PETROLEUM FUEL BURNERS FOR THE GENERATION OF RADIANT ENERGY FOR FROST CONTROL

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INTRODUCTION

Review of Need and Methods of Frost Control

Nature of the problem

One of the main hazards to fruit and truck crops is radiation-type frost damage (26). This damage includes late maturity of crops (due to late planting), poor quality and quantity, and in some instances a total loss of produce. In the United States, losses because of 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 (6).

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; which at the same time decreases the net loss from the earth and plants. This implies that, void of its atmosphere, the earth would become extremely hot during the day and extremely cold during the night which corresponds to the teaching of physicists in general. Therefore, the atmosphere serves 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. Its formation can be explained as follows on the theory of heat transfer. 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. 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. For example, when the wind velocity is in the magnitude of five miles per hour, the condensate is carried off the vegetation, leaving no moisture to form visible frost. Another condition occurs when the dew point is lower than the minimum plant temperature for that freeze. 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. The moving air also convects heat to the plants, keeping their temperatures above the freezing point. However, 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.

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; and, (3) add additional heat from a so-called artificial source.

Numerous attempts have been made to gain these three objectives, but the methods tried have been either too expensive, required too much labor to install and operate, or were 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 and promotes fertility loss through leaching. Flooding is effective, but often causes water damage. Efforts to make artificial clouds have not been successful. Large motor-driven propellors have been used to stir the air, which in turn convects heat to plants, but topography, climate, and the value of crop limit this application.

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. While these units are more expensive, only about fifty per acre are required. In addition to radiating a part of the liberated heat, 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 primary purpose of these heaters is to warm the air under the inversion point to the necessary degree. It is most effective if the day temperature has been high and, therefore, it is necessary to heat less air. Even though these heaters are effective for the control of radiation-type frost, they are 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.

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 commercial flower and fruit growing; a large part of which cannot be contaminated as would result from the present orchard heaters. The problem of frost damage, while always important, became more so during World War II when the crop values increased.

By 1945 the problem of frost protection had become so acute that the Michigan Agricultural Experiment Station 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 were effective under selected conditions, they would be impractical for the conditions surrounding Michigan agriculture.

Careful study showed that convected heat was limited in that it is dependent upon the atmospheric conditions. In the fall of 1945, A. W. Farrall, Head of the Department of Agricultural Engineering at Michigan State College, proposed the use of infrared radiant energy as the principal source of additional heat for a solution to this problem.

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 input 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 (9).

Tests were made during natural radiation-type frosts (7). Although actual temperatures of the vegetation and 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 electric 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 (8). 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 original figure of three watts per square foot was found to be the average intensity requirements for protection against normal frosting conditions during the fall.

Theory of the Emission, Transmission, and Absorption of Infrared or Thermal Radiation

There are three well-known means by which heat is transferred from a hot to a colder body. They are convection, conduction, and radiation, and all three are generally involved or associated in any one process. The third method, radiation, is unique in that it involves no material means of transfer, and for this reason there apparently are advantages and justification for experimental work in evaluating this means as a frost control measure. Radiant energy is transferred as electromagnetic radiation and is found to traverse a vacuum without attenuation, but will be absorbed to some extent by gases or vapors.

As to the source of thermal radiation, it was first advanced by Prevost, in 1792, that all matter above absolute zero temperature emitted energy in the form of radiation. Since all matter absorbs such electromagnetic radiation at some wave length, it would seem that the second law had been invalidated by this hypothesis; however, even though a hot body may receive energy from a colder body, there is experimental evidence to the fact that the net exchange will invariably show a gain for the colder body. This is best illustrated by placing objects at varying temperatures within an insulated vacuated container and noting that the objects approach an equal temperature, the temperature of the container.

Quantitative laws for "blackbody" radiation follow; however, a few explanatory remarks about this special classification of radiation is in order. There are several defining features which characterize "blackbody" radiation. The important features are: (1) a blackbody absorbs all the radiant energy which falls upon it; (2) no body possesses a radiancy greater than that of a blackbody; and, (3) blackbodies obey Lambert's Cosine Law while non-blackbodies do not, which means that the intensity at any direction from the normal equals the product of the normal intensity times the cosine of the angle that the direction in question makes with the normal. As a consequence of (3), the steradiancy or brightness of a surface is the same from all directions of view. These three conditions or characteristics hold for spectral values as well as total emissive values.

As previously stated, the derivations of quantitative laws are based on "blackbody" radiation and since it is admitted that there are no surfaces of matter which correspond perfectly to a blackbody (even though such materials as carbon black, platinum black, zinc black, and carborundum are among the best approximations), there seems little justification or experimental proof to warrant such derivations. However, for theoretical considerations and calibration purposes, a true source of "blackbody" radiation is attained simply by studying so-called cavity radiation. This is the radiation emitted from a small aperture in the side of a uniformly heated enclosure of opaque walls. It is understandable that this aperture will absorb all the impinging radiation, for once it gets within the cavity there is only a remote probability that it will come out again. The second condition is satisfied since the radiation density is a maximum (which can be shown theoretically) for the given enclosure temperature, and since the aperture is essentially the inside surface, this consideration gives the radiation intensity for the aperture a maximum value for that temperature. As the radiation from the aperture is uniform in all directions (in the outward hemisphere), the intensity will vary as the cosine of the angle with the normal; thus satisfying the third condition.

In this study oxidized sheet steel was generally used for the radiating surface. This surface has total emissivity values ranging from .8 to .95 (18) which is the ratio of its total emissive power to that of a blackbody at the same temperature. Also, the variation of this surface from Lambert's

Cosine Law is illustrated in Fig. 1, and it is noted to compare very closely with a blackbody emitting surface. Since the total emissive power and hemispherical distributional characteristics approach that of a blackbody the quantitative relationships for blackbody conditions are applicable to a first order of approximation for the real surfaces. Therefore, the following relationships are included to further an understanding of the application to be made.

Quantitative laws for blackbody radiation (24)

Attention is first directed to the spectral energy distribution or spectral emissive power of the radiation as a function of wave length and temperature (Fig. 2). This plot is possible through the application of Planck's analytical expression for the spectral energy distribution of "blackbody" radiation. Planck was able to derive this relationship, which is in agreement with experimental results, by introducing the quantum theory in conjunction with the classical statistical theory (theory of elastic or electronic vibrations). Einstein and Bose each have subsequently derived the same relationship through the use of statistical mechanics. Without carrying through the derivation, the result is given in the following equation:

$$E_\lambda = 3.740 \times 10^{-5} \frac{\text{ergs cm}^2}{\text{Sec.}} \lambda^{-5} \left[e^{\frac{1.438 \text{ cm. deg.}}{\lambda T}} - 1 \right]^{-1}$$

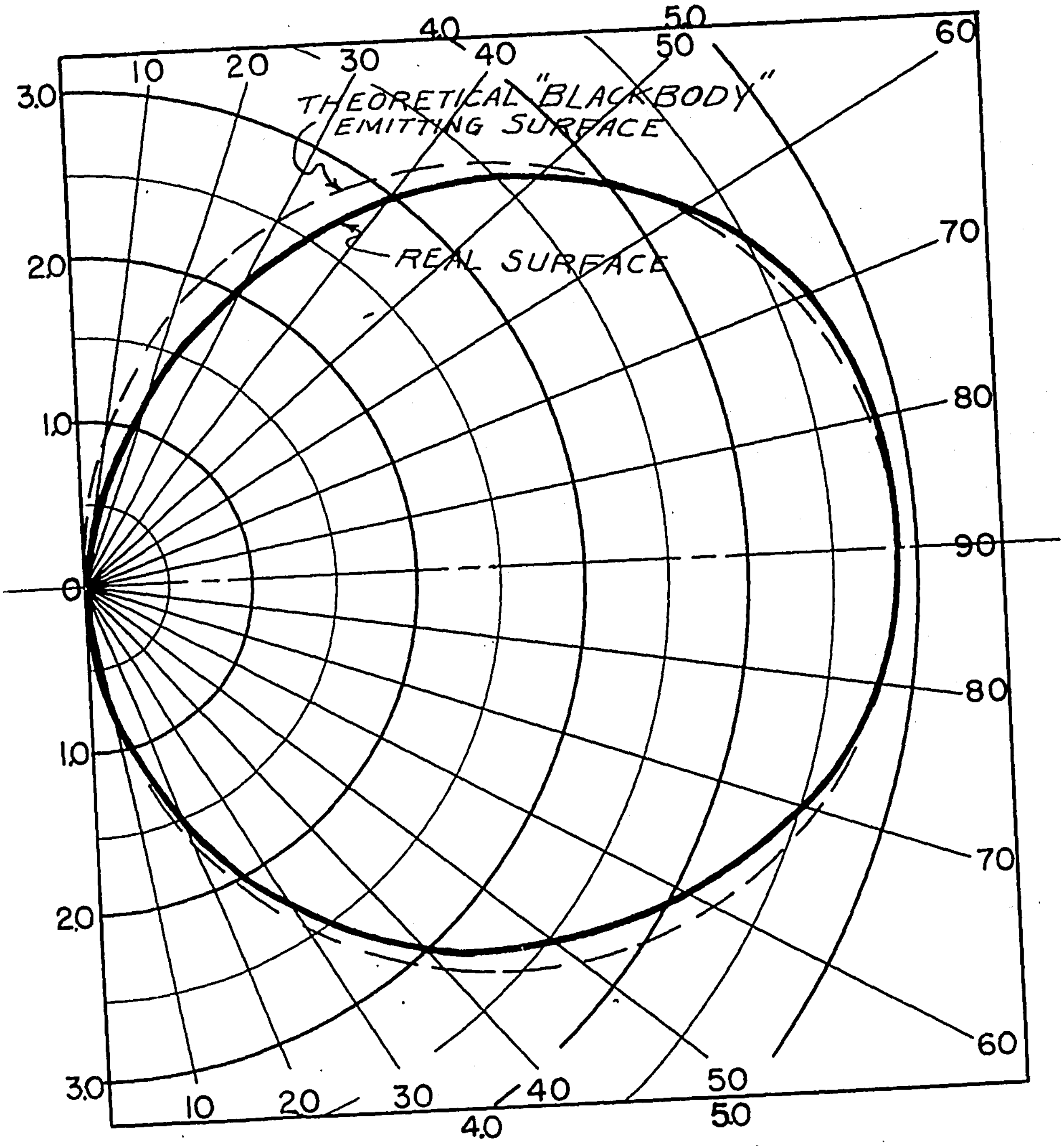


Figure 1. A comparison of the radiant energy distribution from an oxidized steel surface with a theoretical blackbody.

Based on this relationship the curves (for 1000°F. and 1500°F.) in Fig. 2 were developed.

Following Planck's derivation of the spectral energy distribution for "blackbody" radiation, three important relationships were directly derivable. The first to be included here gives an expression for the total emissive power. This is found by integrating the spectral energy equation between the wave length limits of 0 and ∞, giving

$$\int_0^\infty E_\lambda d\lambda = \int_0^\infty \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1} d\lambda = \frac{2}{15} \frac{\pi^5}{c^2} \frac{k^4}{h^3} T^4$$

$$= 5.672 \times 10^{-5} \frac{\text{ergs}}{\text{cm}^2 \cdot \text{sec.} \,^\circ K^4} T^4$$

For a 1500°F. emitting surface (assuming "blackbody" radiation) this equation gives a total emissive power equal to 25,600 BTU/Hr./ft^2.

As a comparison the area under the curve was measured with a planimeter from which the total emissive power was calculated as 29,000 BTU/Hr./ft^2. It is possible that a better agreement would be obtained by plotting the energy distribution to a larger scale.

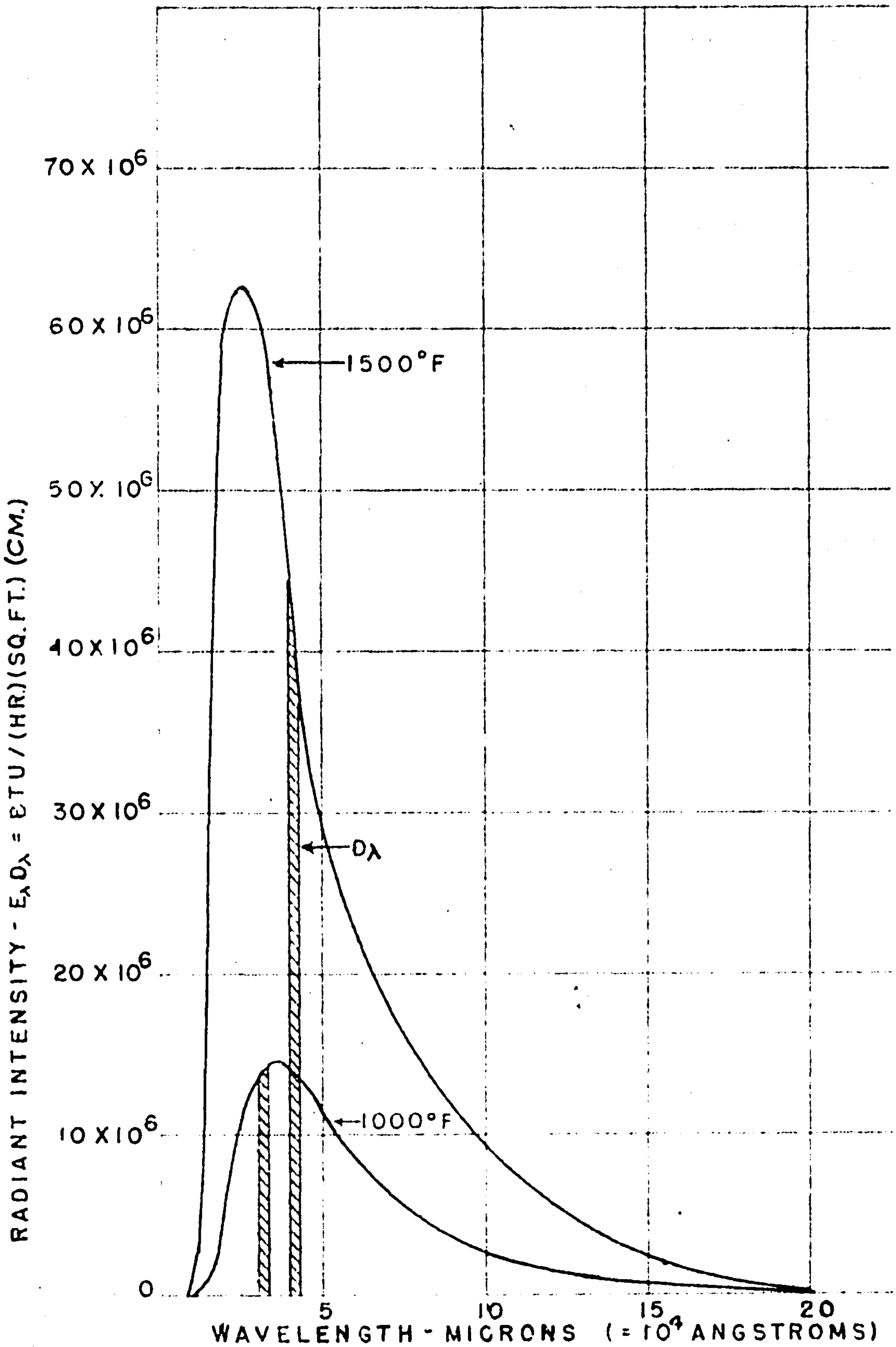


Figure 2. Spectral energy distribution as a function of temperature.

A graph of the total emissive power as a function of temperature is illustrated in Fig. 3.

Another derivation based on Planck's spectral energy distribution gives the relation that the modal wave length of the radiation (the wave length for which the monochromatic emissive power of the blackbody is a maximum) is inversely proportional to the absolute temperature of the blackbody. This is found by differentiating Planck's equation with respect to the wave length, and solving for the wave length which makes the resulting expression equal to zero,

or

$$\left[3.740 \times 10^{-5} \lambda^{-7}\right]\left[e^{\frac{1.438}{\lambda T}} - 1\right]^{-2}\left[(1.438 - 5\lambda T)\, e^{\frac{1.438}{\lambda T}} + 5\lambda T\right] = 0$$

satisfied by $\lambda = \infty, 0,$ and $0.2897/T$

or $\lambda_m T = 0.2897$ cm. deg.

This expression is known as Wien's Displacement Law since he had realized the relationship and determined the constant, experimentally, at an earlier date.

From this equation the wave length at which the monochromatic emissive power is a maximum for a 1500°F. temperature source is 2.658 microns.

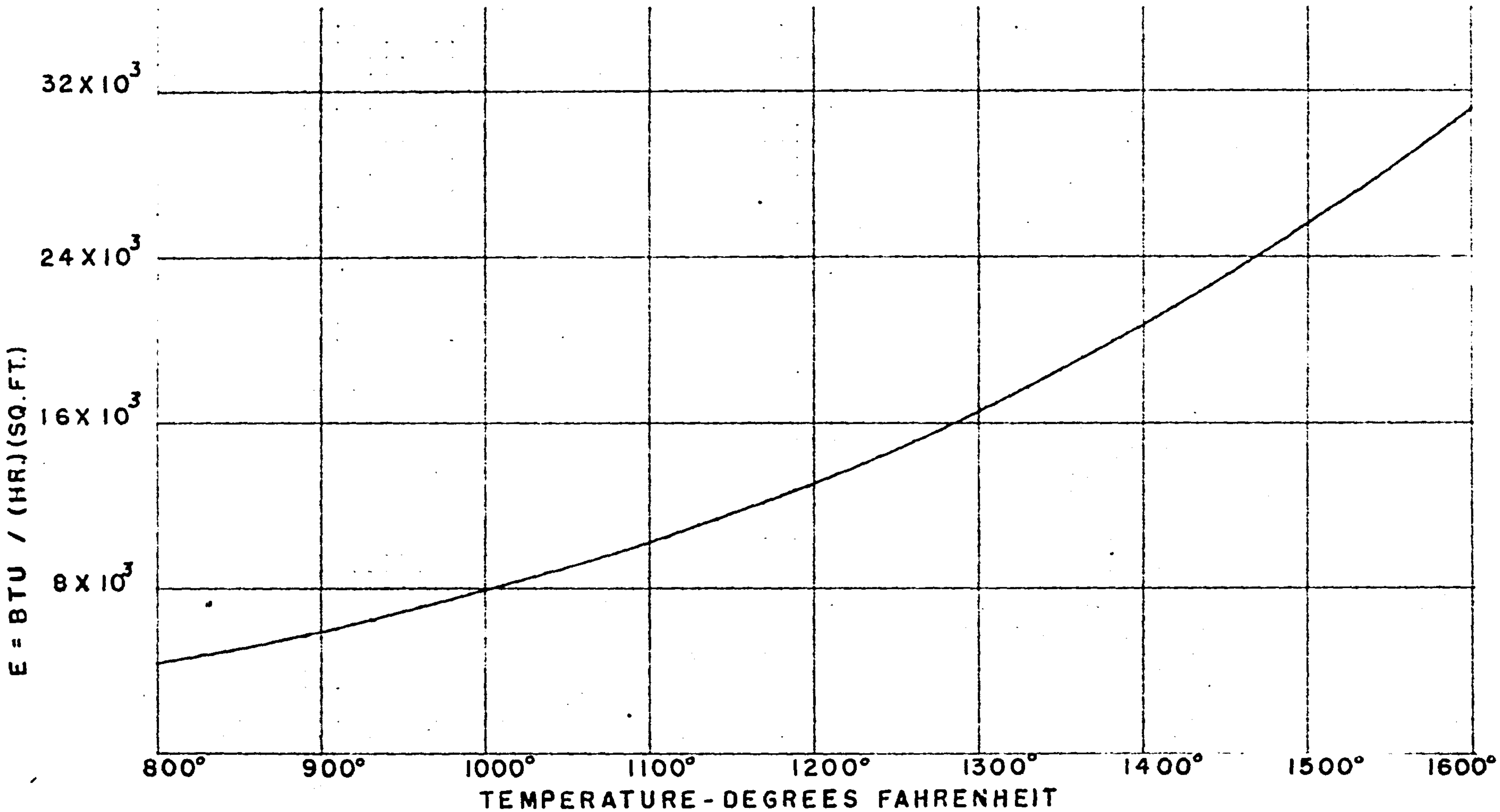


Figure 3. Total radiation as a function of temperature.

The third dependent relationship states that the maximum monochromatic emissive power of a blackbody, viz., that within the wave-length interval $d\lambda$ at the modal wave length λ_m, is proportional to the fifth power of its absolute temperature. The derivation simply requires the substitution of the value of λ_m into Planck's equation, giving

$$dE_m = 1.288 \times 10^{-4} \frac{ergs}{cm.^3 \, sec. \, °K^5} T^5 d\lambda$$

Transmission of infrared radiation

The quantitative laws deal with the source of radiation only and there are other important factors which influence the amount of energy that is transmitted.

One of these factors, which is by far the most important, is that resulting from the so-called Inverse Square Law of Radiation. This law is illustrated in Fig. 4 from which it is noted that the radiation from a point source covers four times as much area at two feet as compared to the area at one foot; giving the relationship that the intensity is inversely proportional to the square of the distance.

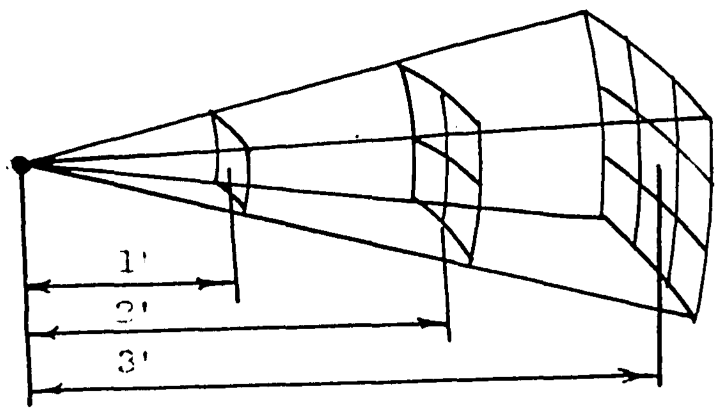


Figure 4. Diagram showing the principle of the inverse square law of radiation distribution from a point source of origin.

The other factor to be considered is the absorption of the radiant energy by the atmosphere or the attenuation of the intensity as the radiation traverses the distance from source to plant. Therefore, it is erroneous to acclaim that this form of heating can be transferred directly to the vegetation independent of the intervening medium. The extent of this factor on the intensity of radiation from a given source at a chosen point is dependent on the components of the atmosphere. Since water vapor is essentially the only variable component, it is logical to assume that the relative humidity is a factor in determining the efficiency of radiant energy transmission.

The Beer-Lambert Law of Absorption which expresses the following relationship is applicable for calculating the resulting intensity (25):

$I/I_o = e^{-kx}$, where I = intensity at x, I_o = initial intensity, x = distance through absorbing medium, k = absorption coefficient, and is a function of both wave length and density of water vapor.

It has been observed spectroscopically that there are wide ranges of wave lengths which are not affected by the atmosphere while others are absorbted at varying degrees; some wave lengths are totally absorbted by a short distance of travel in the atmosphere. This factor has not been given sufficient study to warrant further discussion in this paper; however, since the data are available in physics' journals, future investigation of this problem should prove significant in connection with the use of radiant energy for frost control.

Absorption of radiation by vegetation

After the electromagnetic radiation of infrared energy impinges upon the surface of vegetation or other matter, there is the phenomenon of transformation to sensible heat. To form an analogy with electromagnetic radiation of radio frequency, the vegetation must act as a "radio receiver". As would be expected from this analogy, the vegetation should exhibit selective absorptive properties or be more receptive to different frequencies or wave lengths. This is exactly the case and the phenomenon is explained either on the classical wave theory or the more modern quantum theory which we will not attempt to explain in this paper. However, this property is easily evaluated experimentally with the spectrophotometer or spectrograph. Generally, aside from isolated intervals throughout the infrared spectrum, it has been found that transmission and reflection of radiation by green vegetation increases with wave length in going from visible light into the near infrared spectrum (5), which means in fact that the absorption or heating effect decreases with this change in wave length. This fact is of importance in consideration of the efficiency of a source of radiant energy as a frost control measure.

Previous Work and Present Status of the Utilization of Infrared Radiant Energy for the Protection of Vegetation from Frost Damage

Original investigations

As described earlier in this paper, the initial work in the investigation of the application of infrared energy as a frost control measure was carried out with an electrically powered source. At that time the major emphasis was placed on the visible evaluation of the extent of protection or area that was kept free from frost formation under freezing temperatures at the ground level. The temperature was measured with a chemical or mercury-in-glass thermometer. From this it was found that infrared energy, applied with sufficient intensity, would afford frost protection to vegetation. Later it was found that a radiation intensity of 10 BTU/sq.ft/Hr., measured normal to the direction of propagation, would protect a heavy six-inch bluegrass sod under moderate to severe frosting conditions.

The intensity-protection relationship was found to hold true for tests under similar conditions with the original oil-burning unit; the only exception being that the intensity required varied somewhat with the type and amount of foliage in that a lower intensity safely protected sparse vegetation which was growing appreciably above the ground level.

Laboratory experimentation was carried out in 1947 (11) to investigate the plant temperature-radiation intensity relationship. The tests were made at both room temperature and within a cold storage where the ambient temperature was held at 35°F. The results of this work indicated that within the leaf of an exposed plant a radiation intensity of 10 BTU/Sq.ft/Hr. raised its temperature approximately 2°F. This held true in both environments indicating that, within the temperature interval tested, the plants failed to exhibit physiological changes to regulate their temperature when being heated by infrared energy. Since the net gain in plant temperature is directly proportional to the difference in temperature between the plant and surroundings, the only factor that would change the interval of temperature increase would logically be of physiological origin. Also, it was found that a shaded or shielded leaf, even though it was adjacent to an exposed leaf, failed to indicate an appreciable increase in temperature.

Even though there was no attempt made to determine the temperature of the surface which was irradiated, it is logical to assume that this temperature would have been considerably in excess of the interior temperature. This is founded on the hypothesis that the greater part of the transformation of radiant energy to heat takes place in a comparatively thin layer of plant tissue.

The assumption that the irradiated surface of the plant has a considerably greater increase in temperature gives explanation to the fact that frost fails to form on a surface which is exposed to a radiation intensity of only 10 BTU/Sq. ft/Hr. at an ambient air temperature of 25°F. Since the surface temperature is above 32°F. and if the plants are exposed to sufficient radiation intensity before the plant temperature has fallen to 32°F., then, in view of the fact that heat flows from a hotter to a cooler region, the temperature of the interior of the plant should be maintained at all times above this critical temperature. This would emphasize the importance of applying the radiation before the plants had fallen to the critical temperature.

The above factors are of primary importance, especially where protection is carried out through the application of infrared energy.

Studies to develop a high capacity non-powered liquid petroleum fuel burner

Following the preliminary investigations with the use of electricity as the source of power the next move was to design an oil-burning unit. This was deemed necessary if the method of frost control by radiant energy was to attain practical application. From the standpoint of cost, availability, and burning characteristics, kerosene was believed to be the best fuel for this use. Several experimental units were constructed and tested on a comparative basis to evaluate the advantages of each (12). As a result, one particular design was selected with the intention of interesting a manufacturing company who would make and distribute a limited number of such units for further experimentation and evaluation of the practicability of its use. This plan was carried through and the distribution included not only Michigan but many other states. The principal application was on truck and flower crops.

The results of these operations generally substantiated the findings of the original work at the Agricultural Engineering Department of Michigan State College which are summarized as follows:

1. For a radiation-type frost where the frost line

did not extend higher than sixteen inches, each unit protected out to ninety feet.

2. For the most severe radiation-type frost most likely to occur during the normal growing season (against which the unit must protect to be practical) the frost line was approximately sixty-five feet from the unit.

3. For cold wind-blown freezes the units protected a very small area.

4. Units would not operate satisfactorily in wind in excess of five miles per hour.

5. The burner was found erractic in its operation under all conditions, and could be corrected only by an experienced operator.

This last factor was of grave consequence since satisfactory operation at all times was essential if a crop was to be assured protection from all possible frosts throughout the growing season.

The results also indicated the limitation of application of this method of frost control. It was found that only those crops of higher value could economically support the initial and operational cost.

Reflector studies

Extensive experimental work and study has been done on reflectors for infrared energy in connection with this application (13) as reflectors are one proved method of reducing the adverse effect of the inverse square law of radiation from a relatively small source of radiation. As previously pointed out, a plot of the intensity from a flat surface describes a sphere (exact for a blackbody) in which the intensity in any direction equals the product of the normal intensity times the cosine of the angle which the direction in question makes with the normal to that surface. Fig. 5 illustrates an application of reflectors for aiding in the effective distribution of radiant energy for frost control. In contrast Fig. 6 brings out the little advantage of using a comparatively small reflector in conjunction with a large source of radiation..

The reflector studies in connection with this problem were: (1) the selection of the best material from the standpoint of cost, availability, and durability; (2) the most effective shape and arrangement of reflectors and radiating surfaces; and, (3) an overall viewpoint toward keeping the material and fabrication cost to a minimum.

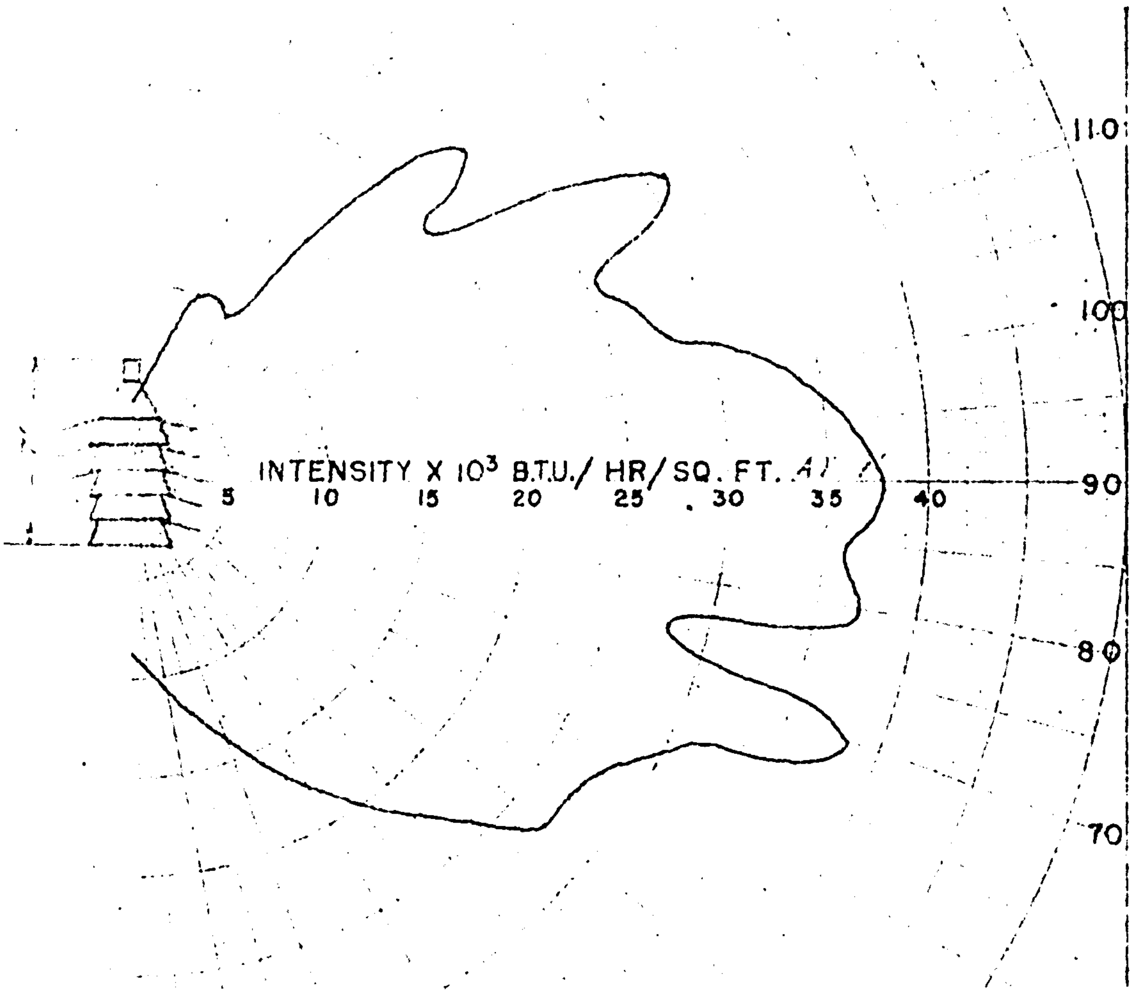


Figure 5. The effect of comparatively large reflectors on the distribution of radiation from a straight surface.

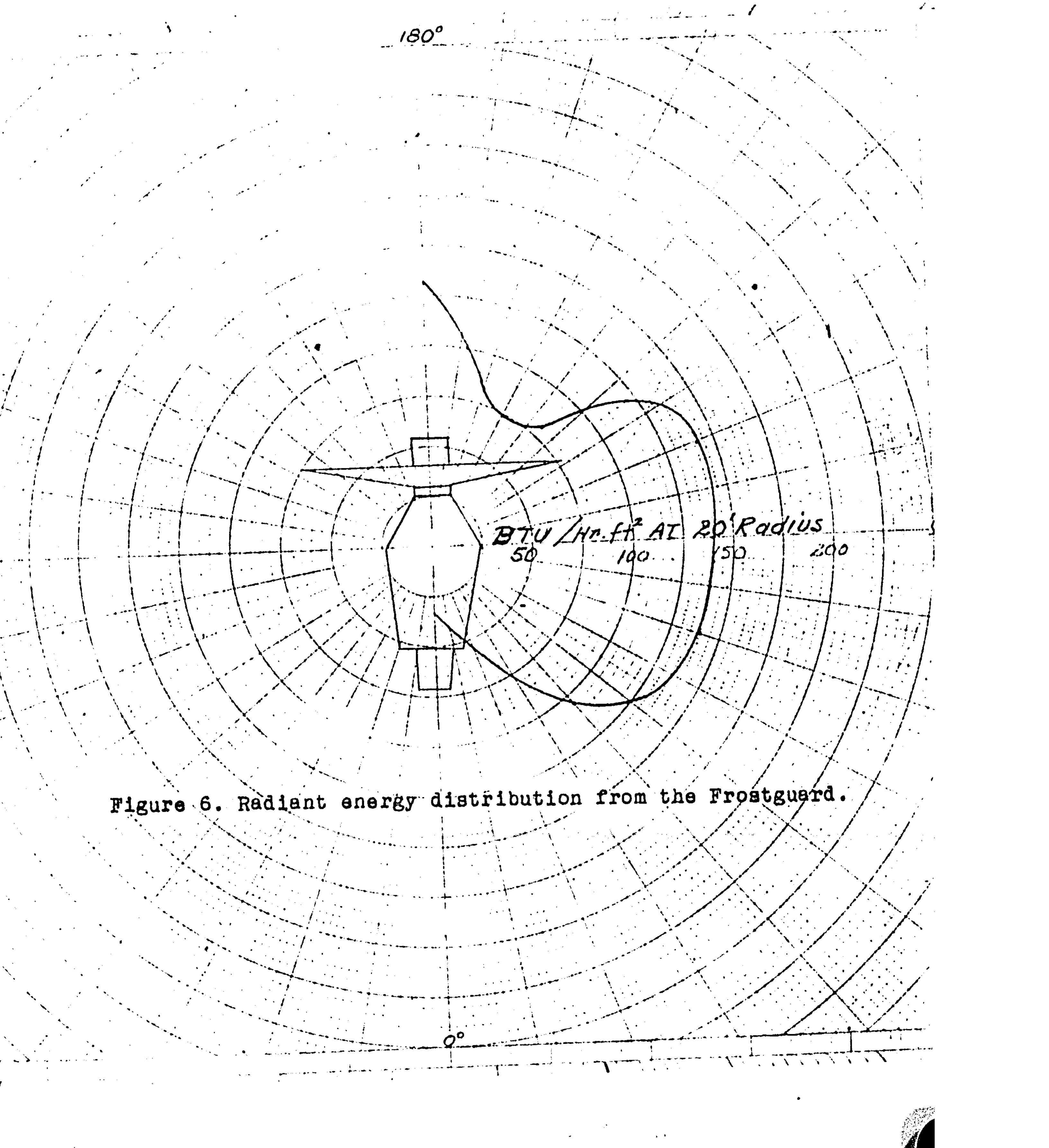


Figure 6. Radiant energy distribution from the Frostguard.

The results of these studies are summarized as follows:

1. Anodized aluminum is presently the best material.

2. The larger the reflector in relation to the radiating surface, the better the distribution.

3. In order to offset the inverse square law to a reasonable degree, the proper reflection of a large part of the radiation is required.

4. Curving the radiating surface and/or the reflector gave positive evidence of aiding in the distribution of the radiation, but the gain in effectiveness apparently would not offset the added cost of construction.

EXPERIMENTAL

Studies to Improve the Evans Frostguard

As stated in the introduction (P.27), the design of a petroleum fuel (kerosene) burner for the generation of radiant energy for frost control, the "Frostguard", Fig. 7, was released to Evans Products Company of Plymouth, Michigan, for manufacture and distribution on a limited scale. This was deemed necessary in order to gain further information as to its operation under various field and frosting conditions. The results of these tests placed the practical use of this type of unit for frost control in a limited category or otherwise restricted its use to certain areas and particular crops.

There were two principal factors which limited the use of this heater: (1) its failure to operate satisfactorily at all times, i.e. lack of dependability; and (2) in view of the initial and operating costs, it was found to be impractical from an economical standpoint except for crops of comparatively high value. Therefore, the next move was toward improvement, and the work that was done in the Agricultural Engineering Department follows.

A study of liquid petroleum fuels (kerosene and No. 1 fuel oil)

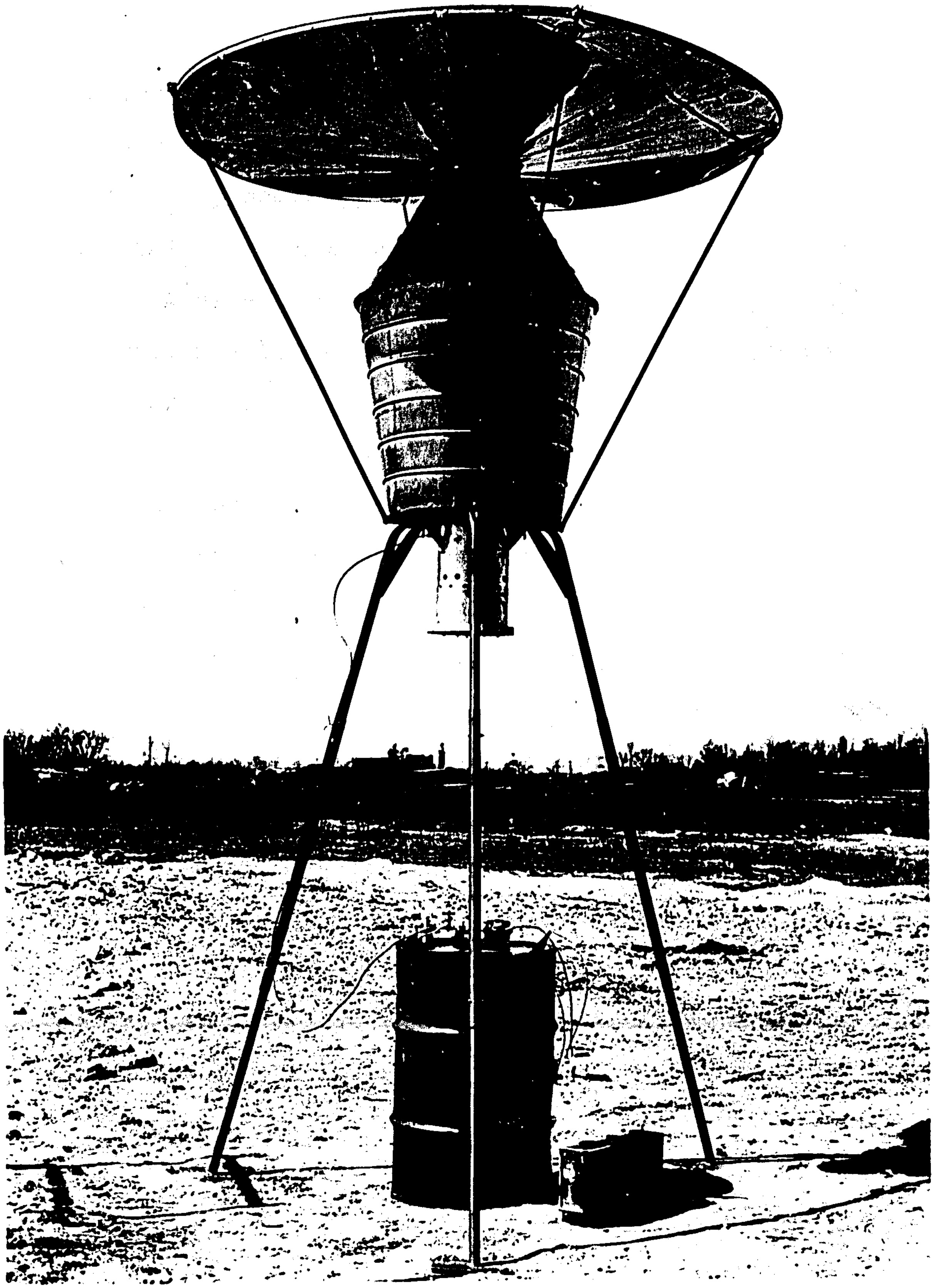


Figure 7. The Evans Frostguard

Before attempting modifications of the Frostguard unit, it was necessary to make a further study of the physical and chemical properties of the fuel used, and to study the fundamental principles underlying liquid petroleum fuel burners. A brief discussion of the fundamental principles of combustion will serve to bring out the basic requirements for all burners.

Combustion of fuel oil may be defined as the chemical combination of the component elements (primarily carbon and hydrogen) with oxygen, resulting in the evolution of heat. The rate of an exothermic reaction, such as the burning of hydrocarbons, increases with temperature. Unless the oxygen is made available in close proximity to the elements carbon and hydrogen, delayed burning will result. Also, any physical barriers, such as the presence of inert gases or if these elements are buried within a complex molecule, will cause delayed burning. Regarding temperature, each fuel has its own characteristic ignition temperature--this being the temperature (of the oxygen and fuel molecules) at which the chemical process of combustion takes place. This ignition temperature ranges from over 1200°F. for natural gas down to as low as 550°F. for fuel oils. An explanation of this variation is found in the fact that natural gas is made up of saturated hydrocarbon molecules which require greater heat energy to break down the bond between the carbon and hydrogen than that for unsaturated hydrocarbon molecules--those found in kerosene and fuel oils. Therefore, a lower temperature will cause burning to start in the unsaturated hydrocarbons, subsequently releasing heat which produces the temperature and heat energy to support a "chain-reaction" for continued combustion of all other molecules in that fuel.

In addition to raising the temperature of the reactants in the combustion process to as high a temperature as practical (but below the ignition temperature), any means of promoting intimate mixing of the air for combustion with the elements to be oxidized, carbon and hydrogen, will enhance the rate of the combustion reaction. This proves to be the advantage exhibited in the ease with which a natural gaseous fuel can be burned quickly and cleanly, for, since these molecules are relatively small and widely separated, the air is easily mixed to produce an air-vapor mixture which burns readily once the proper temperature is reached. The difference between gaseous fuels and liquid fuels is appreciated when one considers the problem of having first to break up the liquid fuel into its component molecules (to vaporize them) before other than superficial mixing with the air will take place. Another problem enters in that, if heat is used to vaporize these molecules, and if the lowest ignition temperature for this group of molecules is reached during this vaporization, burning is initiated which spreads to other molecules; thus, inhibiting further mixing of air with the fuel molecules. As a result, carbon atoms will coalesce giving body to the flame, which produce a luminous flame if they burn or pass off as smoke if they fail to burn completely.

Gaseous fuels are thought of as inherently burning with a non-luminous flame, and liquid petroleum fuels as giving a luminous flame. This is purely a measure of the completeness of the mixing of the air and fuel vapor (primarily before burning starts). There are in use so-called "oil-to-gas" converter burners which take the heavier fractions of fuel oil and burn them with the flame characteristics of gaseous fuels; this emphasizes the importance of proper air-fuel mixing.

The fuel under consideration for this application was straight-run kerosene or No. 1 househeating fuel oil. Since these two fuels have little difference in their boiling point temperatures, they are very nearly identical in the present-day refining process. The existing demand regulates the classification, rather than the small difference in properties. This same fraction is represented in cracked petroleum;

however, cracked petroleum yields a fraction which is considerably more difficult to burn and should not be used in this application.

A typical fuel used in this application is characterized by the following analysis of recent heater oil as manufactured by Standard Oil Company (Indiana) (4):

Standard Heater Oil (Straight run)

Gravity, °API	40.3	
Doctor	Sweet	
Color	18	
Flash	133	
Sulfur	.214	
Carbon Residue on 10% Bottoms	.01	
Co. strip 3 hrs. @ 212°F.	1	
Vis. Saybolt Therme	440	
Initial Boiling Point °F.		338
10		382
20		398
30		410
40		422
50		436
60		448
70		464
80		480
90		508
End Point		562
Water & Sediment %		None
Diesel Index		63.8

From these data it is possible to determine other physical and chemical properties which are pertinent to the problem of burner design. Because of the difference in the crude petroleum (paraffins, naphthenes, and aromatics) and the wide range of types and sizes of molecules which make up any one fraction, the derived empirical relationships expressing these properties are approximations which have proved to be sufficiently accurate to satisfy the petroleum industry and consumers of petroleum products. These relationships are based on the specific gravity and average boiling point of the petroleum fraction.

The following properties of the above fuel were determined by the latest accepted graphical methods (15):

Specific Gravity = 0.825

Average Boiling point = 459°F. (19)

Average Molecular weight = 186

Critical Temperature = 780°F.

Hydrogen content, % by weight = 13.5%

Average specific heat of liquid at constant pressure (C_p) = 0.575 BTU/°F/lb.

Heat of vaporization (1 atm.) = 108 BTU/lb.

Higher Heat value of fuel = 19,720 BTU/lb.

Theoretical Amount of air for combustion = 14.5 lbs of air/lb. of fuel

Ignition Temperature = 563°F. (20)

An analysis of the burning characteristics of the Frostguard

Using the fuel discussed in the previous section, the next consideration was its use as fuel for the Frostguard burner. This burner, illustrated in Fig. 8 is of the pressure heat-vaporizing type which operates on a fuel pressure of from 50 to 80 psig. The liquid fuel (kerosene) is self-vaporized and throttled through the nozzle or jet, and is ignited as it enters the combustion chamber, the surface of which serves as the source of radiant energy. This principle is the same as that of a common blow torch and requires an external source of heat for starting. A reasonable time lag must be allowed before the burner takes hold and becomes self-generating, which is a disadvantage in this application; and it has been found generally that this type of burner is subject to considerable variation in its capacity. It was hoped that through careful study, this variation or lack of dependability could be corrected and at the same time decrease the flame volume required for the original rate of burning.

If combustion could be accomplished within a smaller flame volume, then either of the following two improvements could be employed: (1) the rate of burning could be increased for the same size combustion chamber, thus increasing the

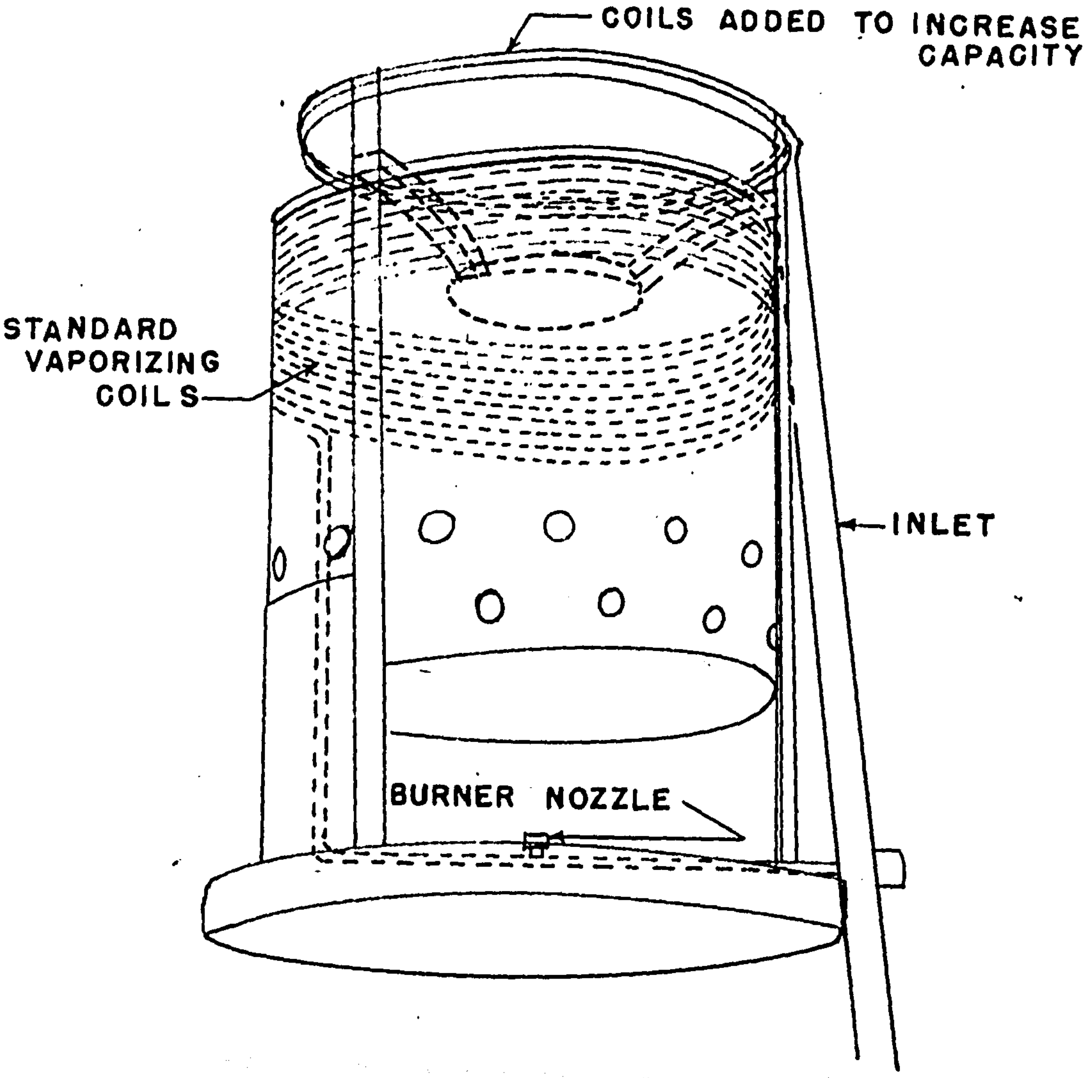


Figure 8. Pressure heat-vaporizing type kerosene burner.

surface temperature of the present unit; or, (2) the size could be reduced as well as raising the surface temperature. Reflector designs would then be more practical for aiding in the proper distribution of the radiant energy. Since the total radiation is proportional to the fourth power of the absolute temperature of the source, it is evident that any increase in surface temperature would be a considerable improvement.

Through methods used in the petroleum industry (21), the saturated vapor temperature at 80 psig was found to be 655°F. which is significant in that it is above the ignition temperature (563°F) of this fuel.

From the specific heat of the liquid fuel and its heat of vaporization at 80 psig (which was found to be of negligible difference from that at 14.7 psig), it was found that the heat required to raise the fuel from 50°F. to a saturated vapor temperature of 655°F. is approximately 452 BTU/lb..

The use of this fuel in a pressure heat-vaporizing type of burner brought up the important point as to the temperature of the fuel vapor after it was throttled through the burner jet. Considerations were given to methods for making this calculation; however, since there were no published works on the equation of state or Mollier Charts for this type of fuel, it was impossible to make a direct determination of the temperature drop as the vapor was adiabatically expanded from 80 psig and 655°F., to 14.7 psia. From the assumption that the vapor had the properties of a perfect gas and using the best obtainable values for the specific heats at constant volume and pressure (1), it was found that the temperature drop was less than 10°F.

Through proper operation of this burner under normal conditions, it was found that a burning rate of eight gallons per hour could be attained within a flame volume of ten cubic feet. This rate of efficient burning proved adequate for maintaining the average temperature of the radiating surface at approximately 1400°F. The operation of the burner was generally stable in wind of less than five miles per hour; however, if the wind velocity exceeded this figure, even for short gusty periods, the burner required constant attention for satisfactory operation. Factors such as fuel temperature, surrounding air temperature, and cleanliness of vaporizing coil were found to reduce the burning efficiency. This could be corrected only by reducing the rate of burning.

Experimental trials to improve the Frostguard

The original burner. The relationship of the burner to the unit proper is illustrated in Fig. 9. The air is introduced at two places--the primary air at the base of the burner and the secondary air is brought in at the base of the unit. Through a flue gas analysis it was found that under favorable conditions eight gallons of kerosene per hour could be burned completely within the combustion chamber. This was carried out with 30% excess air and a flue gas temperature of 2000°F.; giving a radiant surface temperature of approximately 1300°F.

The temperature of the fuel vapor was measured as 660°F. at the point just before it was throttled through the jet. This measurement was taken by means of a thermocouple in a temperature-well extending into the vapor stream. Therefore, the measured temperature checks with the calculated temperature of 655°F. for the saturated vapor.

Because of unfavorable air-fuel vapor mixing and the short path of travel for the flame, the high percent of excess air was required to insure complete burning. The air was forced in almost entirely through the effect of a seven-foot stack and had very little velocity or turbulence.

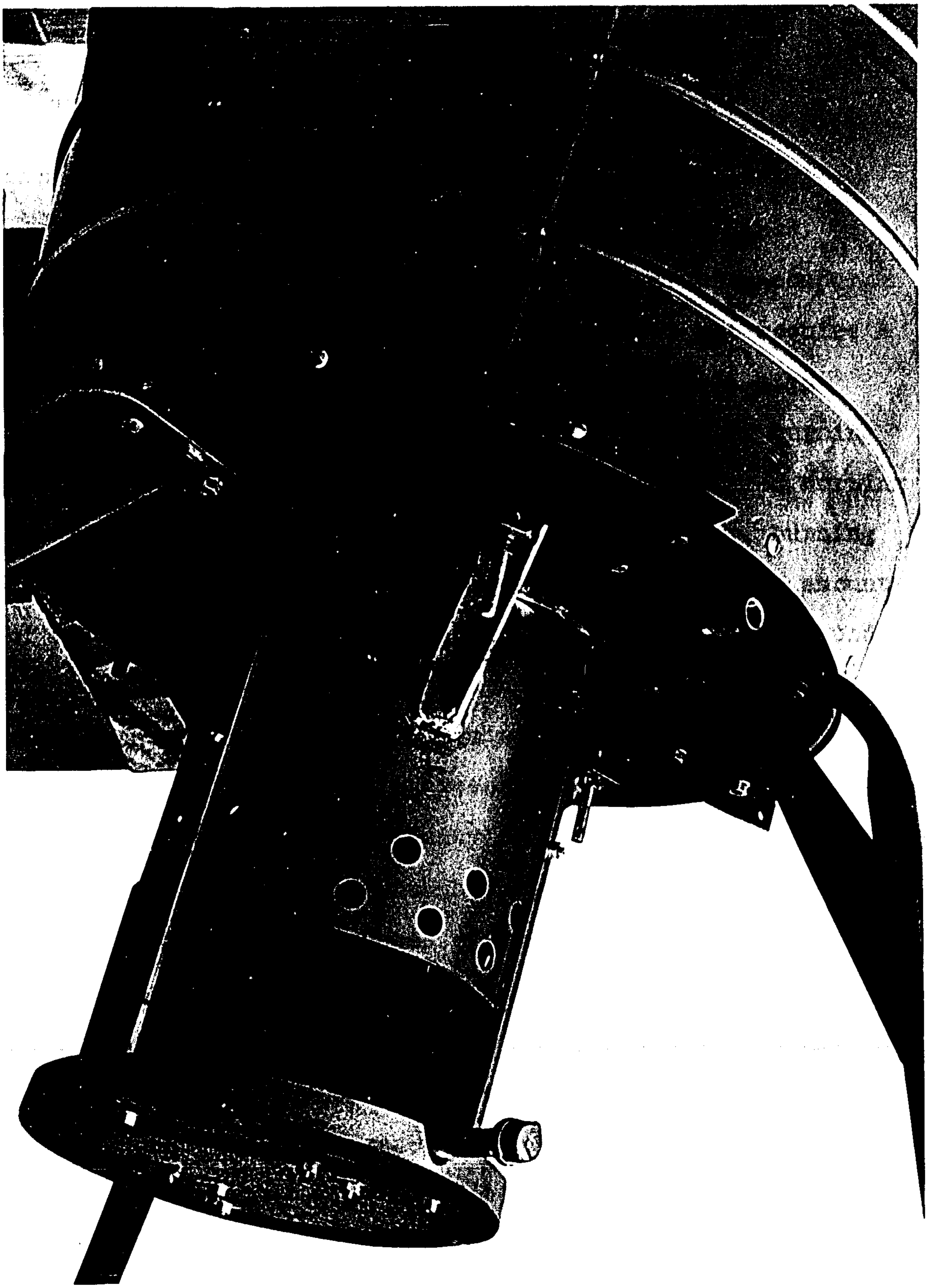


Figure 9. The arrangement of the burner and combustion chamber of the Evans Frostguard.

The requirement for a high surface temperature demanded a high flue gas temperature; thus, giving rise to the exceptionally high loss in sensible heat out the stack. However, the nature of utilization, which means a comparatively few hours of operation per year, does not require a high overall operating efficiency; but rather, a high radiation intensity. For this reason the rate of burning was normally ten gallons per hour, allowing delayed burning to follow the flue gases out the stack. However, burning has to be nearly complete to prevent an appreciable amount of smoke formation. These conditions were easily met under normal operating conditions which are characterized by weather conditions with a surrounding minimum air temperature of 32°F. and a wind velocity not in excess of 6 MPH. Colder air reduced the vaporizing capacity of the burner coil by direct contact and indirectly through the cooling of the flame temperature. Wind in excess of the critical velocity of 6 MPH apparently reduced the temperature of the combustion chamber by reducing the rate of incoming air to the point where it was not adequate for the selected rate of burning. This affected the vaporizing capacity of the coils such that liquid fuel was ejected from the burner jet.

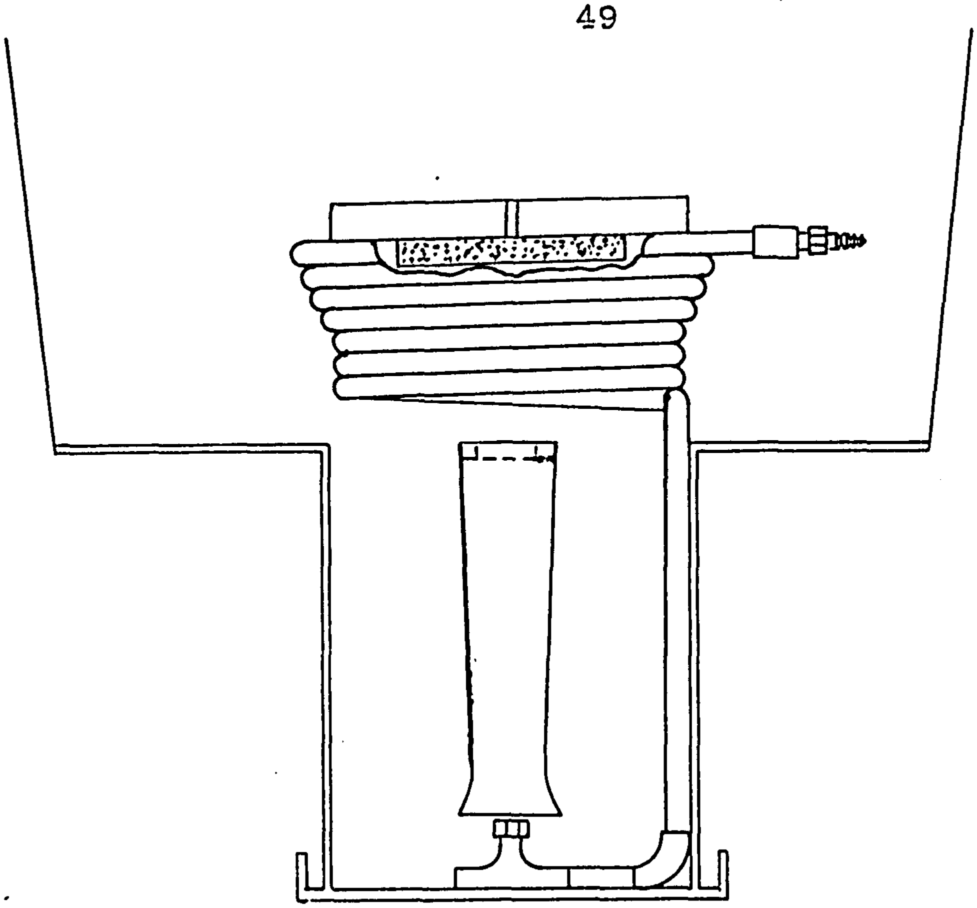
The above conditions either reduced the burning capacity or caused a fluctuation in the operation which required constant attention.

First modification. The first approach toward improvement of the Frostguard was designed to increase the air-vapor mixing before burning started, followed by the proper introduction of secondary air to complete combustion in as short a time as possible.

Concentric holes were drilled in the base of the burner as inlets for the primary air, while larger holes were drilled in the base of the unit as inlets for the secondary air, Fig. 10. Each group of holes was fitted with a cover by which the size of openings could be varied.

An inspirating-mixing venturi was shaped from two-inch copper tubing and positioned relative to the burner jet to inspirate air and facilitate a better mixing of the air and fuel vapor. The outlet from this inspirator was directed toward a ceramic target, mounted at the top of the vaporizing coils, to serve both as a flame retainer and to diverge the flame so that more heat would be directed against the vaporizing coils.

The results of the operation of this burner as modified gave evidence that no improvement had been made. After the



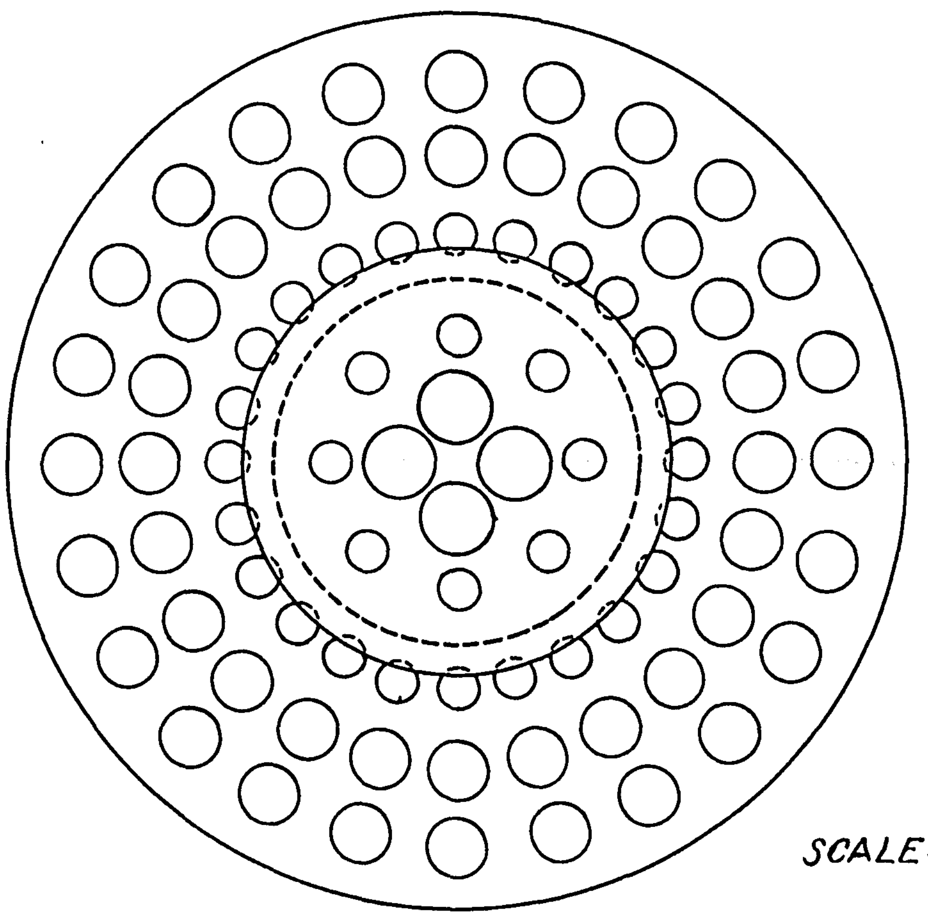


Figure 10. Illustrating the first modification of the Frostguard.

burner became self-generating and reached equilibrium otherwise, the fuel vapor started burning within the inspirator, thus eliminating any chance for improving the air-fuel vapor mixing.

Following the adjustment of the air inlet openings, the burning characteristics (as related to wind effect and capacity) were no different from that of the original burner arrangement.

Second modification. In place of the copper inspirator a large industrial inspirator was positioned as illustrated by Fig. 11. This had the same disadvantage as the copper inspirator in that burning started within the inspirator; thus, again eliminating any possibility for improving the air-fuel vapor mixing.

Following this test it was concluded that since the saturated vapor temperature of the fuel was higher than its ignition temperature, little could be done toward mixing the vapor with the air without burning taking place; particularly within the confines of an inspirator which maintained the vapor relatively close to the temperature at which it was ejected from the jet, for as soon as mixing reached a combustible concentration, burning would invaribly start. Also,

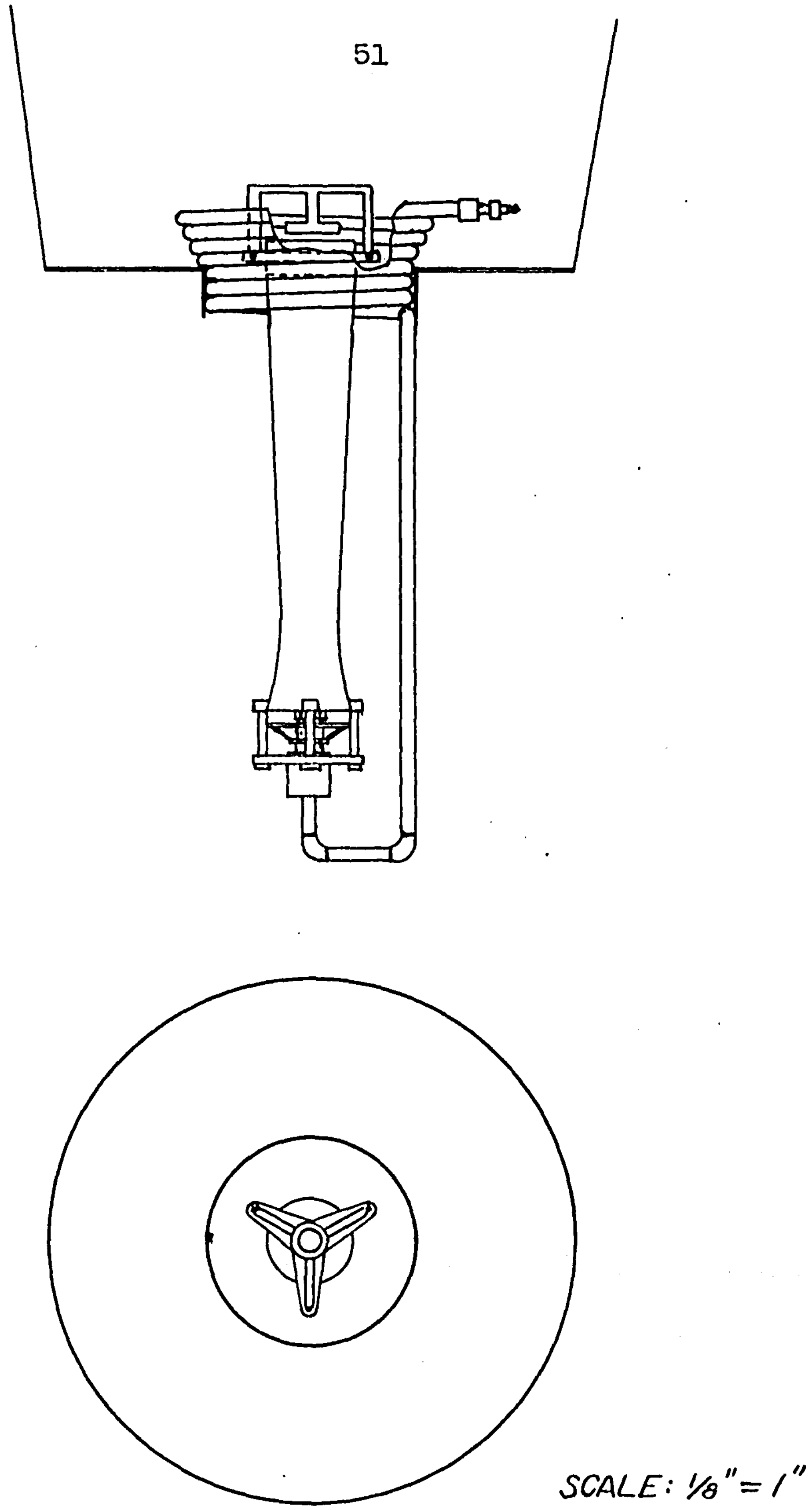


Figure 11. Illustrating the second modification of the Frostguard.

regarding the vapor temperature, it must be realized that because of the arrangement of the coils for vaporizing the fuel, there will surely be superheating of the fuel vapor during part of the operation; this was found to be true by actual temperature measurements (P.45). Therefore the air-fuel vapor mixture will be above its ignition temperature even after considerable air has been added; at least, after enough has been added to produce a combustible mixture.

Third modification. The fact that burning took place within each of the experimental inspirators ruled out this approach as a likely improvement to the existing burner.

Realizing the adverse effect that the wind has in reducing the capacity of the unit, it seemed advisable to position wind deflectors or scoops which would take care of a reasonable velocity range of continuous wind. However, gusty conditions would still have the effect of upsetting stable or equilibrium burning since gusty wind conditions had been found to reduce the air supply required for a suitable rate of burning. This condition lowered the flame temperature which resulted in incomplete vaporization of the fuel for that pressure; thus, causing the burner to go out unless necessary pressure adjustments were made. It was believed that this factor could be corrected by surrounding the vaporizing coil with a ceramic which would hold the heat and give sufficient thermal inertia to correct for the fluctuations in the flame temperature caused by the gusty wind conditions.

This idea of providing thermal inertia was taken into consideration and the unit was modified as illustrated in Fig. 12. In addition, wind deflectors were positioned at the top and bottom of the unit to offset the effect of continuous wind upon the air supply for combustion.

The modified unit was tested and the following data are typical of the operating characteristics:

Air temperature --- 58°F., Humidity --- 50%

Wind condition --- varied in velocity between 5 and 15 MPH

Fuel consumption --- 12.5 gallons/hour

Fuel vapor temperature --- 670°F. (thermocouple)

Exhaust flue gas temperature --- 2100°F. (thermocouple)

Surface temperature --- 1450°F. 50°F. ("tempil-sticks")

Excess air for combustion --- 25%(orsat analysis)

The results of this modification showed a decided improvement in the burner. The burning of 12.5 gallons of fuel per hour took place completely within the unit proper

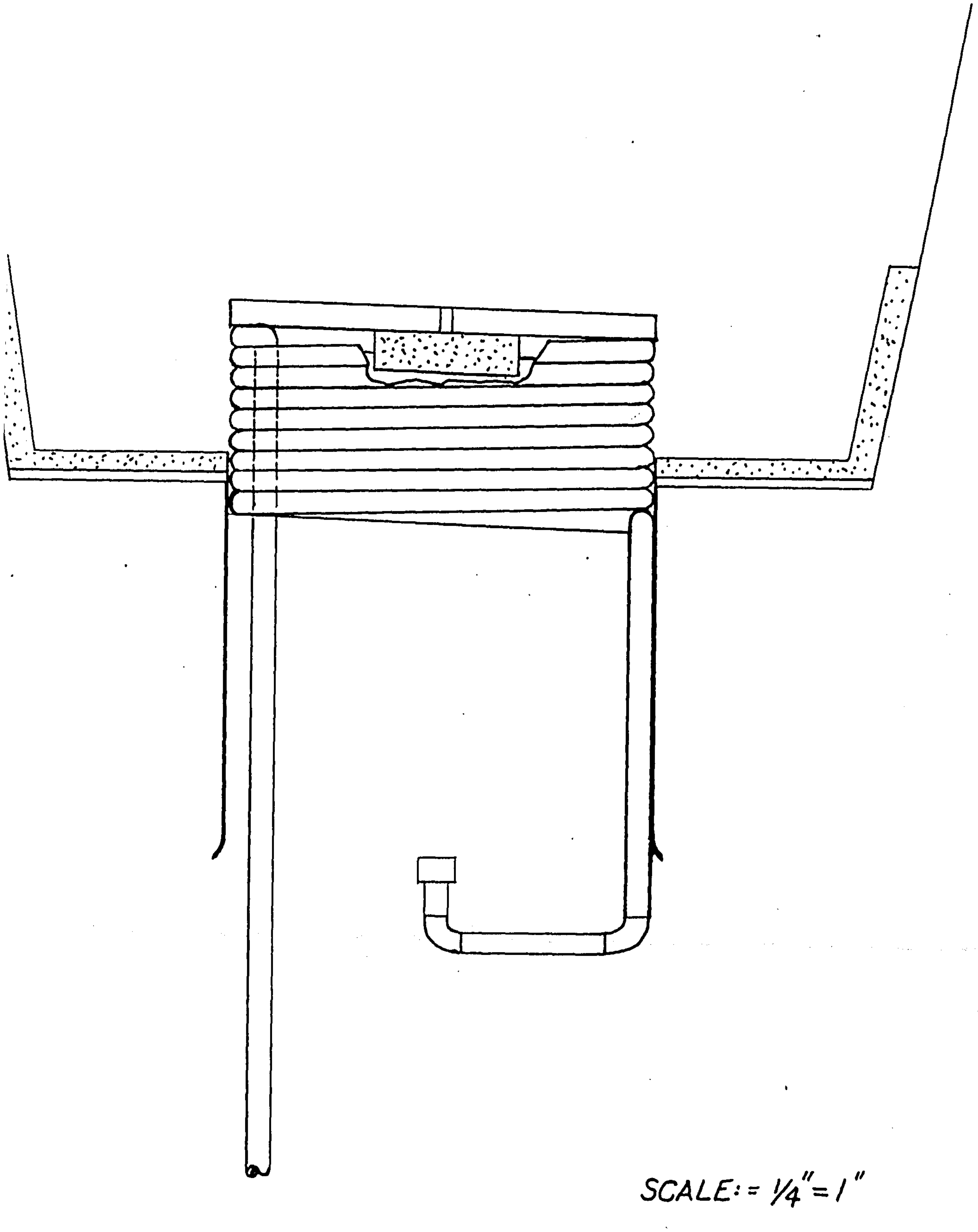


Figure 12. Showing the position of the ceramic material to stabilize the burner for the Frostguard.

which was much better than the capacity of the original unit. This resulted in a higher surface temperature--giving a considerable increase in the total emissive power of the unit.

During the intervals of gusty wind the burning became somewhat incomplete. However, in all cases the vaporization of the fuel gave no evidence of being affected and the burner would regain its equilibrium as soon as the wind dropped to its normal velocity and allowed the proper intake of air for complete combustion.

Discussion of results

The requirement that the Frostguard operate satisfactorily under a wide variation in weather conditions imposed a difficult problem in consideration of the type of burner employed. The pressure heat-vaporizing type burner, operating on kerosene, has been found to be comparatively erratic even under constant burning conditions, such as experienced inside a building. The use of this type of burner out in the weather is a far removed condition from the more or less ideal condition inside an enclosure. For this reason there seemed little justification for considering modifications which gave only marginal improvements at optimum conditions for burning.

The modifications tried and tested were founded on the following two principles: (1) facilitating better air-fuel vapor mixing before burning starts; and (2) aiding the vaporization of the fuel by adding thermal inertia to offset the lulls in the burning rate as a result of gusty wind conditions.

The first two modifications were attempts at principle number one in that an inspirator-mixer was placed relative to the fuel jet to draw air in by the venturi action of the arrangement. This failed due to the fuel igniting within the confines of the inspirator which greatly reduced the air drawn in. This was more or less suspected upon learning that the ignition temperature of kerosene was 563°F. The last temperature was measured and found to be 670°F. which would indicate that the vapor was superheated and thus more subject to pre-ignition.

It is possible that, through proper design and adjustment, the ignition of the fuel vapor could be delayed until after passing through the inspirator; however, to make this principle work satisfactorily for an appreciable variation in the weather conditions seems highly impractical.

The third modification, which exemplified the advantages of the additional thermal inertia through the use of ceramic, offers an economical and practical method for improving the stability of operation and the total emissive power of the Frostguard. In conjunction with the air scoop and deflector at the bottom and top respectively, this innovation was found to increase the surface temperature by at least 100°F. and allowed the unit to operate satisfactorily under a continuous wind of 5 MPH with fluctuations as high as 15 MPH.

Studies to Develop a High Capacity Non-powered Liquid Petroleum Fuel Burner

The various field tests of the Frostguard proved that infrared energy would protect vegetation from frost damage if the intensity was sufficiently high. The required magnitude of this intensity depends on the minimum air temperature, the accompanying weather conditions, and the type of vegetation to be protected. For the freezing conditions most likely to be encountered during the time when crops are vulnerable, and for those plants which have their foliage well exposed, such as strawberries, tomatoes, etc.; the required radiation was determined to be between nine and ten BTU's per hour per square foot--measured perpendicular to the direction of the radiation.

The Frostguard generally maintains this intensity at seventy feet from the unit. Since reflectors of practical length and shapes do not offset appreciably the decrease in intensity with distance (this relationship is accurately expressed by the Inverse Square Law of Radiation from a point source), there is an excess of energy impinging upon the vegetation within the circle of a seventy-foot radius, with the vegetation in close to the unit receiving energy greatly in excess of that required for safe protection.

Of course, the effective distance of seventy feet could be increased by building the units larger or increasing the surface temperature; however, this would necessarily increase the already excess energy for closer vegetation. This would surely make the application of this unit questionable from an economical standpoint, even for the higher-valued crops.

The alternative was to consider smaller units (reduced emissive power) spaced closer together. This is the solution used by illumination engineers in order to accomplish satisfactory light distribution where reflectors are not practical. However, to make use of smaller units requires that the initial maintenance and operating cost be proportionally reduced.

Objective

The smudge pots and so-called orchard heaters which are presently used in the citrus fruit areas are one answer to the use of small burner units for frost control. (As a fact of historical interest these same units were used in Michigan during the twenties). These heaters unquestionably are a source of considerable infrared energy in addition to the sensible heat transferred to the air. They have been proven to be an effective frost control measure. The greatest objection to the use of these heaters, particularly in the citrus areas of California, is that the generous amount of smoke given off contaminates households in the surrounding urban areas, which are generally located in the valleys. This factor does not appear to be of primary importance in Michigan due to the advantage of more level topography and the wide separation of the farm and urban areas. However, the smoke contamination would affect the commercial value of some crops.

Other citrus areas have found the smudge pot and orchard heater insufficient as protection against the occasional cold wind-blown freezes and for this reason farmers are not too anxious to stock them as a frost control measure.

From this discussion it is obvious that any developments will have to be at least an improvement over the existing small-type heaters. Improvements which reduce the excessive amount of smoke liberated will surely be welcomed. Also, any means of increasing the infrared emissive power of small units will increase their effectiveness for frost control under all conditions.

The object of this investigation was to develop a non-powered burner of small size which gave a radiation intensity of 10 BTU/ft^2/Hr. at 25 feet, burning no more than 1.5 gallons of kerosene per hour with less than one gram of smoke per minute.

Procedure

The primary requirement was to design a kerosene burner which would accomplish the above specifications. It may appear from a casual observation to be a rather simple problem; however, after a few attempts, it became certain that failures were the rule instead of the exception. It is true that to increase the output or rate of burning of a liquid fuel burner requires only that more fuel be turned on, for the lighter fractions will burn readily and perpetuate an ever increasing rate of burning. However, at the same time there will be a greater increase in the smoke output. Also, it has been proven through the various types of commercially available burners, that vaporizing, either thermally or mechanically, in combination with a blast of air from an externally powered fan will facilitate clean efficient burning at practically any chosen rate. This, however, is far removed from the requirements that no power source be used and that the conditions under which the burner will operate are subject to wide variations.

The problem is also complicated by having to incorporate the requirement for proper distribution of the generated radiant energy. This means that the surface which is to produce the radiation must be sized, shaped, and heated so that the best practical distribution of the radiant energy can be accomplished with the least reflector cost.

Based on these considerations, it was advisable to construct burner designs which seemed to offer the greatest possible chance that the liquid fuel would be vaporized, mixed with sufficient air, and then burned with the greatest possible efficiency with a minimum of smoke formation. Other than studying the basic requirements for burning a fuel of known physical and chemical properties, this was a trial and error method of development.

Several different burners were built and in order to facilitate a comparative test of these burners and to study the relative advantages of subsequent modifications on each burner, a testing arrangement was assembled whereby controlled conditions could be maintained. In addition to affording a comparative test to enhance development, the standard test provided absolute data which enabled an evaluation of the burner for field applications.

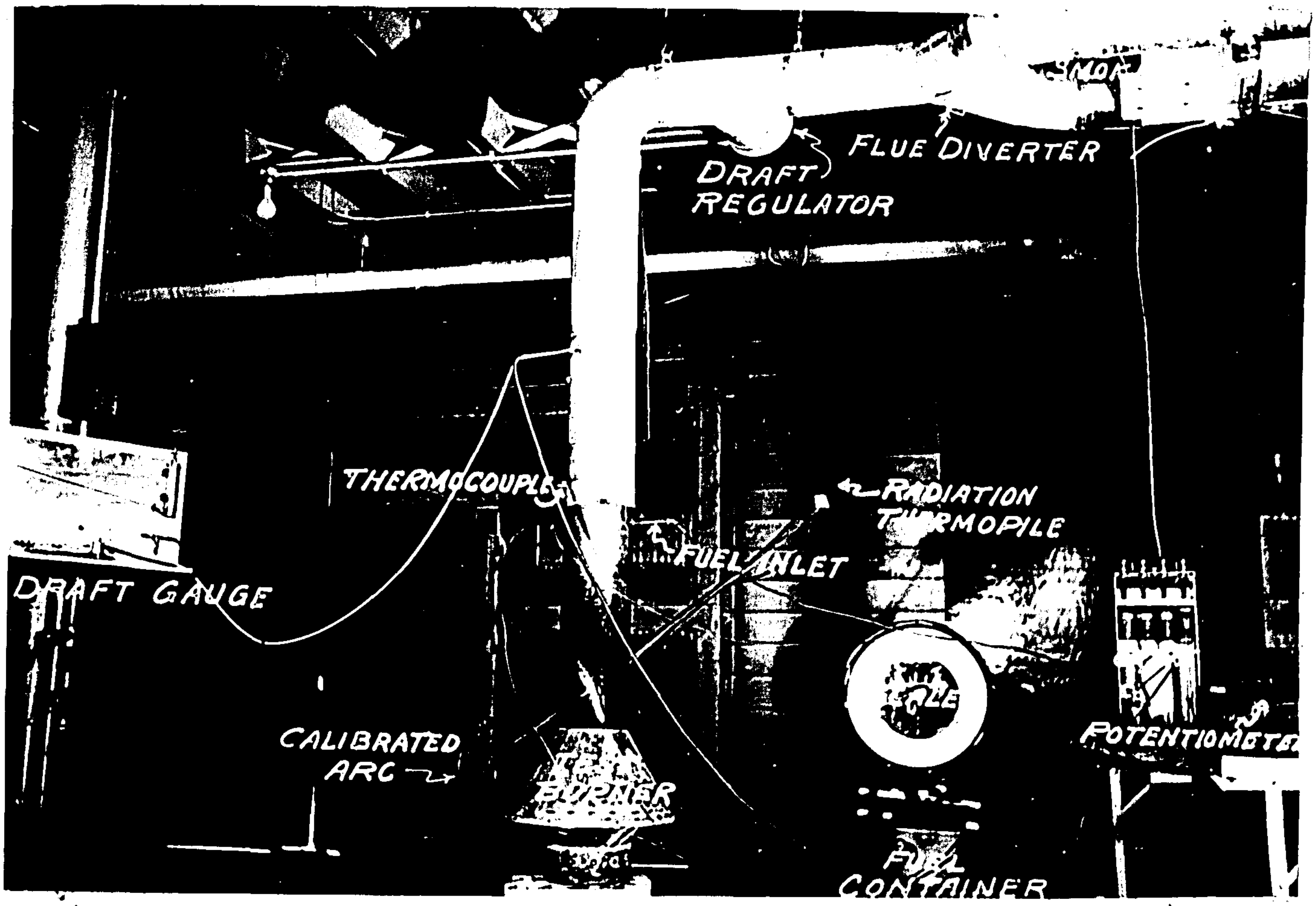


Fig. 13. Arrangement for Testing Non-powered Liquid Petroleum Burners.

The complete testing arrangement is illustrated in Fig. 13. This is essentially an exhaust stack with the necessary attachments and outlets to afford a complete analysis of the exhaust gases from each of the several burners tested. This included a measure of the composition of the gases with a conventional orsat; exhaust gas temperature with a chromel-alumel thermocouple; and fiberglass filters for catching the smoke which gave a measure of the time rate of smoke liberation. To accomplish the latter, the exhaust stack was branched into two separate pipes with provisions for inserting fiberglass filterpacks across each of the branch pipes, and with the use of a flue diverter, the exhaust gases were allowed to pass through either of the filters for a measured interval of time. This arrangement proved inadequate for an accurate absolute measurement of the smoke given off; however, an approximation was possible which allowed a relative comparison for this feature of the burners.

The draft was induced by both the chimney effect and a suction fan. This fan aided in smoothing out variations, and in conjunction with the draft regulator or balancer, it was possible to maintain a very nearly constant draft of 0.2" H_2O.

The radiant energy distribution was determined with a calibrated thermopile at the end of a seven-foot arm which was pivoted at the center-line of the radiating surface, Fig. 14. At the pivoted end a pointer moved on a calibrated arc to give the angular position of the thermopile above and below the horizontal.

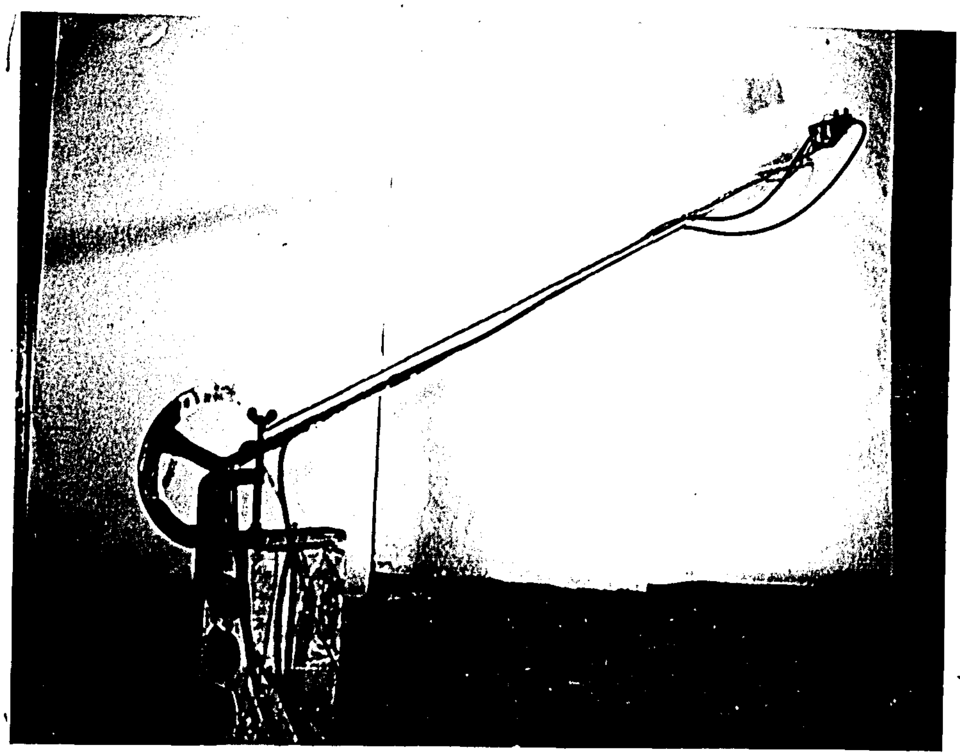


Fig. 14. Apparatus for Measuring the Radiant Energy Distribution from Heater Units.

The fuel consumption rate was measured directly by having the fuel container resting on sensitive platform scales (2 oz. per division).

The results from this test arrangement could be duplicated with sufficient accuracy; such that, with the exception of the smoke measurement, the data afford a measure of the absolute values as well as giving a relative comparison for the different burners.

The burners were noted to have a higher rate of fuel consumption (approximately a twelve percent increase) when burning indoors under the testing apparatus as compared to free burning outside the building. The 0.2" H_2O draft the burners experienced under test is somewhat higher than the draft produced by the same burner when operating freely, and this, coupled with a still ambient air temperature of 70°F., explains the difference in fuel consumption. As a result, the total emissive power of a burner unit was somewhat higher for the indoor conditions as compared to outdoor conditions.

Not all the different burners constructed were tested, nor all the tests recorded in this paper. A considerable part of the work was cut-and-try resulting in modifications which proved to be of no apparent value for the investigation or to be of no consequence in future work along this line. Only those units constructed along different basic arrangements for carrying out the process of combustion are recorded herein and these are believed to be developed as far as practical.

Existing non-powered liquid petroleum fuel burners

The simplest of all types of burners used for frost

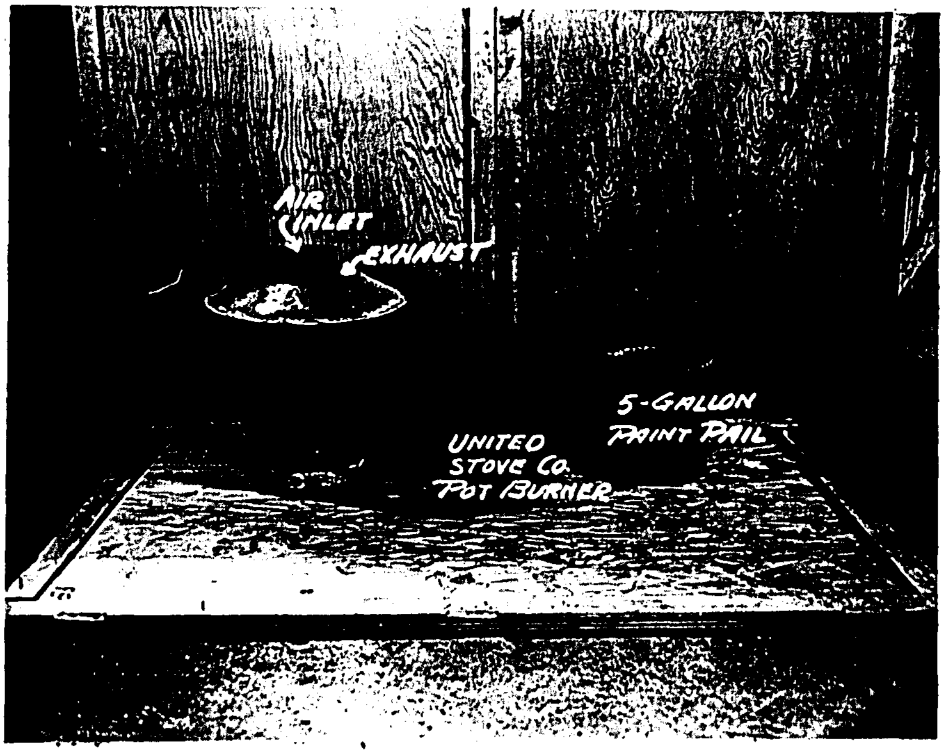


Fig. 15. Open Pot Burners.

control is the "smudge-pot", which may be any open-top container such as a lard pail, bucket, or other inexpensive container of similar type. This heater has had extensive use in the citrus areas; however, the nuisance of the smoke and the labor required to maintain and service them has practically eliminated their application. United Stove Company of Ypsilanti, Michigan attempted an improvement by fitting the top of the container with a special lid which would presumably increase the burning efficiency, thus reducing the smoke problem, Fig. 15. For purposes of comparison, particularly with open-top containers, this heater was tested and the results are given in Fig. 16.

A similar test was made of the burning characteristics of an open-top five-gallon paint bucket. The results of this test are given in Fig. 17.

For further purposes of comparison, the "Return-Stack" orchard heater, developed at the University of California, Fig. 18, was tested and the results are given in Fig. 19. This heater uses the thermal siphoning effect of the stack-gas return tube to dilute the concentration of fuel vapor within the bowl of the heater. This dilution reduces the rate of formation of free carbon during that part of the burning process when there is insufficient oxygen for complete burning (17). Then, as the diluted vapor passes up the stack, the additional air required is introduced through louvres in the stack; as a result, the burning is practically complete.

First trial burner

Efforts were made to approach the efficiency of the return-stack orchard heater and at the same time to increase the burning capacity in order to provide a high temperature

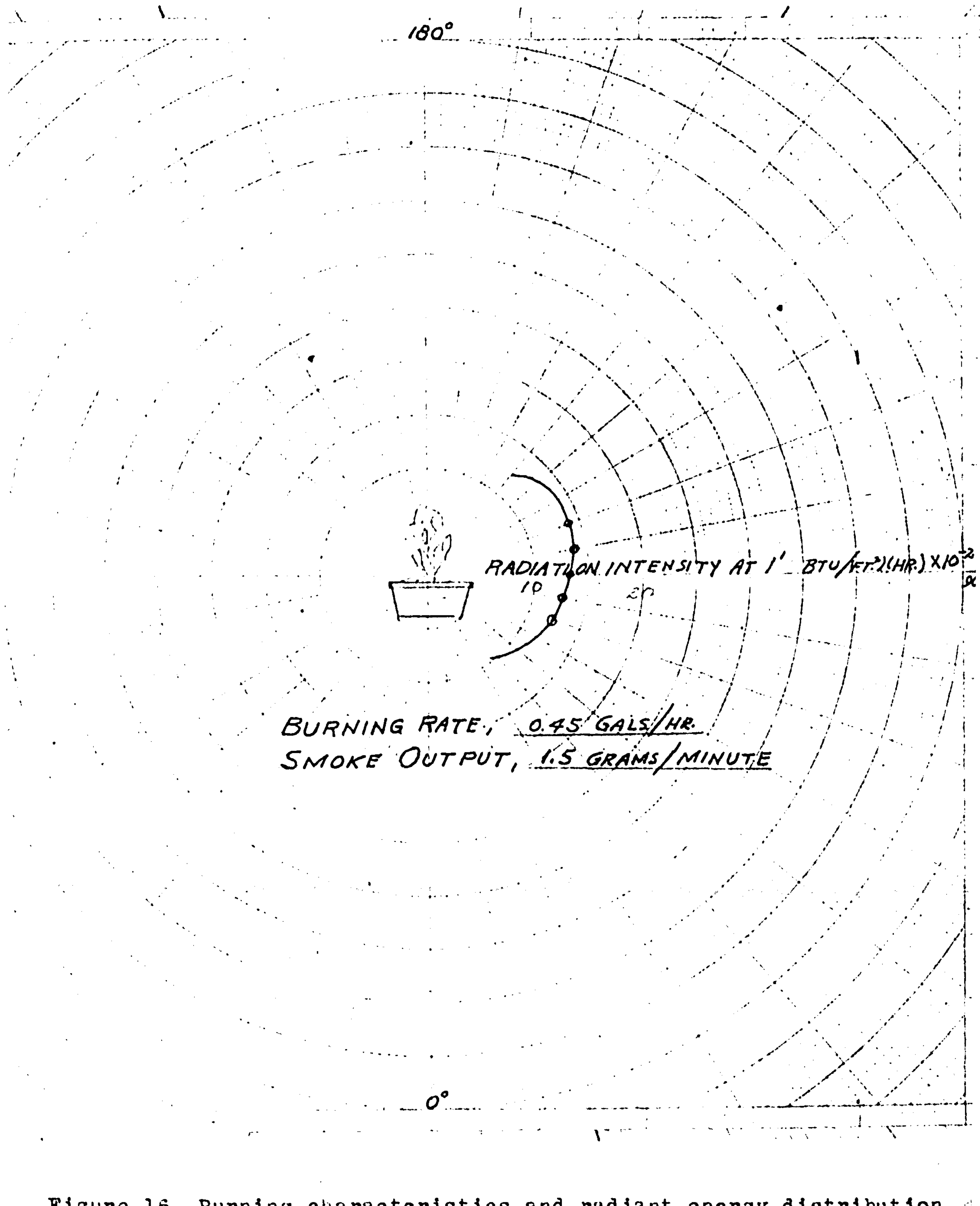


Figure 16. Burning characteristics and radiant energy distribution for the United Stove Company Orchard Heater.

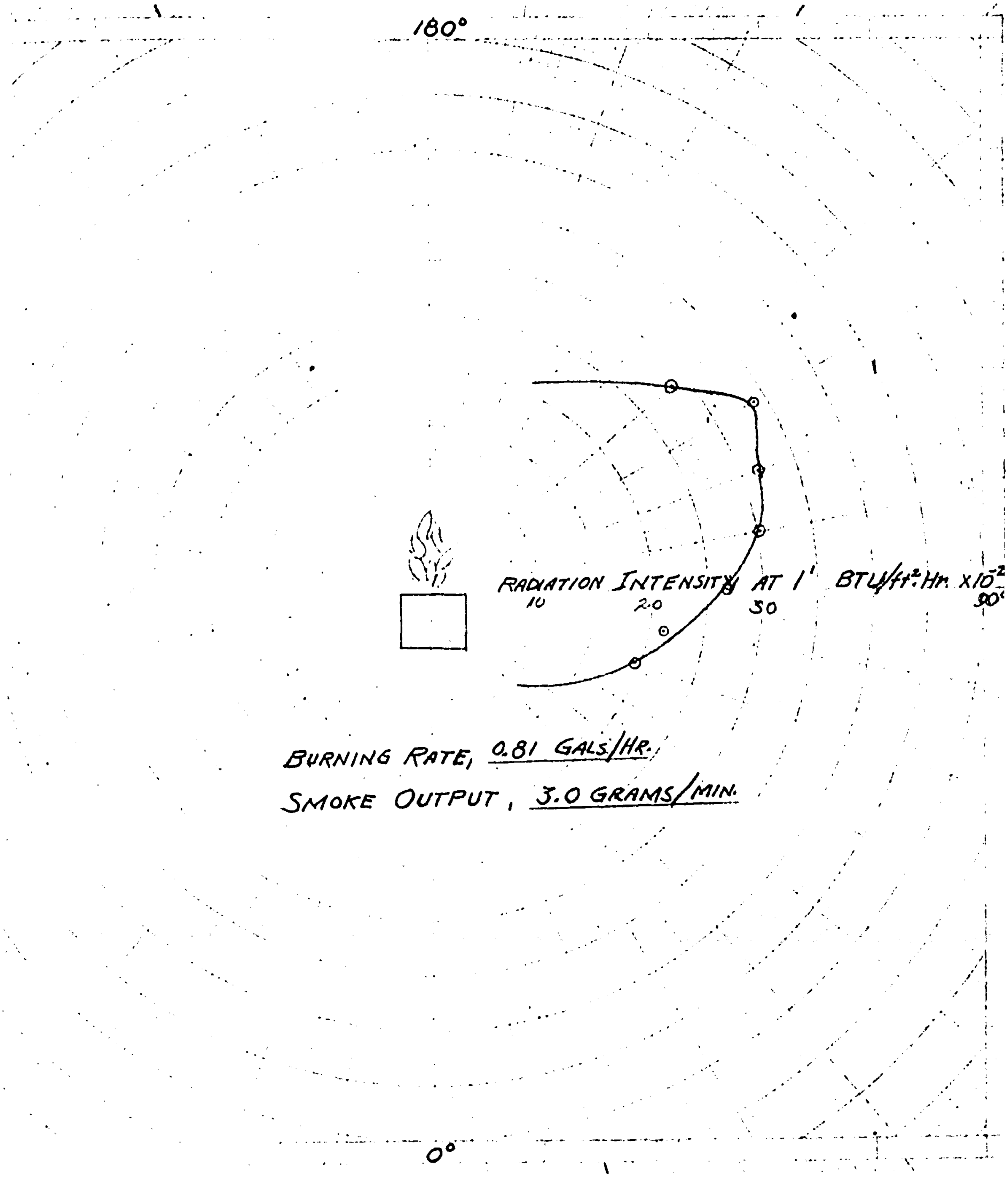


Figure 17. Burning characteristics and radiant energy distribution for an open-topped container.

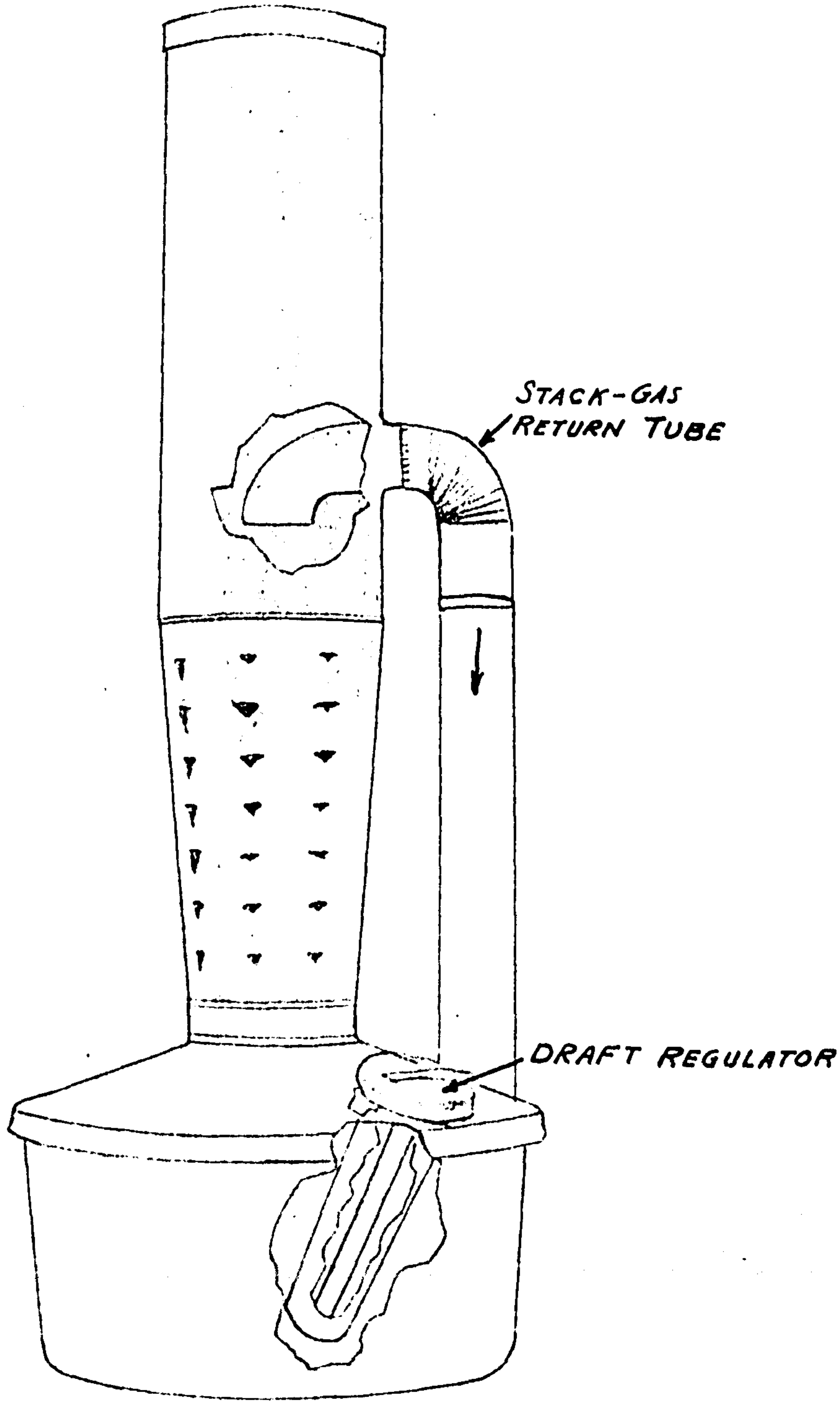


Figure 18. The Return-stack Orchard Heater developed at the University of California.

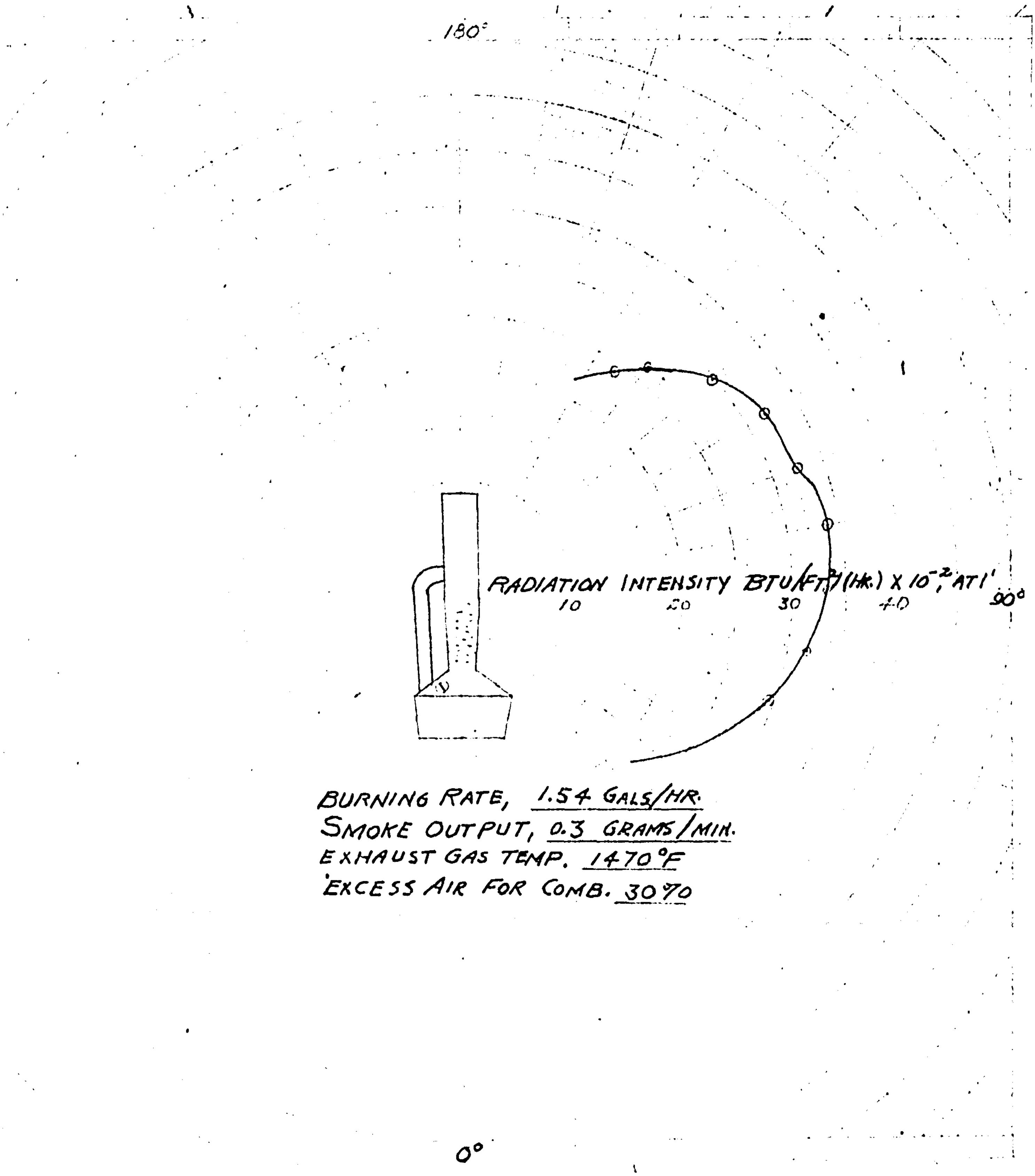


Figure 19. Burning characteristics and radiant energy distribution for the Return-stack Orchard Heater.

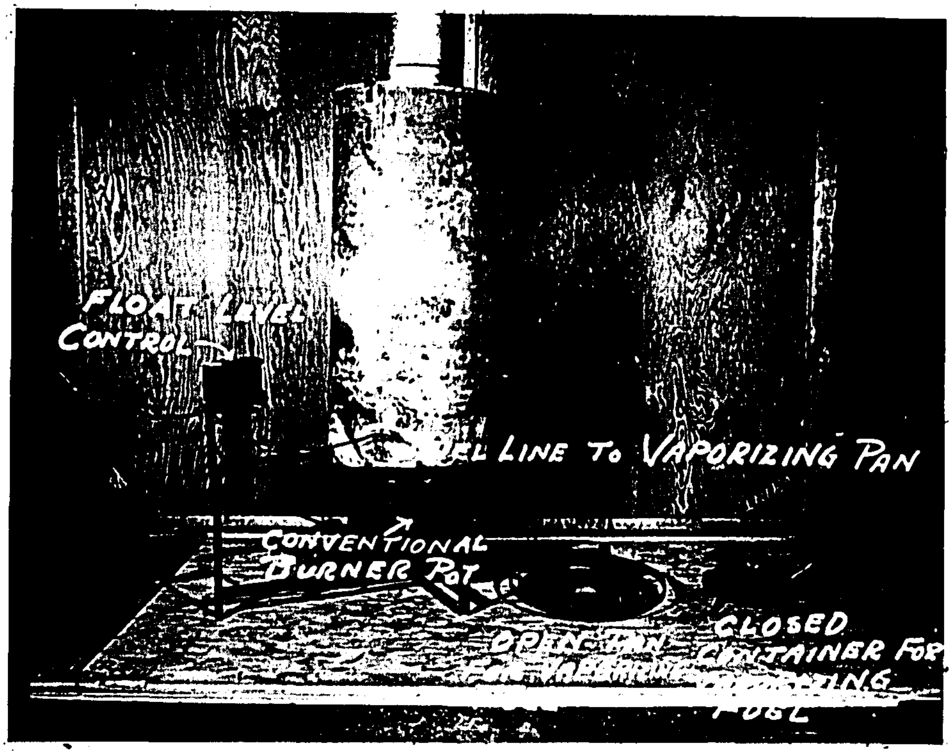


Fig. 20. First Trial Burner.

surface as a source of infrared energy.

Realizing the need for vaporizing the fuel in the presence of sufficient air to allow adequate intermixing or aeration, in a large part before burning has progressed appreciably, the first attempt was a design which would presumably satisfy this condition.

Fig. 20 gives an overall view of the burner and the following discussion should make clear the ideas which were taken under consideration at that time. The bottom pot-shaped section will be recognized as the vaporizing bowl of a standard burner used extensively for domestic heating, either with or without a fan. For the application at hand this part of the unit furnished the heat to vaporize the bulk of the fuel from a special pan located up in the main part of the combustion chamber. Air is introduced through the sides of both the bottom section and the combustion chamber. These openings are illustrated in the accompanying figure. As noted, this unit requires the fuel to be in a separate container elevated at least three feet and fed in through a float valve in order to maintain a constant rate of fuel flow.

The extra part shown in the figure is an enclosed container, except for a small opening at the top, which was tried inside the chamber as the container for vaporizing the bulk of the fuel. This was an attempt to prevent burning on top of the liquid fuel; however, it was proven that the open dish-type container was better for this purpose.

The test results are given in Fig. 21. These data show a comparatively high rate of burning (1.8 gallons/hr.) which supports a high emissive power for the radiating surface.

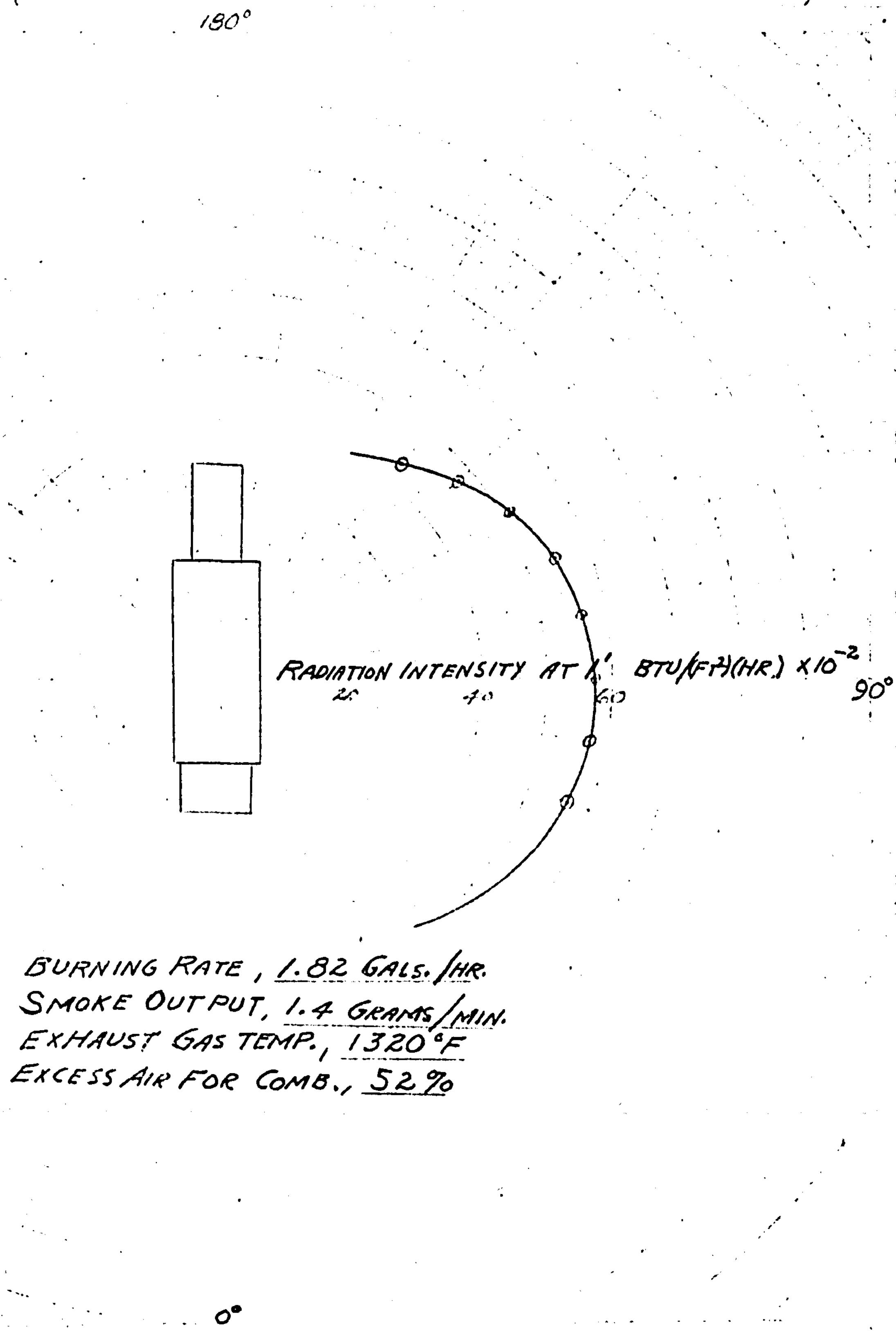


Figure 21. Burning characteristics and radiant energy distribution for the First Trial Burner.

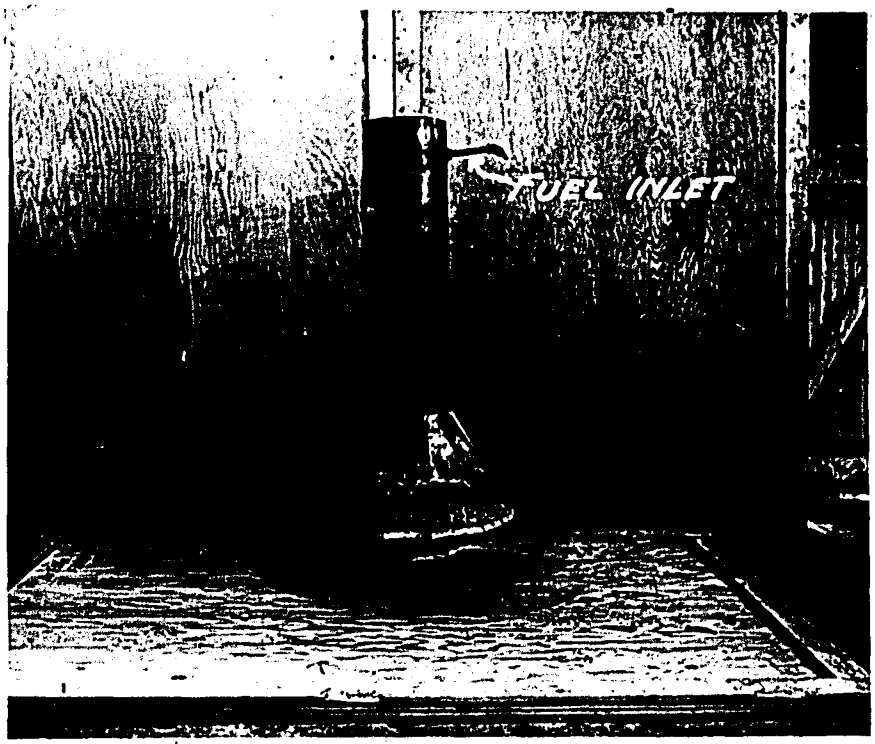


Fig. 22. Second Trial Burner.

The smoke output of 1.4 grams/min. is not necessarily high for the rate of burning, but considerably higher than that for the Return-stack heater. Nevertheless, for most applications the objection to the smoke plus the comparatively high manufacturing cost would prevent its use.

Second trial burner

The second trial burner unit is illustrated in Fig. 22, and the basic principle is to drop the fuel from the top down through the inside of the stack and combustion chamber to strike a target three inches above the base of the unit. There are air holes along the sloping part of the chamber as well as in the bottom and sides of the lowest section; the idea being to have the fuel vaporize as it fell through the intense heat of the enclosure, and at the same time provide sufficiently distributed air to bring about efficient burning. Since temperature increases the rate of a combustion reaction, this arrangement apparently has merit as a means of increasing the rate of burning.

Fig. 23 includes the test data for this unit and again the burning rate (1.5 gallons/hr.) is comparatively high which is reflected in the radiation intensity. However, the smoke output is increased over the first trial burner even though the burning rate is less. It was observed that heavy or large particles of carbon formed along the descending stream of liquid throughout the entire drop. This indicates a high concentration of fuel vapor in the absence of adequate air which evidently accounts for the increase in smoke output.

It is of interest that the radiation intensity of this unit is considerably higher than for the Return-stack heater even though their burning rates are identical. In connection

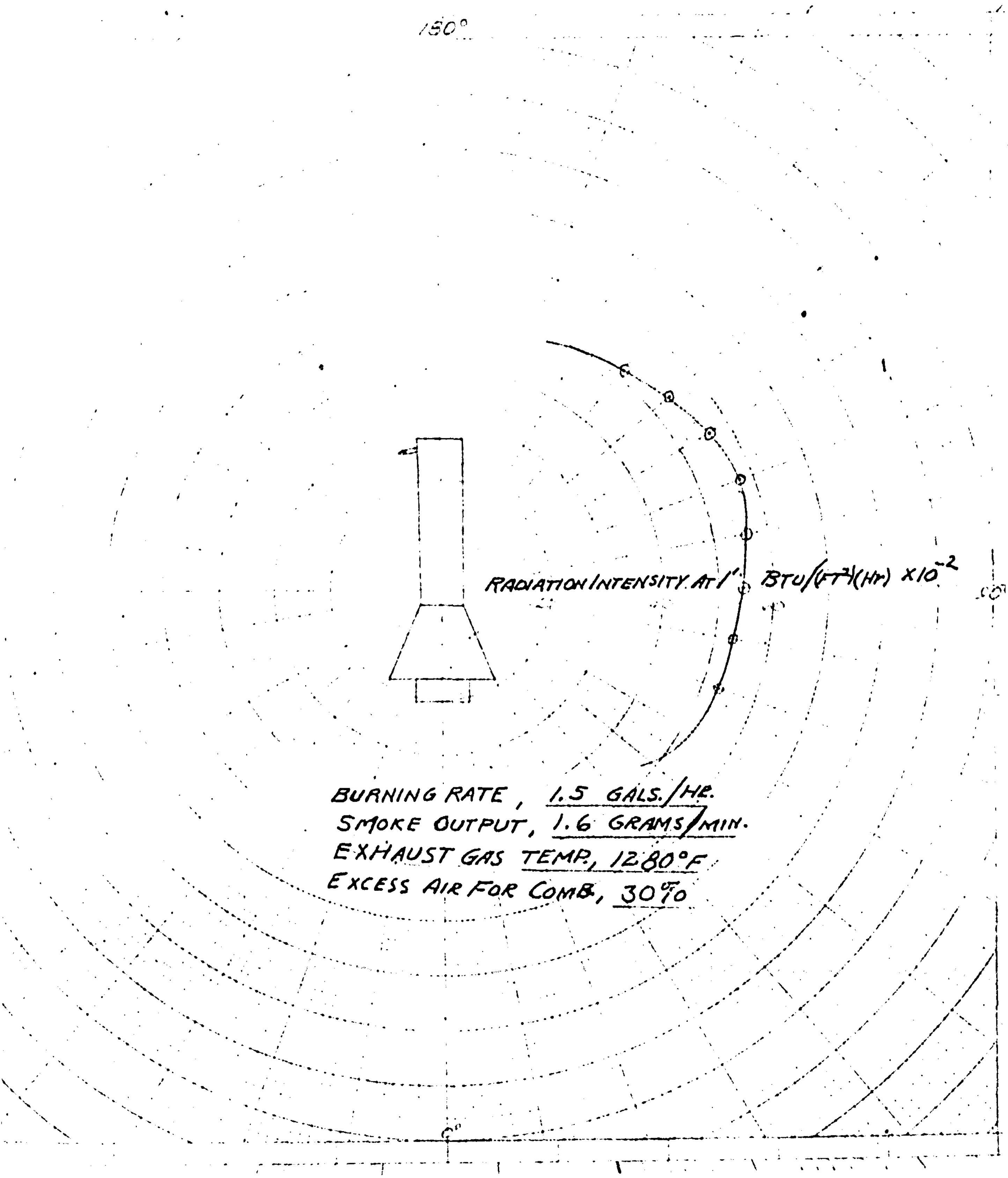


Figure 23. Burning characteristics and radiant energy distribution for the Second Trial Burner.

with this, it was found that the exhaust gas temperature was higher for the Return-stack heater (1470°F. compared to 1280°F.). The evidence indicates that delayed burning was taking place in the case of the Return-stack type, at least more so than trial burner No. 2; this reduces the maximum flame temperature within the combustion chamber since a significant part of the heat is liberated outside the confines of the unit. As a result, less heat is transferred to the surface to be discharged as radiant energy. The Return-stack heater was evidently operated considerably above its rated capacity while burner No. 2 did a fairly complete job of burning within the burner proper.

Third trial burner

As an effort to solve the smoke problem associated with non-powered burner designs, the principle of the old fashioned kerosene cooking stove was borrowed. This will be recognized from Fig. 24 by the concentric rings of perforated sheet steel which make up the channels for effecting burning conditions. Pieces of fire brick were cut to the proper shape and placed at the bottom of these channels to serve as a wick for the kerosene which was maintained at a constant level by the float valve.

This arrangement proved to give complete combustion and

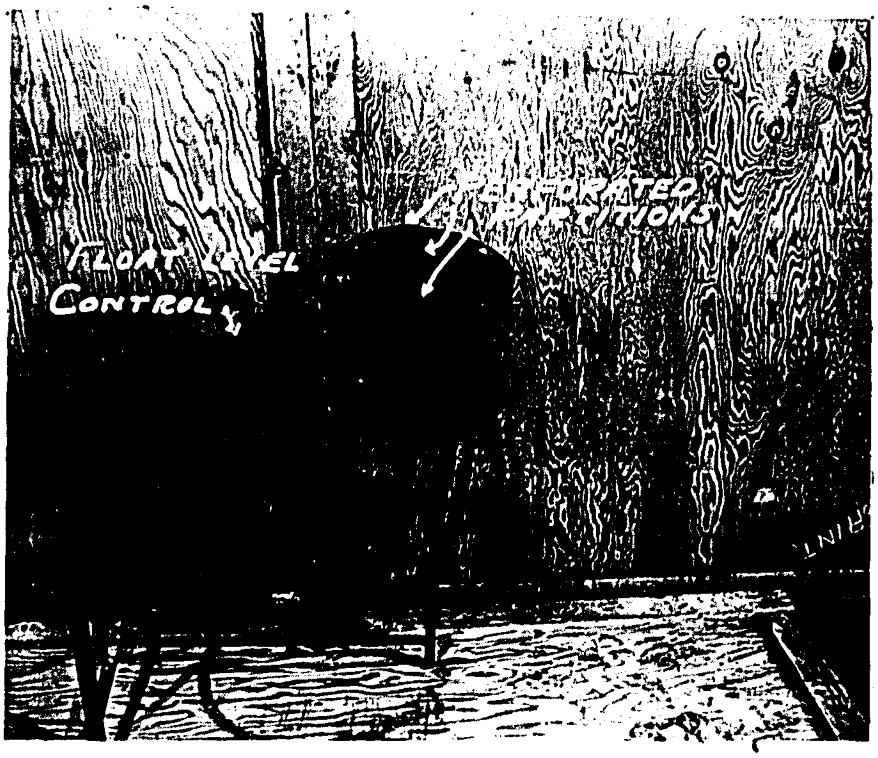


Fig. 24. Third Trial Burner.

the flame was non-luminous or blue in color with very little volume--considering the rate of burning. However, satisfactory operation was sensitive to wind conditions and position with regard to being level. To approach a practical capacity of heat liberation an unusually large amount of channel would be necessary, requiring a high material and labor cost for manufacture; thus, eliminating this approach from present considerations in connection with the frost control problem.

Discussion of results

The two methods of adding heat to vegetation, direct radiation and convection of sensible heat, for its protection from frost damage have been proven effective. Both are employed to a more or less degree depending upon the heat source, weather conditions, and type of vegetation. Each has merit or advantages over the other; e.g. radiant energy shows more effect during windy conditions and on low growing vegetation, while burner designs which release the greater part of the energy through sensible heat are not only cheaper but more practical for still conditions on tree-type vegetation when there is a comparatively high temperature gradient with elevation.

This investigation was aimed to increase the percent of heat liberated through radiant energy from small non-powered liquid fuel burners. The requirements were that this be accomplished without appreciable smoke release (less than 1-gram per minute), and that the initial cost be kept sufficiently low to allow comparatively close spacing during operation (10 to 15 per acre).

The results or findings may be adequately summarized as follows:

1. The "smudge-pot" type heater developed by United

Stove Company gave no evidence of advantages over any ordinary open-topped container. The lid does slow down the rate of burning, but this can be accomplished with a cover of any kind.

2. The first and second trial burners had sufficiently high burning rates to support an increased radiation intensity. However, they gave off comparatively large amounts of smoke and would be somewhat higher in initial cost.

3. The third trial burner had ideal burning characteristics in regard to completeness within a small flame volume; however, to attain sufficient heat release capacity, an elaborate unit both in size and cost would be required. Also, the burning was found to be too sensitive for this application.

4. The Return-stack orchard heater was found to meet the advertised specifications; thus, making this burner very useful for this application in view of the low initial and operating cost. The radiation intensity is lower than that desired, however, this can be offset by spacing them closer together which is possible because of its low cost.

Development of a Liquified Petroleum Gas Burner for the Generation of Radiant Energy for Frost Control

The increasing availability and commercial distribution of liquified petroleum gases (LPG) definitely places this fuel on the list of possible sources of energy. Its inherent high flame temperature, and the ease or simplicity with which clean efficient burning is accomplished, makes it evident that this fuel offers advantages not realized in other fuels. Also, since this fuel has a high vapor pressure at normal temperatures and because of the light molecules of hydrocarbons, it is easily mixed with air to form an ideal combustible mixture. This results in simpler burners, making the use of smaller units placed closer together economically feasible; thus, providing protection against more adverse conditions of frost formation. Also, the smaller units should favor the small operator who will be more able to satisfy his requirements--that for which the larger more expensive units would be impractical.

The turn-down or variation in burning rate of an LPG burner generally has a wide range--from practically off to full capacity--which can be controlled accurately and automatically. This allows for the adjustment of the burning rate to satisfy the prevailing frosting conditions; thus, affecting a saving in the fuel consumption which is either impossible or impractical with the liquid petroleum fuel burners. Another advantage is realized in that the fuel is under considerable pressure of its own accord, making possible the use of central storage tanks with small pipes as distribution lines. This would be an ideal arrangement for larger areas and crops of a permanent nature or for those plots on which the same type of crop is grown year after year.

The disadvantage comes in the cost of the fuel which at present prices is considerably higher than the liquid fuels. This is due in great part to the small total amount distributed and the small lots in which retailed. This fuel is being loaded at the present time in the oil fields at from three to three and one half cents per gallon in tank car lots, which compares favorably with liquid fuels. Therefore, it is assumed that creating a demand in any particular area is the requirement for reducing the cost; and, if an individual consumer's demand warrants, he would affect a considerable saving by buying in tank car lots.

The above comments point up the advantages which LPG offers as a possible fuel with which to generate infrared energy for frost control; and for certain applications these advantages will definitely outweigh the disadvantage--cost.

For this reason work was started on the development of a practical propane burning unit which would serve as a source of infrared energy for frost control.

Objective

Because of the present cost of propane as distributed in 100# containers (approximately 30¢/gallon), it was advisable to work first on designs which would adequately serve the growers of flowers, strawberries, and other higher valued truck crops. Then, as its use expanded or as the farmer became convinced of its value, the application might well spread to other types of crops as the fuel cost was reduced.

Since central storage tanks with permanently installed feed lines are expensive, it was certain that the initial or experimental heaters would have to operate individually as a unit. This indicated that each burner would have to be supplied from a tank at its position. In discussing this problem with the Manager of Shell Oil's LPG bottling plant at Lansing, Michigan, it was learned that the retailers would make the installations for approximately $6/unit. This includes a pressure regulating valve, two 100# containers, and the necessary connections. The maintenance of this setup would be a responsibility of the retailer, who would deliver the propane at 30¢ a gallon thereafter.

Following this encouraging information the object was to design a heater-unit of minimum cost which protected sufficient area to make the setup as economical as possible. With these considerations in mind, plus a knowledge of the energy required to protect against the most likely frost, the following specifications were drawn up which, if met, would make this application practical on the higher valued crops--even under the present retail cost of propane:

1. A heater unit that could be practically supported eight feet above the ground which would produce a radiation intensity of 9 BTU/sq.ft./Hr. at 25 feet from the base of the unit (measured perpendicular to the direction of propagation).

2. Burn less than 1.5 gallons of propane per hour at a pressure less than 26 psig.

3. Cost no more than $5 per heater unit.

4. Easily lighted and dependable in operation.

Procedure

Due to the relatively few hours of operation required per year in Michigan and surrounding areas, the investment cost for any heater unit is the primary consideration. Therefore, the design must be cheap in material cost as well as in simplicity of fabrication or construction. For this reason the most efficient design, in respect to optimum distribution of maximum radiant energy per unit heating value of fuel burned, would not necessarily be the most practical.

The above reasoning led to the conclusion that reflectors would be omitted and that a right circular cone of the proper included angle (determined from the geometry of the relationship between the position of the unit above the ground and the distance from its base) would give the best practical distribution. To determine the size of this cone it was assumed that, since the flame temperature of propane is 3497°F. (16), a surface temperature of 1600°F. could be maintained. This was considered the maximum temperature for which carbon steel would have a useful life. It can be shown that the normal intensity from a unit area of a blackbody is given as a function of the temperature of the body by the following relationship (2):

$$I = \frac{\sigma T^4 \epsilon}{\pi} \text{ - BTU/ft}^2\text{/Hr.}$$

σ = 17.3 x 10^{-10} BTU/Ft.² T^4 (Stefan-Boltzmann's constant)

ϵ = total emissivity (.8 for oxidized steel surface)

T = absolute temperature of body,

From this, assuming .8 as the total emissivity of a steel surface and for $I_n = (25)^2 \times 9$ (intensity required at one foot from the source to give an intensity of 9 BTU/Ft.^{2}/Hr. at 25 feet), the required cross-sectional or projected area for the cone is given as,

$$A_c = \frac{I_n}{\frac{\sigma T^4 \epsilon}{\pi}} = \frac{\overline{25}^2 \times 9 \times \pi}{17.3 \times 10^{-10} \times \overline{2060}^4 \times .8} = .7 \text{ FT.}^2$$

With these data as a basis a 60° right circular cone with a slant height of one foot was formed from 18 gauge hot-rolled carbon steel. Sixty-three 1/4" holes were spaced in the surface of this cone to serve as exhaust ports and openings for direct radiation from the flame and the ceramic plate which covers the top of the cone. This design gives a projected area of approximately .43 square feet which is .27 square feet less than the theoretical requirement. However, since there was no way of evaluating the added effect of the holes in the surface, it was advisable to construct this simple unit until further experimental evidence would justify larger designs. The normal to the surface of this cone will intersect the ground at 14 feet from its base when the cone is positioned 8 feet high.

A 32° right circular cone was formed from the same type and weight material and with the same surface area (slightly less projected area) as the 60° cone. However, 141--7/32" holes were spaced in the surface of this cone which represents 1.7 times more port area than that for the 60° cone.

Each of these cones were attached to inspirators (#70-2-55) made by North American Burner Manufacturing Company. The gas spud or jet was drilled with a #56 drill. All the air for combustion enters through the inspirator. As an economy measure a perforated disk was placed over the discharge end of the inspirator in the place of a more expensive burner tip.

Fig. 25 illustrates these units and the method for connecting the fuel line from the pressure regulator to the 3/8" standard galvanized pipe which serves both as a support and conduit for the gas supply.

Discussion of results

The two units were tried and found to operate satisfactorily. Since they were not tested under frost conditions, the next best evaluation was ~~a heat~~ balance analysis in conjunction with a measure of the radiant energy distribution which is recorded in Fig. 26 and Fig. 27. Based on previous findings this analysis can be interpreted in terms of the

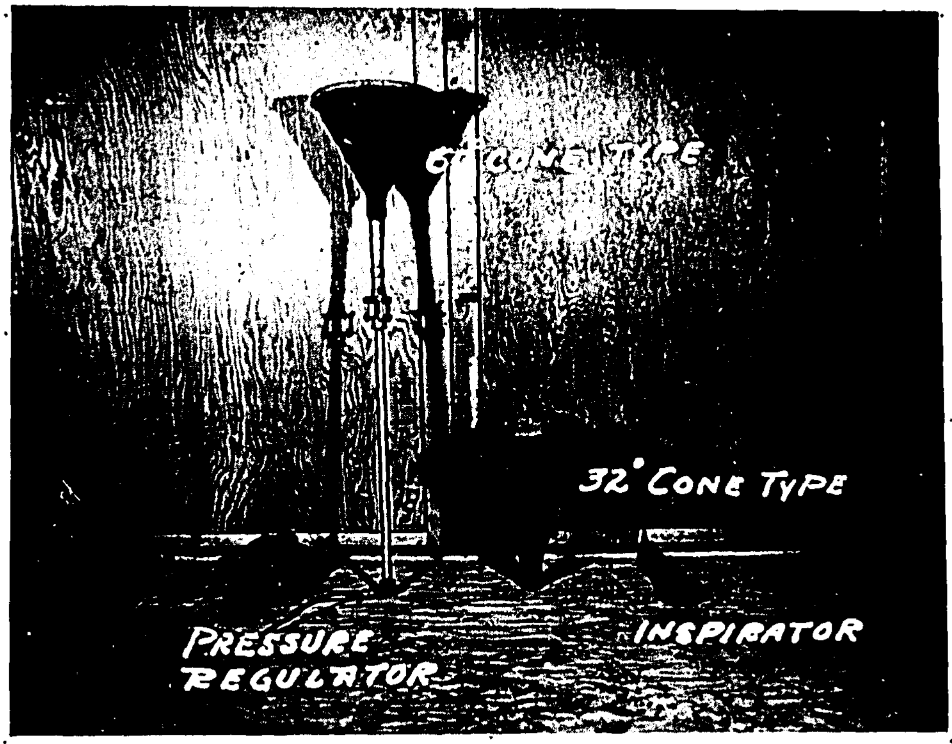


Fig. 25. Experimental Propane Burner Units.

possible protection that may be expected under actual frosting conditions.

The air temperature at the time of this test was 60°F., clear and no wind. The heater units were tested in succession with identical conditions prevailing.

The total emissive power and the radiation that falls below the horizontal were calculated by Wohlaure's method (23). These results are recorded on the data sheets. It is

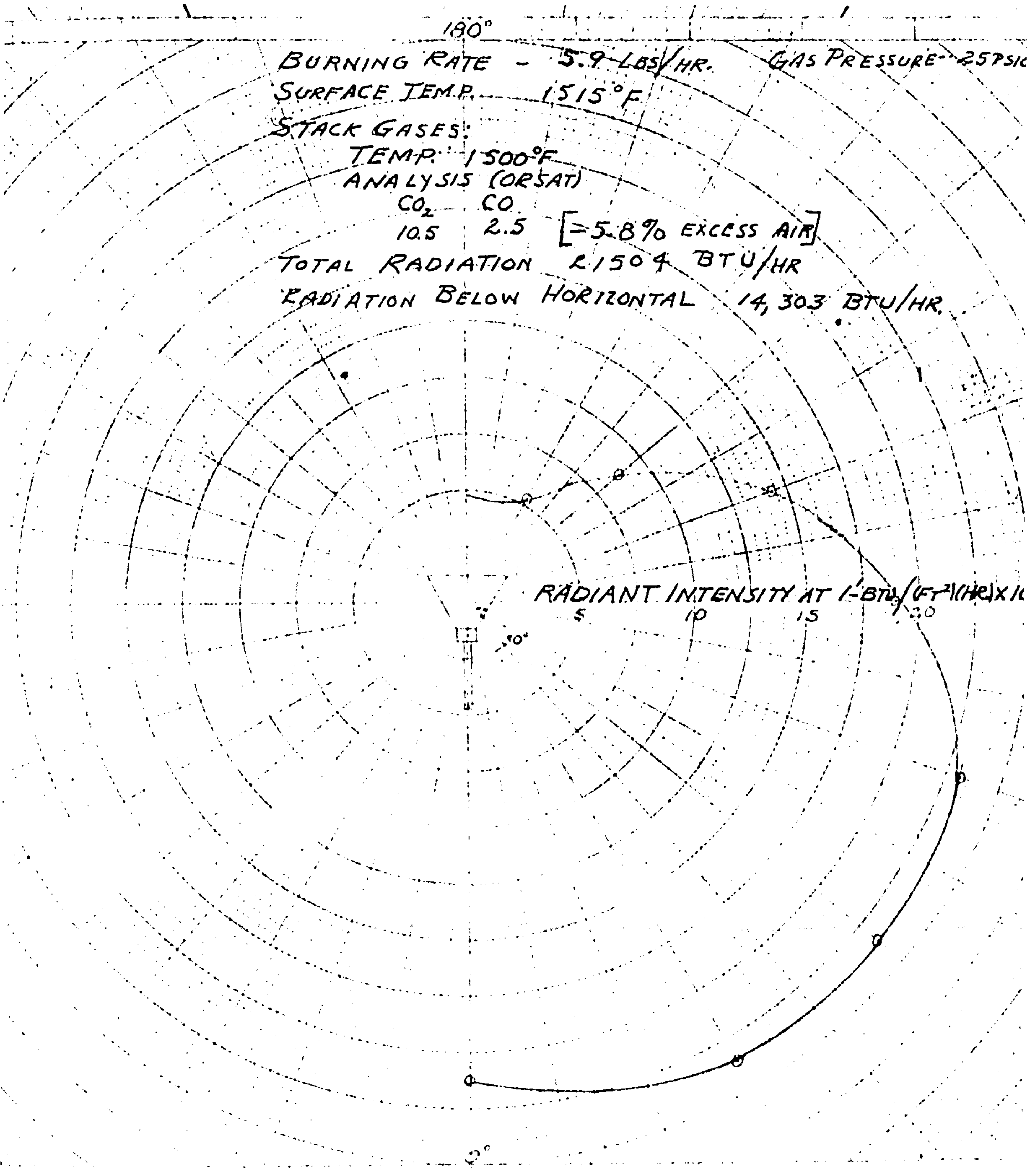


Figure 26. Burning characteristics and radiant energy distribution for the 60° type propane burner.

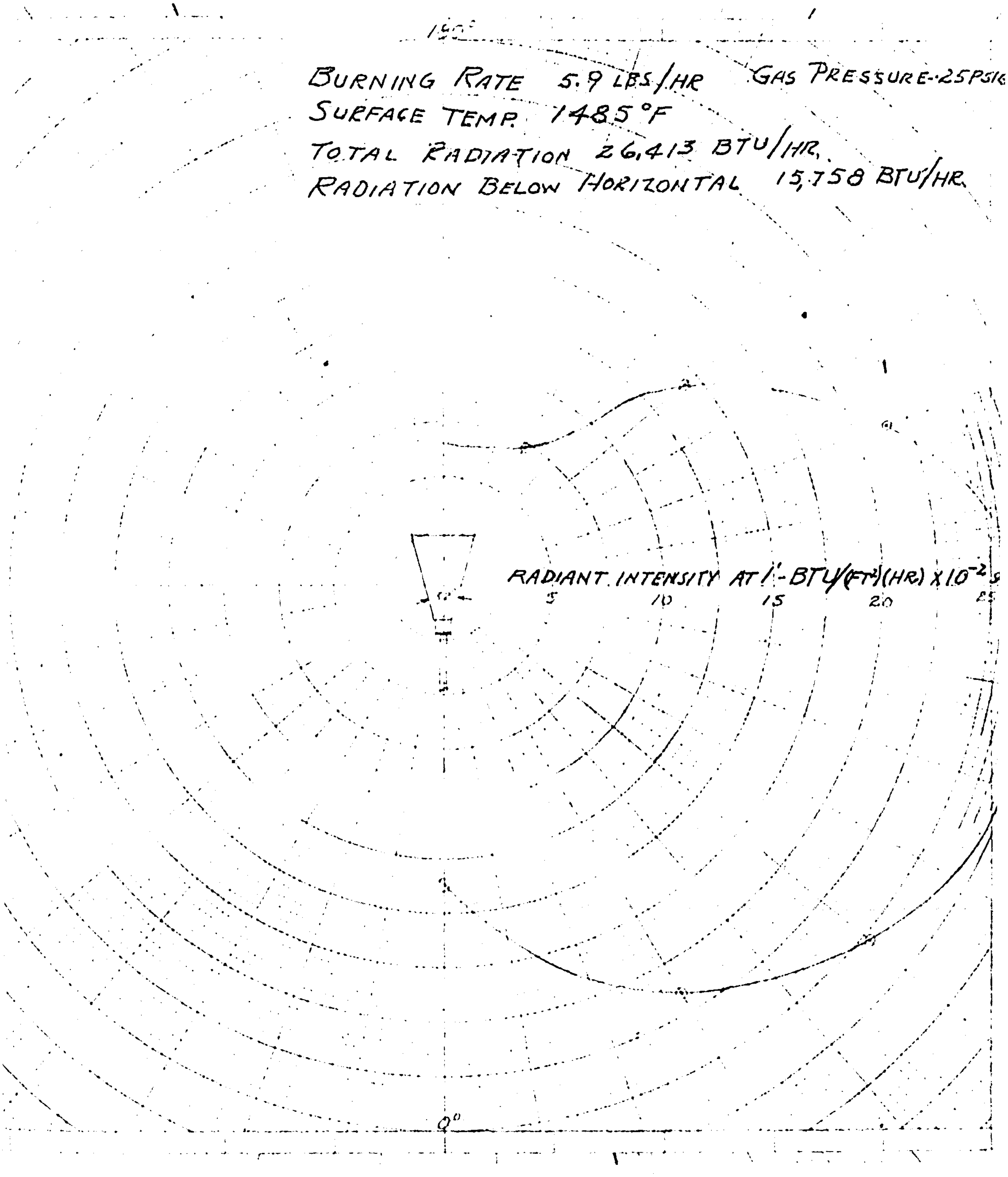


Figure 27. Burning characteristics and radiant energy distribution for the 32° type propane burner.

of interest to note that the 32° cone indicates a total radiation 1.23 times greater than that for the 60° cone, even though the surface temperatures were almost equal as measured with an optical pyrometer.

The orsat analysis indicated incomplete combustion in registering 2.5% CO. This represents a -5.8% excess air over that required for perfect combustion.

The gross or high heating value for propane is given as 21,690 BTU/lb. of vapor (22). At the burning rate of 5.9 lbs./hr. the potential heat release is 128,000 BTU/hr. However, because of the loss resulting from incomplete combustion, which was calculated as 14% of the total possible energy, the actual heat released amounted to 110,000 BTU/hr. From this data it is found that, from the radiation meter readings, the 60° cone radiated 19.5% of the heat actually liberated, while the 32° cone radiated 24%.

This appears to be somewhat less than the amount of energy that should have been radiated, particularly for a surface temperature of 1500°F. There was reason to doubt the accuracy of the radiation meter at the time these measurements were taken due to the fact that some of the thermocouples had been re-arranged since the last calibration. Also, since the thermopile is covered with lithium fluorite, the calibration constant is only an average value which could be much different than the actual calibration for the intensity and temperature under consideration.

Further evidence that the recorded radiation intensities were too low comes from a consideration of the overall heat balance. From the latest values for the specific heats of the exhaust gases (14) the sensible heat discharged by way of the exhaust gases (temperature of 1500°F.) was approximately 54,000 BTU/hr. The rate of convection from the surface of the cone was calculated to be approximately 20,000 BTU/hr. (3). This would leave approximately 36,000 BTU/hr. to be discharged through radiation, which amounts to 33% of the total energy.

Also, from the intensity relationship given on page 87 a surface temperature of 1515°F. and .8 emissivity, the intensity is calculated to be 2900 BTU/Ft^2./Hr. This does not account for the additional effect due to the holes in the surface. The color temperature of these holes was 1750°F. (as measured with the optical pyrometer). Another factor which favors the reasoning that the meter calibration was in error results from the general case that the temperature as measured with an optical pyrometer is somewhat less than the real surface temperature (at least $10^{o}F.$).

In view of the above considerations it seems logical that the intensities as recorded should be increased by 1.3 times their given values.

To use these energy distribution plots for finding the intensity at any point on the ground it is only necessary to assume the heater unit to be located at some selected height (8-feet) and by trigonometry find the angle that the direction to the point in question makes with the 0 or nadir (downward vertical). Read the intensity at 1-foot in this direction from the graph, calculate the distance to the point by trigonometry and divide the intensity by the square of this distance; thus, giving the intensity at that point. As an example the following problem is assumed:

Find the intensity at 20 feet from either unit when they are 8-feet high?

Angle from nadir, $\theta = \tan^{-1} 20/8 = 68.2^{o}$

From energy distribution curves,

For 60^{o} cone -- I_1 (intensity at 1-foot) = 2320 BTU/Ft^2./Hr.

For 32^{o} cone -- I_1 = 2720 BTU/Ft^2./Hr.

L (distance to point on ground) = $[8^2 + 20^2]^{1/2}$

Intensity at 20 feet from 60° cone = $2320/L^2$ = 2320/464 = 5 $BTU/Ft^2./Hr.$ or, by applying the suggested correction, intensity = 5 x 1.3 = 6.5 $BTU/Ft^2./Hr.$

Intensity at 20 feet from 32° cone = 2720/464 = 5.8 $BTU/Ft^2./Hr.$ or = 5.8 x 1.3 = 7.54 $BTU/Ft^2./Hr.$

These calculations show the apparent advantage of the 32° cone over the 60° cone in giving a more favorable distribution of the radiant energy.

Making allowance for the probable errors in the radiation intensity, the evidence favors an experimental application of the 32° cone-type with as many holes as possible through its surface. Also, a ceramic material should be attached to the bottom side of the ceramic top, allowing this addition to project down into the volume of the cone. This would increase the radiation through the holes in the surface.

With the above improvements this type of heater unit should prove to provide sufficient protection when spaced fifty feet apart at an elevation of eight feet. It will require an operation under natural frosting conditions to determine the real value of this unit and the late blooming flowers should provide an ideal proving grounds.

Summary

The principal cause of damage to agricultural crops by freezing results from radiation-type frost. It was found that to use radiant energy alone requires a radiation intensity of 10 BTU/sq.ft./hr. to protect low growing vegetation against the frosting conditions most likely to occur during the growing season. However, for the few cold wind-borne freezes which have occurred, the radiation intensity has to be increased to approximately 65 BTU/sq.ft./hr.

The use of convected or sensible heat has proved to afford protection against radiation-type freezes. This method is practical particularly for vegetation two feet or more above the ground, and when the temperature gradient is sufficiently high (temperature inversion). In contrast, under conditions of appreciable wind little can be done toward heating the surrounding air to provide protection for vegetation against freezing. However, in the majority of cases damaging freezes do not accompany appreciable wind.

The Frostguard, which was designed to provide protection exclusively through radiant energy, was found to be expensive in terms of the amount of protection afforded. Also, the burner was somewhat erratic in its operation. This study

on the Frostguard was made with two objectives in mind: (1) to reduce the flame volume so that the size of the units could be made smaller in order that practical reflectors would facilitate better distribution of the generated radiant energy, and (2) to increase the dependability or stabilize the burning.

Following an analysis of the physical and chemical properties of kerosene, experimental attempts were made to improve the Frostguard along the above two lines. To reduce the flame volume required a better mixing of the air and fuel-vapor before burning started. However, since the ignition temperature of kerosene is below its saturated vapor temperature at 80 psig, burning would start as soon as sufficient air was entrained to give a combustible mixture. Therefore, since the burner is of the pressure heat-vaporizing type, little could be done that would induce a better aeration of the fuel vapor in order to reduce the flame volume.

The reason that the Frostguard failed to operate satisfactorily in wind in excess of 5 MPH resulted from a lack of sufficient air for combustion, which reduced its vaporizing capacity. This problem was solved to a satisfactory degree by placing a wind deflector and scoop at the top and bottom, respectively, of the unit, and by the addition of a ceramic material around the vaporizing coil. The wind deflector and scoop took care of the steady wind while the ceramic held sufficient heat to carry the vaporization through the gusty wind conditions. Also, the ceramic produced a sufficiently high temperature surrounding at the initial point of combustion to reduce the flame volume somewhat. As a result the surface temperature was increased by approximately 100°F. with the same flame volume.

Following the conclusion that better radiant energy distribution could be more practically carried out by the use of smaller units spaced closer together, work was carried on to develop a small non-powered liquid petroleum fuel burner. The objective was to accomplish a high rate of burning in order that a considerable part of the total heat liberated would be discharged as radiant energy; this had to be carried out with a minimum of smoke.

Several different principles were tried with varying degrees of success. However, in view of the cost, operation, and smoke output, it was found that the principle employed by the Return-stack Orchard Heater (as developed by the University of California) was the best.

The increasing distribution of liquified petroleum gases places this fuel as a possible source of heat energy for frost damage control. The simplicity with which this fuel can be burned efficiently to give radiant energy as well as sensible heat gives rise to definite advantages. Presently, the cost is apparently a disadvantage; however, the low first cost of burner units, low maintenance cost, cheapness with which the rate of burning for such a burner can be modulated and automatically controlled, and the possibility of combining such a setup into a permanent installation; may well outweigh the comparatively high fuel cost. One of the objectives of this study was to develop a LPG burner-unit which would be practical for the growers of flowers and higher valued truck crops. Such a unit was designed and tested to evaluate its operating characteristics. The results of this test indicated that the unit was ready to be tried under natural frosting conditions. The type of vegetation and freezing conditions will, of course, determine the extent of protection afforded; however, it is suggested that these units be spaced fifty feet apart and eight feet high. The above spacing is suggested for fairly well exposed vegetation, such as tomatoes, strawberries, etc., and for the frosting conditions most likely to occur during the normal growing season. The cost is estimated at $10 per unit or $160 per acre. This cost includes, (1) rent on tanks (two per unit), (2) regulators, and (3) burner-units.

Conclusions

Both radiant energy and convected or sensible heat are used in varying amounts for the protection of vegetation from frost damage. Radiant energy is more effective on low growing vegetation, and if applied with sufficient intensity will protect under freezing conditions which are accompanied by appreciable wind. Convected heat is more practical for vegetation above two feet when there is little or no wind and on comparatively level ground surface. Any burner discharges both types of heat energy; however, the particular design determines the relative amounts. Both methods are more effective when released at several places over a certain area than from only a few places--favoring small heater-units.

Large radiation equipment is inefficient in its distribution of radiant energy and sensible heat, and is necessarily expensive--a factor which restricts its application to the higher valued crops. The pressure heat-vaporizing type of burner used in the present unit is inherently erratic in its operation and requires considerable maintenance for satisfactory operation.

The principle employed by the Return-stack Orchard Heater serves very well to bring about the efficient clean burning of a comparatively high fuel rate. It is evident that this heater was designed primarily to heat orchard type crops; however, by re-designing so that more of the radiation would be directed downward, this principle could be used for the protection of low growing vegetation. Because of the low initial cost, lack of need for maintenance, and low operating cost, a heater constructed on this principle could be positioned close enough together to afford protection against the most probable freezes.

The liquified petroleum gas burner-unit offers practical frost damage control on crops such as flowers or other higher valued crops, and particularly those crops which may become contaminated by other burners. Also, this type of burner could be incorporated into an automatically controlled setup, which could be modulated to a rate of burning that would protect against the prevailing freezing condition; thus, effecting a saving in the fuel consumption.

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