seven gallons per hour, is the lowest of the three units tested. On the other hand, the effective range is less, as it extends to between forty and fifty feet for one unit. It was



SCALE 1/2"= 1'

FIGURE 32. TYPE "C" FROST PREVENTION UNIT

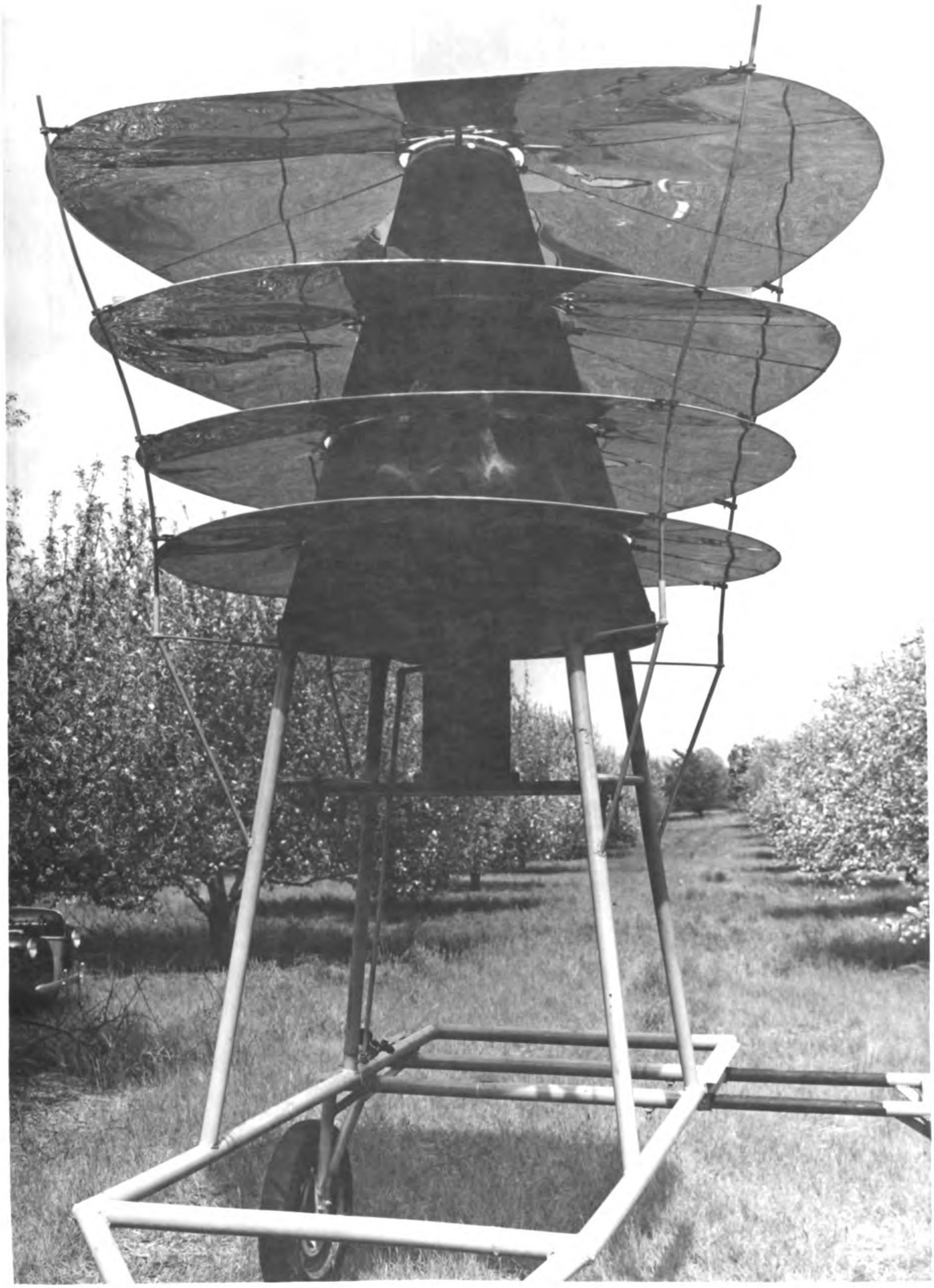


FIGURE 33. TYPE C UNIT.

TEST DATA FOR FROST PREVENTION UNITS

DATE 5-5-47 TAKEN BY A.W. FARRALL, C.H. HANSEN, J. PORTER, G.T. GIBSON, F.J. HASSLER

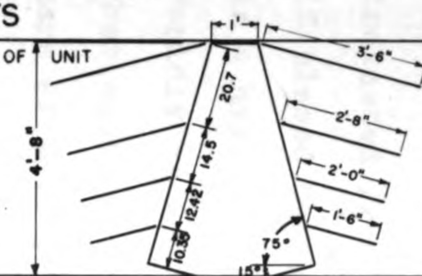
PLACE SOUTH OF CHEMISTRY BUILDING

TYPE OF UNIT TYPE "C" TYPE OF BURNER AIROIL, NOT MODIFIED

MODIFICATION OF UNIT

CENTER LINE HEIGHT OF UNIT 9'-5"

ILLUSTRATED DRAWING OF UNIT



TIME UNIT STARTED	TIME TEST STARTED	TIME TEST ENDED	ELAPSED TIME	WEIGHT OF FUEL AT START OF TEST	WEIGHT OF FUEL AT END OF TEST	WEIGHT OF FUEL CONSUMED	POUNDS PER HOUR	GALLONS PER HOUR	TIME TEMP TAKEN	TEMP OF SURROUNDING AIR	TEMPERATURE OF RADIATING SURFACES AT 1'-4"					OIL PRESSURE	
8:25	0:00	6'20"				5	47.5	7.08	9:30	47.1°						30-45	
	6'20"	12'51"				5	46.1	6.88	9:50	45.8°							
	12'51"	19'13"				5	47.1	7.03									
	19'13"	25'40"				5	46.5	6.94									
	25'40"	32'00"				5	47.4	7.08									

RADIANT ENERGY MEASURED IN MICRO-VOLTS

TIME	10'	20'	30'	40'	50'	60'	70'	80'	90'	100'	110'	120'	130'
9:10	1500	540	220	130	79	56	36	28	18	15	12	10	8
9:35	1500	530	220	130	80	56	37	28	19	15	12	10	8.5

ELEVATION	
2'	15
4'	14.5
6'	14.5
8'	14.5

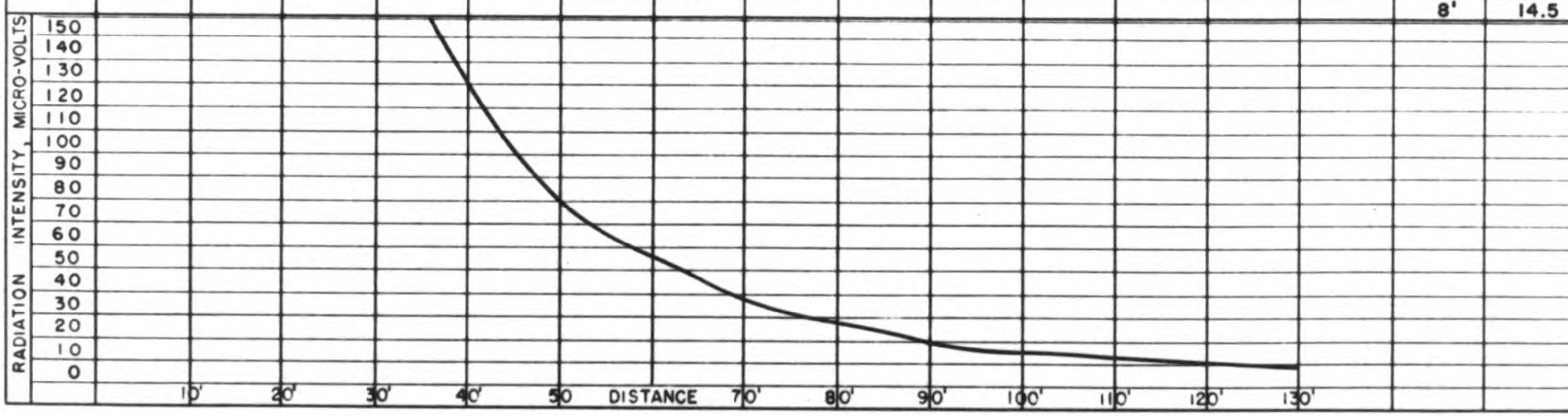


FIGURE 34. FIELD OPERATION DATA FOR TYPE C UNIT.

indicated from the test that two units would protect if placed between 120 feet and 140 feet apart. There is a high intensity near the unit, which drops off rapidly as the distance from the unit increases. Further experiment with the reflectors may make this unit more effective.

7. The Commercial Design: Type AA Unit

The primary problem was to develop a unit that would be feasible for commercial manufacture. The three units constructed were not practical for commercial manufacture. Types A and B were too expensive, while Type C did not have the proper energy distribution. The constructed units were now evaluated to determine changes that could be made to cut down construction costs while still retaining effectiveness. Since the radiation intensity varies as the fourth power of the absolute temperature, it was found that the radiating surface area could be reduced to one-half of the original surface area without reducing the effectiveness if the temperature of the radiating surface were raised from 1200°F. to 1500°F. This would be a major step towards reducing construction costs.

Aluminized steel was tried as a heat-resistant metal for the radiating surface. The unit was then constructed with the same shape as the original Type A unit, but on a reduced scale. Figure 35 shows the cross-sectional drawing, and Figure 36 is a photograph of the unit.

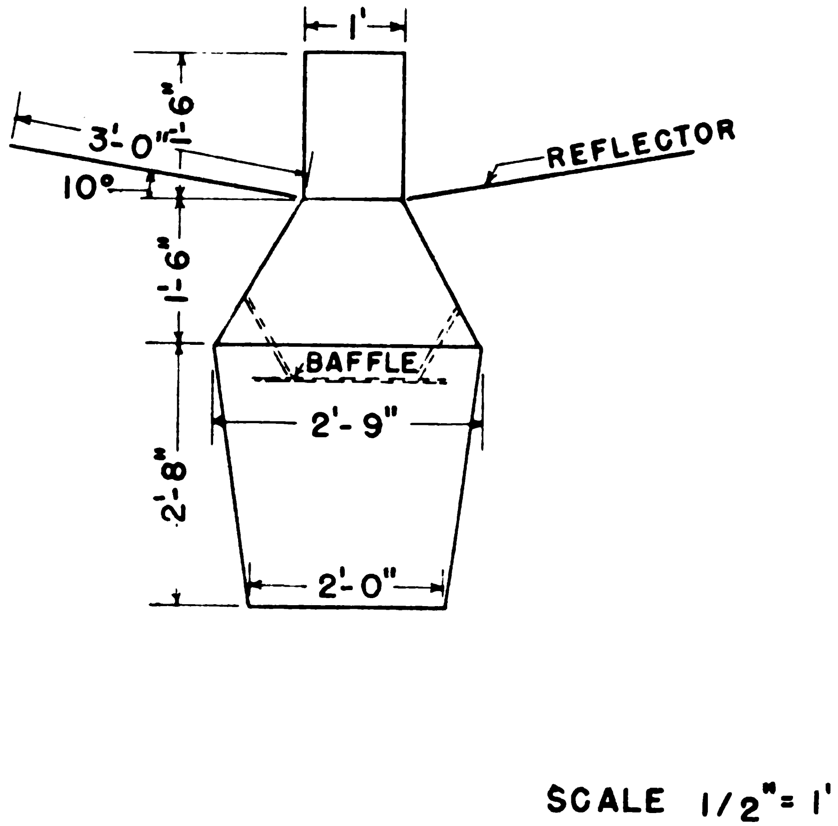


FIGURE 35. TYPE "A-A" FROST PREVENTION UNIT

FIGURE 36. TYPE AA UNIT.

The field tests, the results of which are illustrated in Figure 37, showed the unit to operate satisfactorily. The fuel consumption of ten gallons per hour is less than that of the A unit. The effective range of one unit was from sixty to seventy feet, and it was indicated that two units would be effective if placed from 220 feet to 240 feet apart.

The tests also showed that aluminized steel would not withstand the high temperatures which are necessary. This unit is now being manufactured commercially with stainless steel replacing aluminized steel as the radiating surface.

TEST DATA FOR FROST PREVENTION UNITS

DATE 10-31-47 TAKEN BY F.J. HASSLER, L.H. LAMOURIA

PLACE OUTSIDE OF AGR. ENGR. LABORATORY

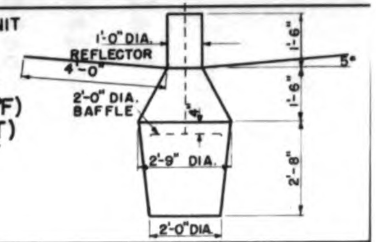
TYPE OF UNIT AA TYPE OF BURNER AEROIL

MODIFICATION OF UNIT BURNER NOZZLE OPENING REDUCED FROM .151 TO .143 REFLECTOR ANGLE 5° ABOVE HORIZON.

CENTER LINE HEIGHT OF UNIT 9'-0"

NOTE:
1. CLOUDY AND MISTING
2. NOTICEABLE SLIGHT DARKNESS ON SIDE READINGS TAKEN (1400°F) (CAUSED BY TARGET ARM SUPPORT)
3. NO FLAME VISIBLE OUT STACK.

ILLUSTRATED DRAWING OF UNIT



TIME UNIT STARTED	TIME TEST STARTED	TIME TEST ENDED	ELAPSED TIME	WEIGHT OF FUEL AT START OF TEST	WEIGHT OF FUEL AT END OF TEST	WEIGHT OF FUEL CONSUMED	POUNDS PER HOUR	GALLONS PER HOUR	TIME TEMP TAKEN	TEMP OF SURROUNDING AIR	TEMPERATURE OF RADIATING SURFACES AT: TIME	HOTTEST		SIDE READINGS TAKEN		OIL PRESSURE
10:25	10:43	11:18'30	:35'30"	129	90	39	66	10	10:50	49.5	10:48	1430°F		1400°F (STAYED UNIFORM)		41 P.S.I.

RADIANT ENERGY MEASURED IN MICRO-VOLTS

TIME	10'	20'	30'	40'	50'	60'	70'	80'	90'	100'	110'	120'	130'	TIME FINISHED
11:00	1900	790	390	225	150	110	88 (CHANGED SCALE)	68.5	58	51	45.5	42.5		11:08

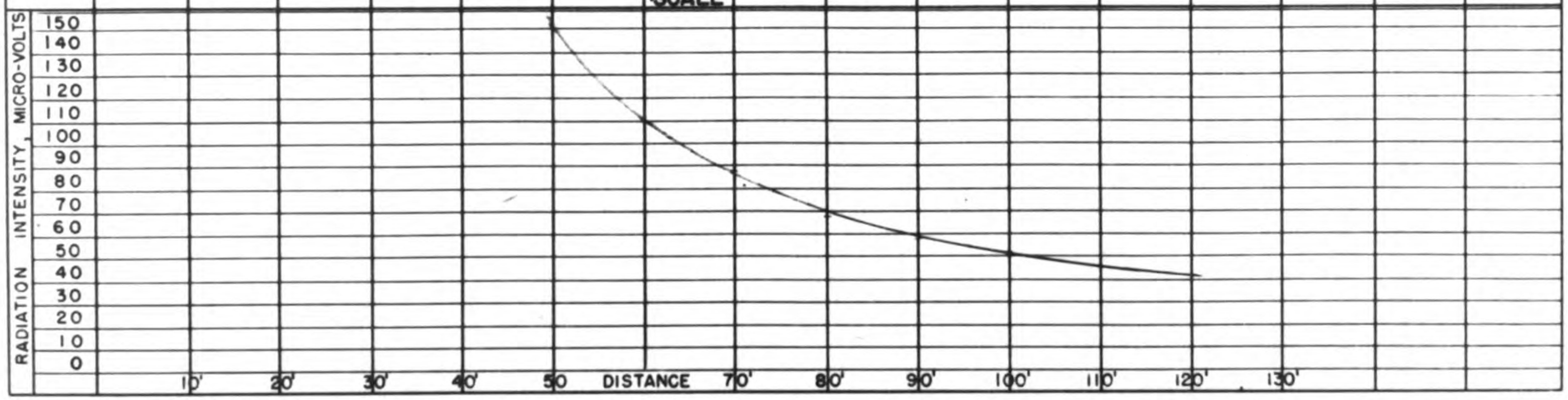


FIGURE 37. FIELD OPERATION DATA FOR TYPE AA UNIT.

E. Tests Under Natural Frost Conditions

The units had been tried in the field, and their relative radiation intensities determined with a radiation meter. They were now considered ready to be subjected to natural frost conditions.

1. Test One[20]

Units A and B were used for this test. Figure 38 shows the positioning of the units. They were placed on an East-West line, with unit A being on the West position. The units were 130 feet apart.

For this experiment plants with various degrees of resistivity to frost were selected from the horticulture greenhouse at Michigan State College. These plants, listed in order of increasing resistivity to frost damage, were: Coleus, tomatoes, Marigold, and Phlox Drummondi. The positioning of these plants were:

1. Control plants: one pot of each variety placed 300 feet East of B unit;
2. Plants placed at ten-foot intervals between the units;
3. Plants placed on a line South of the mid-point between the units at ten-foot intervals.

Climatic conditions were ideal for radiation-type frost. The air was moderately cool, with a clear, starry sky. There was no noticeable wind. At 10:30 P.M. the temperature was 32^o one inch above the ground, and frost began to form. The readings, which were taken

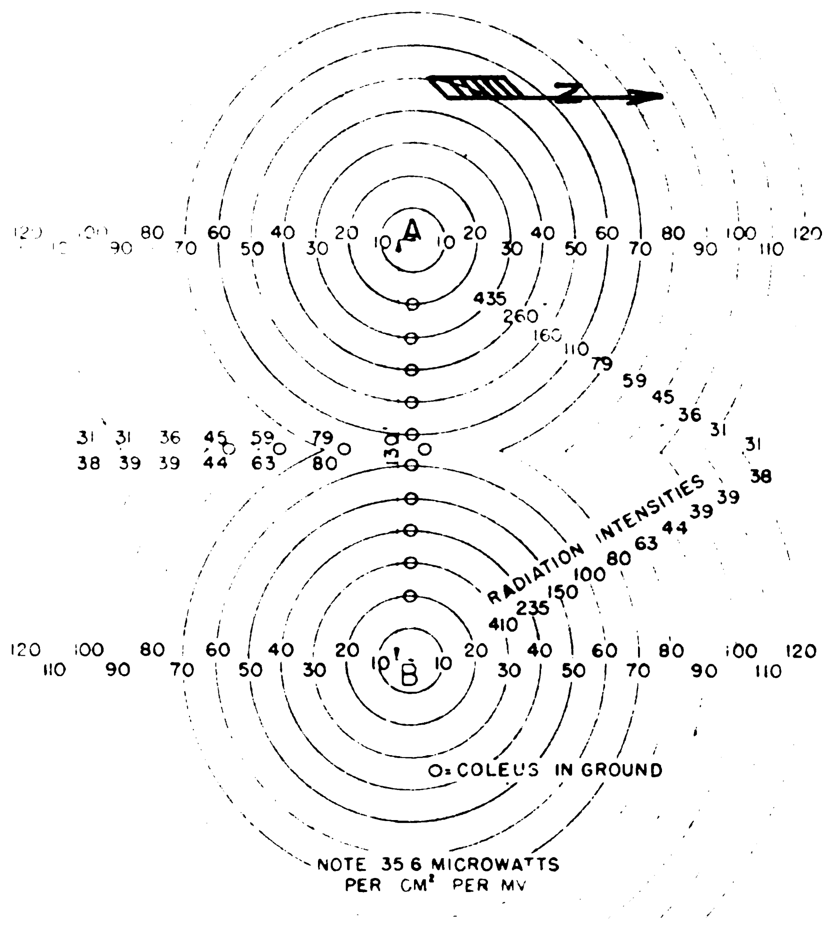


FIGURE 38. DIAGRAM OF THE SET-UP FOR THE FIRST TEST UNDER NATURAL FROST CONDITIONS.

all night, are given in Table I.

The units were started at 10:20 P.M. and were operated until 6:30 A.M. The data on the units are shown by Figure 39. No effort was made to operate the units above normal. They both heated fairly uniformly at about 1150^{o} F. It will be noted that Type A was burning about 14 gallons of fuel per hour, while Type B was burning about 10 gallons of fuel per hour.

Radiation intensities, taken at ten-foot intervals out to 120 feet from each unit, are given in Figure 39.

There was heavy frost on the grass beyond the protected area, and the control plants were badly frosted to the height of sixteen inches. The potted plants on the center line between the two units were completely free of frost. There was no frost on the standing vegetation for a distance of eighty feet west of the A unit. Beyond this point there was visible frost on the Phlox Drummondi, a fuzzy-leafed plant, but there was none on the Marigold. From fifty feet of either unit the frost on the low-growing grass increased as the distance from the units increased. However, there

TABLE I

AIR TEMPERATURES IN ° F.

Time	POSITION 1: Midpoint between units	POSITION 2: 300 Feet east of "B" unit unprotected control position
10:25 P.M.	34	33
10:45 "	35	31
11:10 "	37.8	30.4
1:15 A.M.	34	28
2:15 "	34	28
3:15 "	34	27.5
4:00 "	34.1	27.3
5:35 "	33	26.5
6:15 "	31.5	26.4
7:00 "	34	32

TEST DATA FOR FROST PREVENTION UNITS -

DATE 10-9-47 TAKEN BY F. J. HASSLER, L.H. LAMOURIA

PLACE NORTH OF FARM CROPS LABORATORY M.S.C.

TYPE OF UNIT "A" AND "B" TYPE OF BURNER AEROIL

MODIFICATION OF UNIT INCREASED BURNER CAPACITY

CENTER LINE HEIGHT OF UNIT 12'-6"

ILLUSTRATED DRAWING OF UNIT

NOTE:
1. CLEAR, COOL, NO WIND
2. SURROUNDING AIR TEMP TAKEN AT 1' ABOVE GROUND

TIME UNIT STARTED	TIME TEST STARTED	TIME TEST ENDED	ELAPSED TIME	WEIGHT OF FUEL AT START OF TEST	WEIGHT OF FUEL AT END OF TEST	WEIGHT OF FUEL CONSUMED	POUNDS PER HOUR	GALLONS PER HOUR	TIME TEMP TAKEN	TEMP OF SURROUNDING AIR	TEMPERATURE OF RADIATING SURFACES AT					OIL PRESSURE
A- 10:25								APPROX 14	10:25	33						42 PSI
									11:00	30.5						
B- 10:20								10	11:30	29.2						35 PSI
									2:00	28.0						
									4:00	27.3						
									6:00	26.4						

RADIANT ENERGY MEASURED IN MICRO-VOLTS

TIME	10'	20'	30'	40'	50'	60'	70'	80'	90'	100'	110'	120'	130'
A 1:45	1300	1000	435	260	160	110	79	59	45	36	31	31	
B 1:40	1400	700	410	235	150	100	80	63	44	39	39	38	

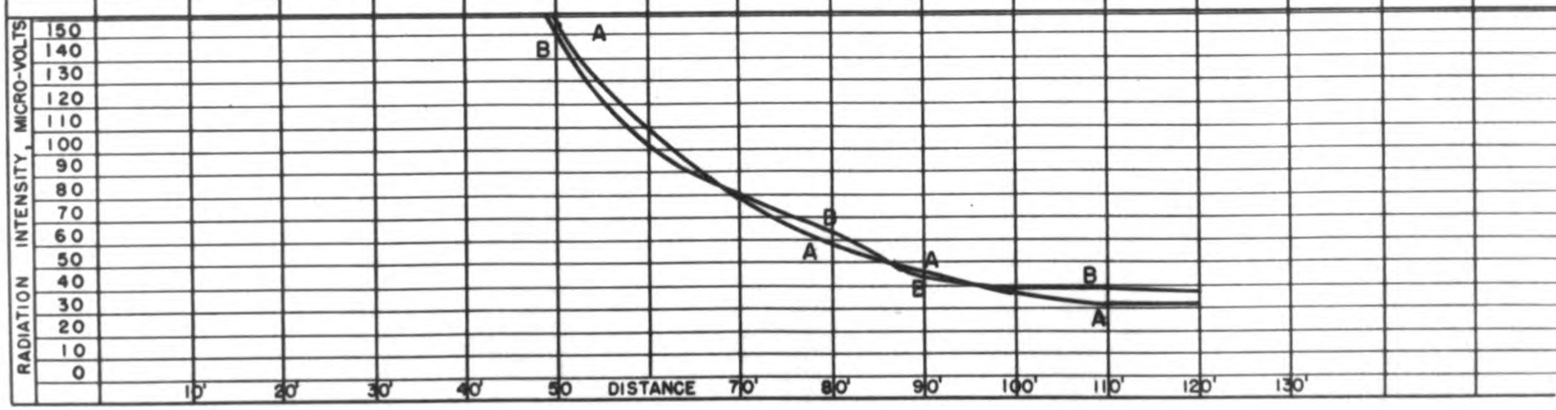


FIGURE 39. FIELD OPERATION DATA FOR THE FIRST TEST UNDER NATURAL FROST CONDITIONS.

was evidence of protection to the taller blades of grass at a distance of one hundred and fifty feet from either unit. It was interesting to note that no frost appeared on the stakes facing the units out to a distance of 120 feet, but that the side of the stake away from the unit was frosted beyond sixty feet.

The Coleus was the most sensitive to frost of those plants exposed. Figure 40 pictures the Coleus plants ten hours after the test. The plant on the extreme right of the photo is the test plant. The numbers indicate the feet from the units. Number 65A was at the mid-point between the two units, and numbers 70,80, and 90 feet were taken from the group set perpendicular to the mid-point of the line between A and B. It will be noted that the leaves and lower branches of the control plant were badly withered and damaged by the frost, while the leaves and branches of all the plants in the protected area were in good condition and showed no evidence of withering or frost damage.

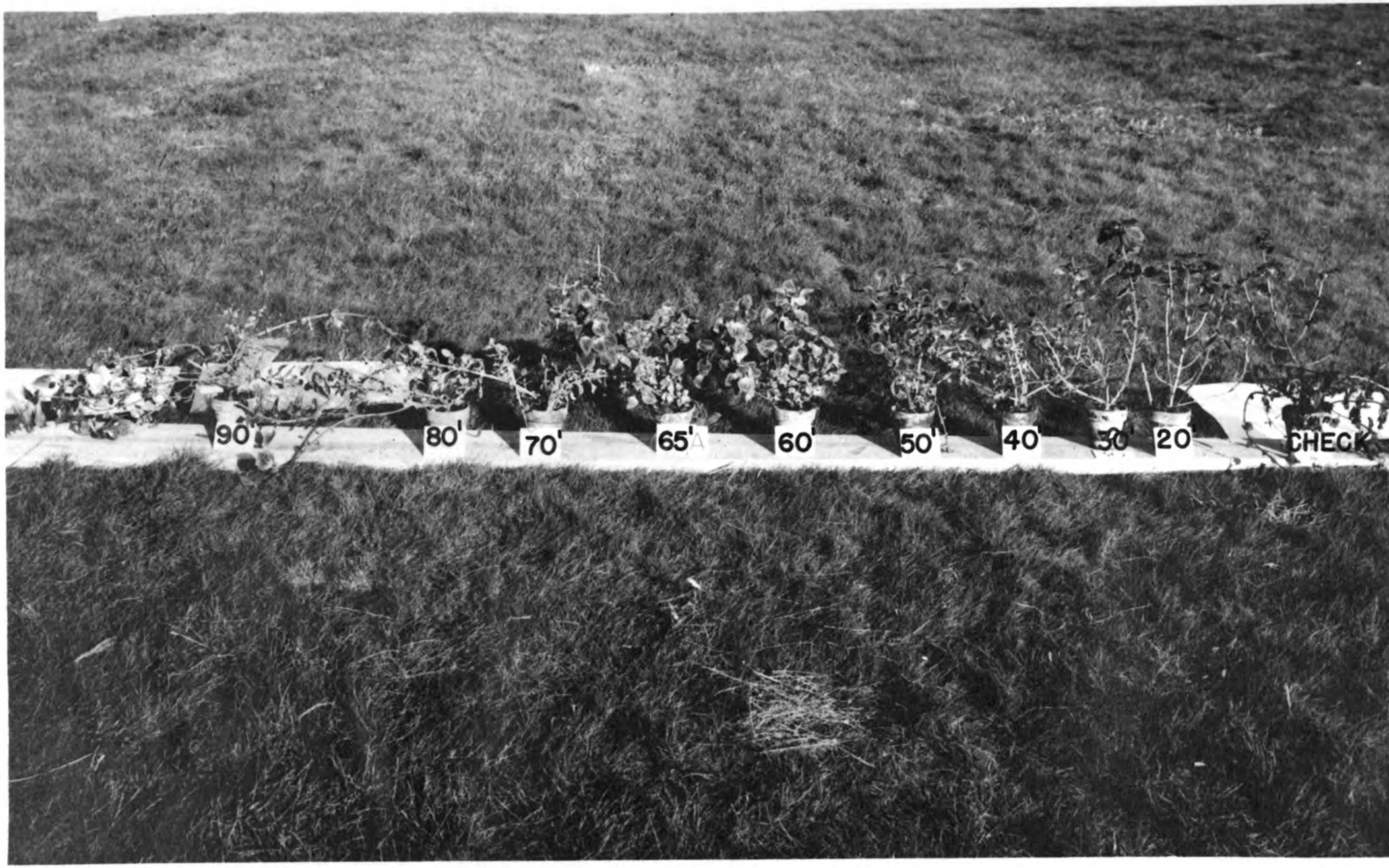


FIGURE 40. THE COLEUS PLANTS TEN HOURS AFTER THE FIRST TEST UNDER NATURAL FROST CONDITIONS. NUMBERS INDICATE FEET FROM THE UNITS. NOTE THE CONTROL PLANT ON THE EXTREME RIGHT. THE OTHER PLANTS WERE UNDAMAGED.

2. Test Two[21]

Units A and AA were used for this test. The test was made late in the fall, and the temperatures were considerably lower than those from which the agriculturist would normally have to protect his crops. The temperature was 36^{o} F. at sundown, and preceding this test there had been several days and nights of sub-freezing weather and the ground had been frozen to an appreciable depth.

Tomato, begonia, and geranium plants used for this test were placed as illustrated by Figure 41. It will be noticed that the plants in Group I and II were placed over a blue grass sod with grass blades to a height of four inches, while most of the plants of Group III were sitting in open or fallow ground that had sparsely drilled wheat growing on it.

The air temperature was taken with mercury bulb thermometers at different elevations, and at widely separated points. These temperature readings are given in Table II. However, radiation intensities were not taken during this test.

Figure 42 shows the tomato plants from Group III

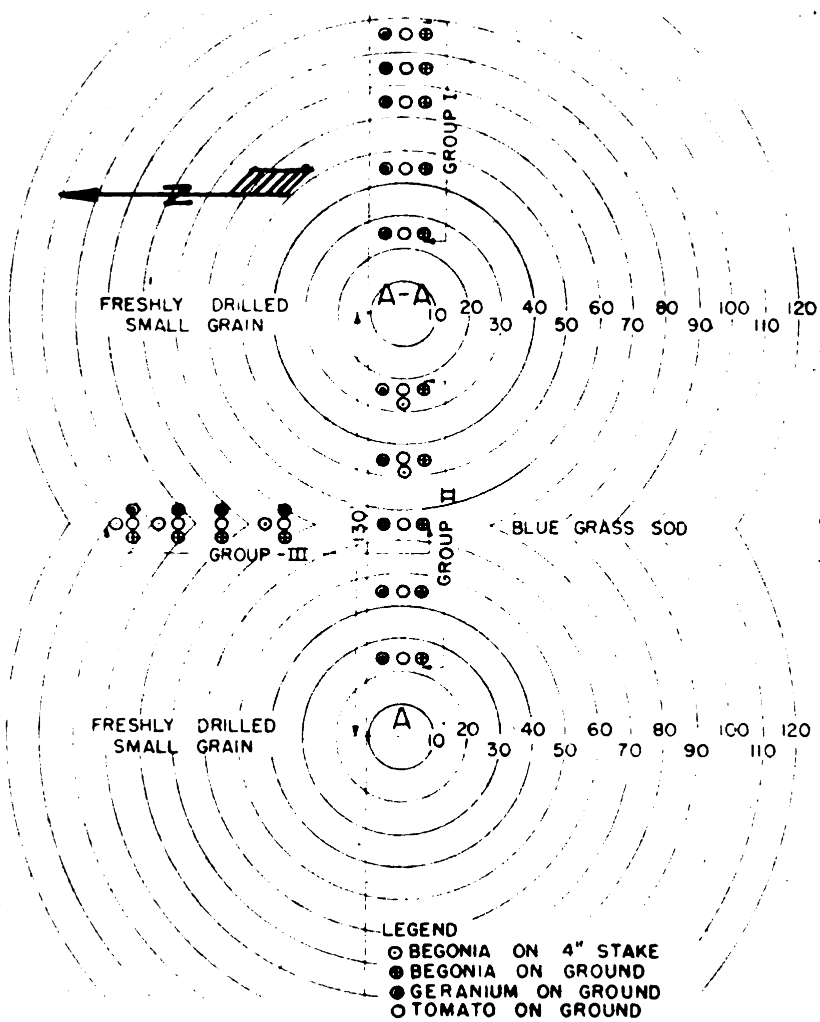


FIGURE 41. DIAGRAM OF THE SET-UP FOR THE SECOND TEST UNDER NATURAL FROST CONDITIONS.

TABLE II

AIR TEMPERATURE IN ° F.

Time	1			2	3
	1 Inch	1 Foot	2 Feet	1 Inch	1 Inch
8:30 P.M.	19	27	29.4	....	....
8:55 "	20	28	29	....	....
9:15 "	22	29	30.5	16	19
9:45 "	22	28	29.5	18	20.5
11:00 "	27.5	31.5	33	22	20.5

Temperature in °F.

Location: 1 - 325 Feet west of "A" unit in grass cover.
2 - 300 Feet southeast of "AA" unit in grass cover.
3 -1500 Feet southeast of "AA" unit in stubble.

FIGURE 42. TOMATO PLANTS USED IN THE SECOND TEST UNDER NATURAL FROST CONDITIONS BEFORE EXPOSURE. THEY WERE PLACED IN THE GROUP III POSITION (SEE FIGURE 41).

before exposure. Figure 43 shows these same plants after exposure. The plants were exposed from 8:45 P.M. until 11:05 P.M. The numbers on each pot represent the distance in feet from the units. The plant at 65 feet froze not because of distance from the units, but because of the ground covering. An interesting phenomenon is the fact that the plant at 95 feet froze, while that at 105 feet did not. This may be because of imperfection in the two units, or because of air currents set up by the difference in temperature of the bare ground and the grass-covered areas. The evidence seems to indicate that on a clear, calm night less artificial heat is needed to protect vegetation over an open ground than over a ground which is covered with a thick mat of grass or similar growth.[22] This may be true only when the ground is carrying a maximum of heat as in the early fall; however, the same should be true when the night was preceded by a day or more of sunshine. Bare ground absorbs the heat during the day and releases it at night. When plants cover most of the ground they reflect or absorb the sun's heat to a limited extent, allowing little to reach the ground. During the night

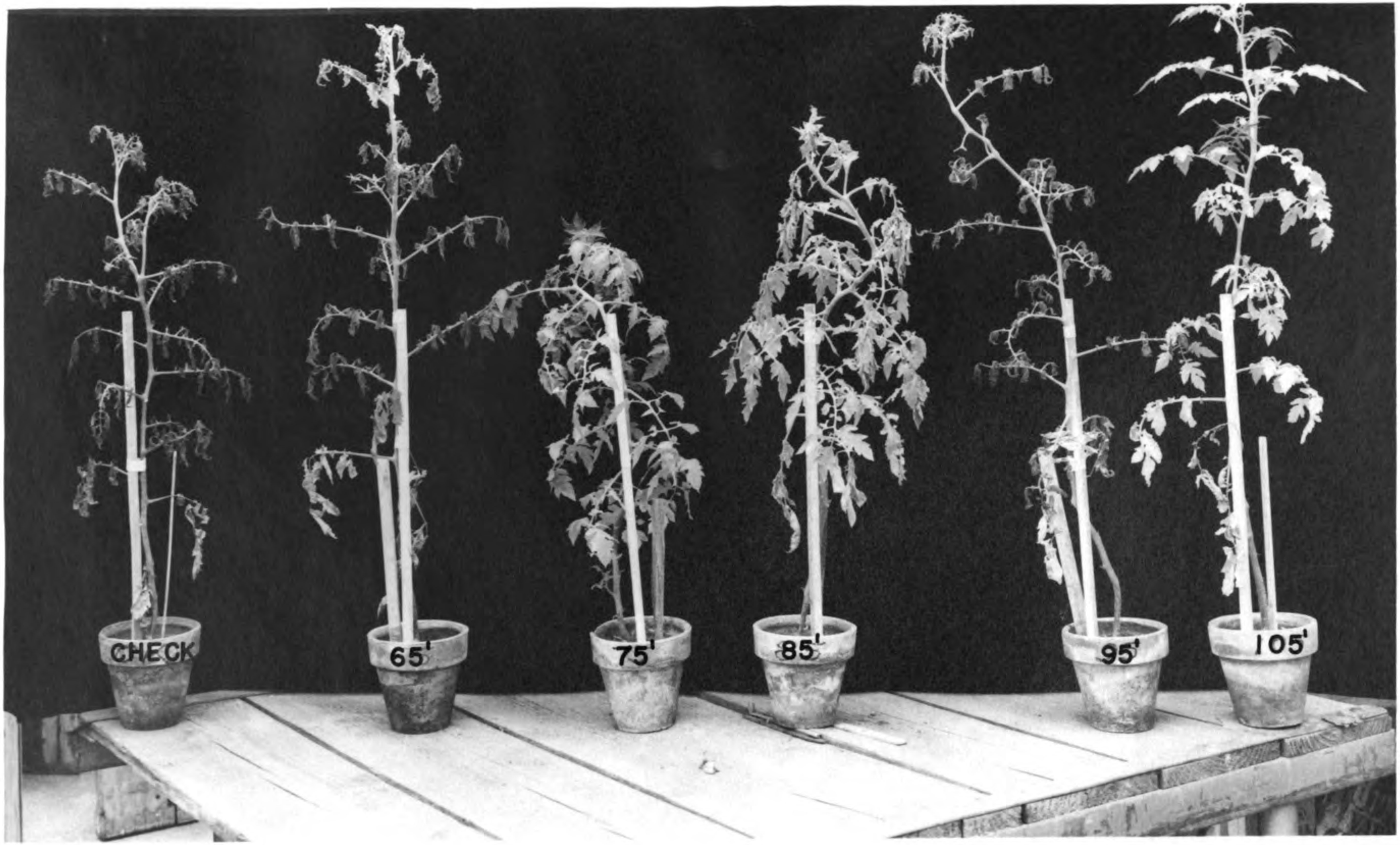


FIGURE 43. THE TOMATO PLANTS SHOWN IN FIGURE 42 AFTER EXPOSURE.

the plants lose their heat rapidly since they are good radiators and because their heat capacity is limited. Thick, low-growing vegetation would also prevent the ground's heat from reaching vegetation which would be growing above it.

III. Summary Conclusions

On the basis of the work done to this point, and reported in this paper, it might be concluded that:

(1) It has definitely been established that positive results for frost prevention can be obtained with radiant heating. This has been proven by the theoretical investigation, the laboratory experiments, and the actual field tests with constructed units.

(2) The extent of the protection, however, is conditional. The protection is for a frost, and not a freeze. The protection is designed to combat radiation-type frost, which occurs on calm, clear nights, and it has not yet been determined how much protection will be given when there is a wind of varying intensities, and late-season frosts.

(3) A practical and effective unit based upon this study is now being distributed by a manufacturer, and will give further experience under various natural frosting conditions. These units are not necessarily in

the final form, as the design may well be changed after further experiments in regard to:

(a) the length of the reflectors for practical purposes:

(b) the shape and positioning of the reflectors:

(c) the design of the radiating surface:

(d) the height at which the unit should be for various crops:

(e) the amount of protection required by various crops:

(4) The most practical material for the radiating surface appears to be stainless steel. The best gauge seems to be number twenty-four. The metal must be thin enough to readily transmit heat and give a high surface temperature, but thick enough to maintain the proper flame temperature necessary to support complete combustion.

(5) This study must be considered far from complete. Further data, both from laboratory and field experiments, are needed.

FOOTNOTES

1) A.C. Hildreth, J.R. Magness, and John W. Mitchell, "Effects of Climatic Factors on Growing Plants," (in Climate and Man, Yearbook of Agriculture, Washington, D.C.: U.S. Government Printing Office, 1941), pp.297-307. Exact statistics on the money loss because of frost are hard to obtain, but the loss is great. For example, the citrus loss alone because of frost in California in 1922 was well over $50,000,000. See Floyd D. Young, Frost and the Prevention of Frost Damage (Weather Bureau Number 1484, Washington, D.C.: U.S. Government Printing Office, 1947), pp.40-41.

2) A.W. Farrall, W.H. Sheldon, and Clarence Hansen, "Protection of Crops from Frost Damage Through the Use of Radiant Energy," Michigan Agricultural Station Quarterly Bulletin, 29: 53-64, November, 1946.

3) Young, op. cit., p.3.

4) W.J. Humphreys, "Frost Protection," Monthly Weather Review, 42: 562-569, October, 1914.

5) Young, op. cit., p.4. W.H. Hammon, Frost-When to Expect it and How to Lessen the Injury Therefrom (U.S. Department of Agriculture, Weather Bureau, number 186, Washington, D.C.: U.S. Government Printing Office, 1899).

6) Joseph Cline, "Frost Protection by Irrigation in Southern Texas," Monthly Weather Review, 42: 591-2, November, 1914.

7) J.O. Collins, Evaluation of Artificial Oil Fog as a Means of Frost Protection (Esso Laboratories, Standard Oil Development Company, Process Division, 1946)

8) Ben D. Moses, "Blowers for Frost Protection," Agricultural Engineering, 19: July, 1938.

9) Farrall, op. cit., pp.57-60.

10) George Gibson (Master of Science Thesis now in preparation), Department of Agricultural Engineering, Michigan State College, East Lansing, Michigan. These data were checked.

11) Victor R. Gardner, F.C. Bradford, H.D. Hooker, The Fundamentals of Fruit Production (second edition; New York: McGraw-Hill Book Company, Inc., 1939), pp. 416-417.

12) Lewis R. Koller, "Infrared Production and Transmission Reflection and Measurement," General Electric Review, 44: 167, March, 1941.

13) For example, see John H. Perry, editor, Chemical Engineers' Handbook (second edition; New York: McGraw-Hill Book Company, Inc., 1941), pp.1004-1007.

14) William H. McAdams, Heat Transmission (second edition; New York: McGraw-Hill Book Company, Inc., 1942), p.50.

15) Loc. cit.

16) Gibson, op. cit.

17) W.L. Nelson, Petroleum Refinery Engineering (second edition; New York: McGraw-Hill Book Company, Inc., 1941), p.128.

18) William H.Severns, Howard E.Degler, Steam, Air, and Gas Power (third edition; New York: John Wiley and Sons, Inc., 1939), pp.104-110.

19) Eugene E.Schilling, Illumination Engineering (first edition; Scranton, Pennsylvania: International Textbook Company, 1940), pp. 51-52.

20) F.J. Hassler,C.M. Hansen, A.W.Farrall, "Protection of Vegetation from Frost Damage By Use of Radiant Energy--Part III," Michigan Agricultural Experiment Station Quarterly Bulletin, 30: 339-360,February,1948.

21) *Ibid*., pp. 352-359.

22) Humphreys, *loc. cit*.

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