has also been shown by Nunn to be true in the rainfall of Nashville, Tenn.[6] Though on a slightly different basis, these Syracuse results agree closely with Kincer's calculation. The amount of rainfall over this period for the 12 hours ending at 8 a. m. is 45 per cent of the total, but for the 12 hours, midnight to noon, only 42 per cent of the total amount. Considering individual hours it is found that the hour ending at 10 a. m. receives the least amount and the hour ending at 8 p. m. the greatest, 2.2 times as much as the former. The three hours ending at 8 p. m. receive twice as much as the three hours ending at 11 a. m.

These results are what are naturally to be expected as effects of the forenoon warming and afternoon cooling combined with the occurrence of thunderstorms. In general, the month with the greater number and the more energetic thunderstorms has the greater afternoon rainfall. The hump shown in the June record is due in part to a violent storm on the 17th in 1922, when 2½ inches of rain fell between 4 and 5 p. m.

In marked contrast with the preceding summer is that of 1923, with a few thunderstorms and those of little energy, frequently with faint thunder and light rainfall. The total rainfall during six separate thunderstorms in August was 0.30 inch, and the greater portion of the rainfall during the summer months came during the forenoon hours, this being 58 per cent of the total amount.

These results have led the writer to two definite conclusions: In the first place, that the summers of 1922 and 1923 show opposite extremes in convectional and electrical conditions as well as in rainfall amount and hourly distribution; and secondly, that a period much longer than 20 years should be covered in order to make possible any satisfactory discussion of rainfall.

[6] Roscoe Nunn, MO. WEATHER REV., April, 1922, 50: 180-184.

EFFICIENCY OF SMOKE SCREENS AS A PROTECTION FROM FROST.

By H. H. KIMBALL, Meteorologist, Weather Bureau, and B. G. MACINTIRE, U. S. Chemical Warfare Service.

[Washington, August 23, 1923.]

SYNOPSIS

At Edgewood Arsenal, Md., a field was covered with dense smoke, by burning white phosphorus, on nights when conditions favored frost. The temperatures were carefully measured under and in the smoke, and also in a similar nearby field that was free from smoke. Also, the rate at which heat was radiated from a blackened surface exposed horizontally was measured both under and outside the smoke cloud.

The results show that while the smoke cloud decreased the rate of cooling of the blackened surface about-one half, it had little effect upon the air temperature, probably because of an interchange between the air under the smoke and that outside. The slight increase in temperature noted under and in the smoke apparently was due principally to heat imparted to the air by the hot particles constituting the smoke.

The experiments confirm previous conclusions that the most efficient and economical method of frost protection is to heat the lower layers of the air by burning some form of cheap fuel.

The cost of maintaining a dense smoke cover over a field by burning white phosphorus, or by any other known chemical means, is greater than the cost of heating the air in the field by burning crude oil.

INTRODUCTION.

Since the close of the World War numerous inquiries have been addressed to both the Weather Bureau and the Chemical Warfare Service relative to the practicability of utilizing a smoke cloud, such as is used to hide the movement of troops, in protecting orchards and tender vegetation generally from frost. There seems to be a conviction in the minds of many who have had to do with smoke screens that a chemically produced smoke cloud would furnish a cheaper, cleaner, and, perhaps, more effective, frost protection than is obtained from the combustion of crude oil or other fuels.

The Weather Bureau has already made a study of the part played by smoke from burning crude oil in protecting vegetation from damage by frost.[1] The conclusion reached was that "The retardation of nocturnal radiation by the smoke cloud plays an insignificant part in frost protection."

DETAILS OF THE PROJECT.

In the above study by the Weather Bureau it was difficult to completely separate the effect of the smoke cloud in retarding nocturnal cooling from the heating effects of the combustion of the oil. Therefore, the Weather Bureau very gladly availed itself of the privilege extended to it by the Chemical Warfare Service of utilizing the facilities of the Edgewood Arsenal, Edgewood, Md., in conducting jointly with that Service experiments on the efficiency of smoke in retarding nocturnal cooling.

This cooperative project called for the maintenance by the Chemical Warfare Service of a dense smoke cloud for a period of about four hours over an area of approximately five acres on a night with little or no wind and a clear sky. The cloud was to be produced by such material as would most economically give the desired results, and in such a manner that the heating of the air by the combustion of material would be a minimum.

On its part the Weather Bureau was to determine the extent to which nocturnal cooling was retarded by the smoke cloud on nights when the meteorological conditions were favorable for frost formation.

EXPERIMENTAL FIELD SELECTED.

The field used in carrying out the tests was selected from the standpoint of convenience in handling the equipment and raw material required and is designated "M" field. The "M" field is located on the Gunpowder River, surrounded by woods on three slides. Two areas, of a few acres each, separated by a few trees and located about one quarter mile from the water front on "M" field, were selected for the installation of the instrument shelters to be referred to later.

SOURCE OF SMOKE.

White phosphorus was used as the smoke-producing material in all tests, as white phosphorus was readily available in sufficient quantities and as it had the property of producing more smoke per unit weight than other materials.

When phosphorus is burned in the presence of air or oxygen, phosphorus pentoxide, a solid substance, is produced, which in turn readily unites with atmospheric moisture, producing meta phosphoric acid, a liquid. A phosphorus smoke cloud consists of a mixture of the two substances, (phosphorus pentoxide and meta phosphoric acid) the ratio of the two being dependent on the humidity of the atmosphere and the rapidity with which the phosphorus is burned.

[1] Kimball, Herbert H., and Young, Floyd D.: Smudging as a protection from frost. MO. WEATHER REV., August, 1920, 48: 461-462.

METHOD OF PRODUCING SMOKE.

A phosphorus smoke screen is produced by igniting pieces of phosphorus on the ground at definite distances. The burning phosphorus produces a white cloud having little tendency to settle due to the fineness of the smoke particles, the direction of travel being governed by the prevailing wind and air currents. In producing a smoke screen, the distance between the pieces and the quantity used at each point is dependent on the density of cloud desired and the prevailing wind velocity.

METEOROLOGICAL EQUIPMENT.

Wind.—Above the roof of the headquarters building on the "M" field there is exposed a Robinson cup anemometer which records the velocity of the wind on a register in the office below. The record sheets from this register were utilized to obtain the velocity of the wind during the experiments. The wind direction was obtained from the direction of drift of the smoke cloud.

Temperature.—The Weather Bureau installed four cotton region instrument shelters [2] on "M" field, each shelter containing a thermograph, a maximum thermometer, and a minimum thermometer. Shelters No. 1 and No. 2 were placed in a natural basin between an orchard and woodland to the northwest of headquarters. Shelters No. 3 and No. 4 were installed in the center of a level meadow southwest of headquarters. The shelters in each field were about 75 yards apart. No. 1 was north of No. 2 and No. 3 was west of No. 4. The distance between the two fields was about 500 yards.

The instruments and shelters were installed on March 26 and removed on May 2, 1923.

The object of the above installation was, first, to ascertain if temperature conditions were alike in the two fields, and, second, to check the accuracy of the records obtained from the four thermographs, although all the instruments had been carefully standardized by the Instrument Division of the Weather Bureau.

To obtain these desired results the thermometers were read and set by an employee of the Chemical Warfare Service each morning except on Sundays, and at the same time the current temperature was read from the thermograph traces and the minimum thermometers. In Table 1 are given the means of the comparative readings.

TABLE 1.—*Temperature data from thermometers and thermographs, "M" field, Edgewood, Md., March 27 to May 2, inclusive, 1923.*

Shelter.	Maximum.		Mean difference.	Minimum.		Mean difference.	Current.
	Thermometer.	Thermograph.		Thermometer.	Thermograph.		Thermometer minus thermograph.
	°F.	°F.	°F.	°F.	°F.	°F.	°F.
No. 1	60.3	59.2	+1.1	36.6	37.0	−0.4	+0.5
No. 2	60.5	59.4	+1.1	37.0	37.0	±0.0	+0.5
No. 3	60.5	59.9	+0.6	37.0	37.4	−0.4	+0.2
No. 4	60.6	60.0	+0.6	37.0	37.0	±0.0	+0.5

The readings of the thermometers in the different shelters agree well among themselves, not only in the mean values, as shown in Table 1, but also in the daily readings. The thermograph records show the usual lag, due partly to friction between the register pen and the record sheet and partly to sluggishness of the thermograph bulb as compared with thermometer bulbs in reaching the temperature of the surrounding air.

In the present investigation we are especially interested to know if the thermograph traces obtained in the different shelters are identical from day to day. Superposition of one record over another on a sheet of glass with a bright light behind it shows that they are nearly so.

Radiation.—In connection with these experiments two pyrgeometers [3] were installed in such positions that one of them could be kept under the smoke cloud while the other was free from it. From their readings the extent to which nocturnal radiation is diminished by the smoke cloud may be determined.

METEOROLOGICAL DATA OBTAINED.

Since suitable meteorological conditions were necessary for the successful carrying out of the desired tests, the forecaster on duty at the Weather Bureau was asked to give notice by 10 a. m. when clear weather with light winds and nocturnal cooling that would carry the minimum temperature to or near frost conditions could be expected on the following night. This was to enable representatives of the Weather Bureau to reach the "M" field at Edgewood, 70 miles from Washington, in season to set up the apparatus for measuring the intensity of nocturnal radiation and for the Chemical Warfare Service to prepare to produce the smoke cloud.

Following the advice of the forecaster tests were attempted on the four nights April 9–10, 19–20, 25–26, and May 1–2, 1923.

On April 9–10 the sky was clear and the temperature decreased from a maximum of 50.0° F. on the 9th to 29.5° F. on the morning of the 10th. An attempt was made to cover the field containing shelters No. 1 and No. 2 with smoke, leaving the field containing shelters No. 3 and No. 4 free from smoke. Unfortunately, however, while the wind movement averaged only one to two miles per hour, it was so variable in direction that shelters No. 1 and No. 2 could not be kept continuously covered with smoke. Neither was it possible to keep one pyrgeometer under the smoke cover and the other clear of it, except for a short time at about 4:50 a. m. The pyrgeometer radiating to the clear sky then showed a loss of heat at the rate of 0.123 gram-calories per minute per square centimeter of horizontal surface, while the instrument radiating to the smoke cloud showed a loss at the rate of 0.074 gram-calories per minute per square centimeter, or only 60 per cent as much as to a clear sky.

At this time psychrometer readings showed that the air near the ground had a temperature of about 28° F., and was nearly saturated with moisture.

On April 19–20 there were a few clouds near the western horizon at sunset which increased rapidly, so that by 11 p. m. the sky was about seven-tenths covered with A. Cu. clouds, which later nearly covered the sky. The wind was from 5 to 10 miles per hour from the south. The temperature was about 48° F., and changed but little during the remainder of the night. Under these conditions it did not seem advisable to go to the expense of producing a smoke cloud.

The night of April 25–26 was cloudless, with from 6 to 10 miles of wind from the north to northwest. The temperature fell from a maximum of 68° F. on the 25th to a minimum of 41° F. on the morning of the 26th.

[2] Descriptions of these shelters are given in *Instrument Division Circulars B* and *C*, publications of the Weather Bureau.

[3] For a description of the pyrgeometer see MO. WEATHER REV. for February, 1918; 46. 57.

A smoke cloud was maintained over the field containing shelters No. 3 and No. 4 from 9:30 p. m. on the 25th to 1:15 a. m. of the 26th. Table 2 gives the pyrgeometer readings taken, with instrument No. 2 in the field that was covered with smoke and instrument No. 3 on somewhat higher ground to the north (windward) of the line of burning phosphorus that produced the smoke. A few readings of No. 2 were taken before the smoke cloud was produced, and a few more after it had disappeared.

TABLE 2.—*Nocturnal radiation measurements, "M" field, Edgewood, Md., April 25–26, 1923.*

Time.	Pyrgeometer No. 3. Clear sky.	Pyrgeometer No. 2. Under smoke.	Assmann psychrometer. Dry.	Assmann psychrometer. Wet.	Vapor-pressure.	Remarks.
Apr. 25:	*Gr. cal.*	*Gr. cal.*	*° F.*	*° F.*	*Inches.*	
8:55 p. m.		0.162				
9:00 p. m.	0.163					
9:17 p. m.		0.162				
9:20 p. m.		0.162				
9:21 p. m.	0.168		52.7	42.0	0.143	
9:22 p. m.			52.4	41.8	0.146	
9:30 p. m.	0.157					First smoke, 9:30 p. m.; second line of fire, 9:37 p. m.; third line, 9:49 p. m.
9:50 p. m.		0.151				
9:59 p. m.	0.173					
10:17 p. m.		0.143	50.0	40.2	0.139	
10:19 p. m.	0.157					
10:43 p. m.		0.109				
10:49 p. m.	0.170					
11:11 p. m.			46.3	39.0	0.154	
11:24 p. m.		0.081				
11:27 p. m.	0.162					Smoke cloud continuous.
11:32 p. m.			46.0	39.0	0.157	Moon, but no stars, visible through it.
12:00 midnight.		0.082				
Apr. 26:						
12:11 a. m.	0.135					
12:17 a. m.			42.0	37.2	0.167	Bulb of psychrometer 4 inches from ground.
1:15 a. m.		0.102				Smoke ended 1:15 a. m.
1:21 a. m.	0.125					
1:27 a. m.		0.135				No smoke.
1:40 a. m.			45.0	38.2	0.158	Increasing wind.
1:42 a. m.			44.5	38.0	0.157	

The effect of smoke in diminishing the loss of heat by radiation from the instrument to the atmosphere is very clearly seen in these readings. With the densest smoke it is diminished one half, and the readings became comparable to those obtained on April 19–20 with the sky nearly covered with clouds.

A comparison of the thermograph traces in the different shelters shows no appreciable difference between the temperatures in shelters No. 1 and No. 2 outside the smoke cloud, and in shelters No. 3 and No. 4 under the smoke cloud.

On May 1 Cu. St. clouds commenced to form before sunset, the sky became overcast by 8 p. m., and light rain fell for a few minutes. The clouds commenced to break soon afterward, and at 9:30 p. m. preparations were made to cover the field containing shelters No. 3 and No. 4 with smoke.

A smoke cloud was maintained from 10:52 p. m. to 2:15 a. m. of May 1–2. About 800 pounds of white phosphorus was used on a 66-yard front in the presence of an average wind of three miles per hour. The cloud rose at the firing point until the base of the cloud was about seven feet above the ground, then slowly dispersed downward, reaching the ground at the 40-yard line. The top of the cloud reached a maximum height of 40 yards at the 300-yard line but did not increase in height beyond this point.

On following the cloud down its course, it was observed that a heavy screen was produced for a distance of about 200 yards from the line of fire, but the density decreased beyond this point.

The intensity of nocturnal radiation was measured, but on account of the presence of clouds during most of the time no great interest attaches to the readings. A few measurements made with a nearly cloudless sky show that the radiation to the clear sky was about twice as intense as to the dense smoke cloud.

The thermograph traces show little decrease in temperature in any of the shelters during the time No. 3 and No. 4 were under the smoke cloud. Indeed, the two latter indicate a slight rise in temperature, as a comparison of the thermograph traces obtained in shelters 2 and 4, given in Figure 1, shows.

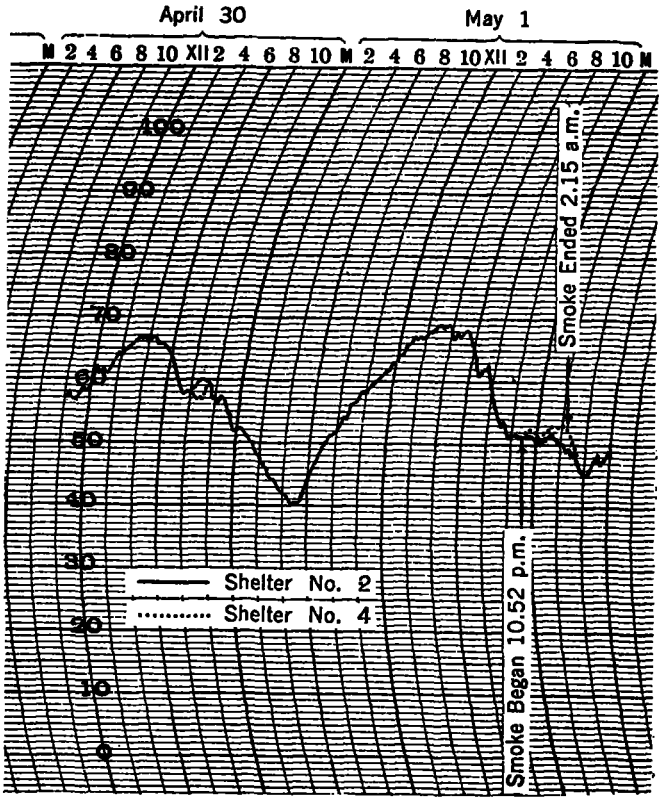

FIG. 1.—Thermograph traces, "M" field, Edgewood, Md., April 30–May 2, 1923.

Advantage was taken of the favorable wind conditions and the resulting form of the smoke cloud to carefully measure with an Assmann psychrometer the horizontal temperature gradient from the line of fire to the line of instrument shelters No. 3 and No. 4. The results are given in Table 3.

TABLE 3.—*Temperature variation with distance from burning phosphorus (temperature at line of shelters taken as standard), "M" field, Edgewood, Md., May 1–2, 1923.*

	Distance from fire (feet).										
	135	100	75	50	30	12	10	8	6	4	2
	° F.	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*	*° F.*
Under smoke	0	−0.3	−0.3	−0.8	+0.7	+1.0	+1.1	+1.5	+1.7	+1.0	+7.0
In smoke	0	.....	+0.5	+0.9	+1.7	.....	+2.2	.....	+25.0	.....	+30.0

The first line of temperature variations shows the departures from the temperature at the line of the shelters, measured by the dry bulb of an Assmann psychrometer, when held at about the height of the eye while kneeling. The temperature at this point was measured in the smoke cloud. The temperature at other points was generally measured under the cloud.

The second line of temperature variations represents readings taken with increased wind movement that beat the smoke down to the ground, perhaps by hastening its cooling, practically all the way from the burning phosphorus to the instrument shelters.

It will be noticed that under the cloud the lowest temperatures were obtained at about one third the distance from the fire to the shelter, or where the base of the smoke cloud was probably the highest. In the smoke cloud the temperature decreased gradually from the fire to the shelters.

At 2 a. m. on May 2 the edge of the smoke cloud was near shelter No. 4 and sharply defined. Outside this cloud the temperature near the ground was 2.1 °F. lower than in the dense cloud at the shelter. Somewhat nearer the shelter in thin cloud it was 1.5 °F. lower; and back of the line of fire it was 3.1 °F. lower.

INTERPRETATION OF THE METEOROLOGICAL DATA.

The horizontal temperature gradients shown in Table 3, and especially the decrease in temperature at 2 a. m. of May 2 from the smoke cloud to points outside the cloud, show very clearly the effect of the smoke in retarding nocturnal cooling. That this is not entirely due to a diminution in the intensity of radiation from the ground to the atmosphere is indicated by the fact that in the first line of temperature departures of Table 3 the lowest temperature was found at the point where the base of the smoke cloud was the highest, and also by the fact that in the second line of temperature departures, where all the measurements were made in the cloud, the temperature decreased with distance from the line of fire.

Evidently heat is conveyed to the air by the particles constituting the smoke. This is more clearly shown in measurements made a few feet from the fire, where they were markedly higher in the smoke than just below it.

We may conclude, then, that the slightly higher temperature recorded between midnight and 2:15 a. m. of May 2 in shelters No. 3 and No. 4 as compared with that recorded in shelters No. 1 and No. 2, was due in part at least to heat conveyed to the air by the heated particles constituting the smoke.

That practically no retardation of nocturnal cooling was noticeable in the smoke cloud of April 25–26 is in accord with the results of investigations on cloth screens,[4] which, briefly summarized, show that:

> Cloth coverings over small areas of orchard or over individual trees do not have an appreciable effect on the temperature, even when the coverings are of heavy cloth or canvas. This is due to the fact that the cloth does not prevent an interchange between the air under the covering and that outside.
>
> Coverings of rather heavy cloth laid directly over garden truck or low-growing plants are effective in protecting against moderate frosts.

In the case of all the smoke tests described in this report, a similar interchange of air undoubtedly took place on account of the relatively small firing front and the short distance between the edge of smoke and the instrument shelters. Only in cases of practically no wind velocity could one expect the blanketing effect of the smoke screen on the earth's radiation to affect the temperature of the air near the ground, and in such cases it is very difficult to set up a uniform smoke cloud over an area.

We may compare the results of the above tests with temperature records given by Young,[5] which show that the temperature in an orchard heated by the combustion of crude oil is frequently 5° higher than in an orchard unheated.

[4] Young, Floyd D.: Frost and the prevention of damage by it. U. S. Department of Agriculture, *Farmer's Bulletin No. 1096*, p. 12.

[5] Young, Floyd D.: *Loc. cit.* pp. 15, 26, 27, 29.

The above results strengthen the conclusion already expressed that "The retardation of nocturnal radiation by the smoke cloud plays an insignificant part in frost protection."

COST OF HEATING AN ORCHARD.

Young[6] also gives estimates of the cost of protecting orchards in southern California from frost by heating with crude oil.

Briefly summarized, the average annual cost per acre of protecting 220 acres of lemon trees for the 6-year period 1913–1918 was $78.90. Fires were lighted an average of 16 times each year. The average annual cost per acre of protecting 40 acres of orange trees, requiring fewer firings than the average orchard, was $26.65

The above estimates include interest on cost of installation, depreciation of equipment, fuel, and labor, at a time when prices averaged about one-half what they do at present.

COST OF PHOSPHORUS SMOKE SCREEN.

A dense smoke screen can be produced by burning phosphorus at the rate of 1.25 pounds per hour per yard of front screened in the presence of a 1-mile-per-hour wind. It is estimated that after forming a screen of sufficient density, this density may be maintained by reenforcing the cloud with a 10 per cent addition of smoke at intervals of 200 yards measured in the direction of cloud travel.

For example, a 40-acre orchard, having a front of 220 yards and depth of 880 yards would require 275 pounds of phosphorus per hour on the front line in the presence of a 1-mile wind and 28 pounds additional every 200 yards measured from the firing front down the length of the orchard. A total of four lines of fire would have to be maintained as follows:

	Pounds per hour.
Front line	275
200-yard line	28
400-yard line	28
600-yard line	28
Total	359

In the presence of a 2-mile wind, the consumption would be twice as great, the increase in consumption being in direct proportion with increase in wind velocity.

With phosphorus at 35 cents per pound, the phosphorus costs of screening a 40-acre orchard per hour would be as follows:

Wind velocity, miles per hour.	Pounds of phosphorus.	Cost of material.
1	359	$125.65
2	718	251.30
3	1,077	376.95

Two men would be required to handle the phosphorus at the first firing front and one man additional at each point of reenforcement, making a total of five men. In the presence of a 2-mile wind, about six men would be required, three on the first line and one each on the other three lines.

It is quite evident from the above figures that the cost of covering an orchard with smoke by the use of phosphorus is very much in excess of the cost of heating it by burning petroleum.

It should also be remembered that white phosphorus must be handled with extreme care, as it ignites when exposed to air at a temperature of 113° F. It should be transported under water in metal containers and handled with rubber gloves.

[6] *Loc. cit.* pp. 33–34.