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The Smokiness of Oil-Burning Orchard Heaters

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WARREN R. SCHOONOVER[3] AND F. A. BROOKS[4]

SUMMARY

In southern California 70,000 acres of orange groves are protected occasionally against frost damage by burning low-grade fuel oil in simple sheet-iron orchard heaters and smudge pots. The great quantity of smoke produced when burning millions of gallons of oil each frosty night frequently results in a serious smoke nuisance. A study of the smokiness of oil-burning orchard heaters was made to aid in the abatement of this nuisance.

Visual methods ordinarily used for smoke estimation in industrial regions are not applicable to a study of the smokiness of orchard heaters because of operation at night and the prevalence of smoke throughout the citrus districts. Four other methods were developed permitting an accurate classification of orchard heaters as to smokiness. Two of these methods classify according to smoke blackness, and two according to smoke weight.

Tests were run to determine the smokiness of the heaters in general use. The tests showed:

1. That the different heaters vary greatly in smokiness.

2. That it is possible to burn ordinary grades of fuel oil in simple, inexpensive heaters without producing visible amounts of smoke at normal burning rates.

3. That the smokiness of many types of heaters can be reduced by proper regulation and frequent cleaning.

4. That the composition of fuel oils available commercially has no consistent influence on the smokiness of different heaters.

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[1] Received for publication July 12, 1932.

[2] This project was initiated under the leadership of A. H. Hoffman. He died soon after the completion of the field trials at Pomona. Mr. C. E. Barbee had charge of the project for several weeks after the death of Mr. Hoffman and has since been responsible for the construction and operation of all the testing apparatus.

[3] Extension Specialist in Citriculture, temporarily assigned by the Agricultural Extension Service to the Experiment Station to continue the investigation.

[4] Associate Agricultural Engineer in the Experiment Station, appointed August, 1931.

5. That laboratory tests run at summer temperatures are a reliable indication of the relative smokiness of heaters as operated in the field during the winter.

Heater manufacturers have availed themselves of the smoke-measuring facilities afforded by the laboratory for a study of heater design in relation to the smoke problem. As a result of these studies new stacks for use on old heaters have been developed which reduce the smoke output at normal burning rates to invisibility.

Portable apparatus was devised in order to measure the smokiness of orchard heaters as operated in the field. Accurate and semipermanent visible records of smokiness were obtained. A method of correlating field records with laboratory determinations was found which permits field records to be interpreted quantitatively.

THE SMOKE PROBLEM

The Origin of the Smoke Nuisance.—Experiments begun in California as early as 1896 gave some indication that smoke or steam was effective in protecting citrus orchards against frost. Smudges of smoldering wet straw were lighted alongside orchards. Growers soon recognized that for frost protection heat was at least as important as smoke.

Coal was used for some years but proved unsatisfactory in burners then available. The first oil heaters employed were open pails which produced both heat and smoke. The grades of cheap fuel available at that time would not burn satisfactorily in open containers. However, the advantages of oil—it is plentiful, cheap, and easily lighted and extinguished—led to the initial efforts for improvement of orchard heaters from the standpoint of better control of the burning rate and ability to burn all of the oil contained in the heater. All of the heaters then in use smoked badly, but the growers, while realizing the importance of heat, still believed the smoke to be of some benefit and no improvements for better combustion were demanded. The public was doubtless annoyed by the smoke but recognized the importance of the citrus industry to the economic welfare of southern California and so little complaint was made.

The steady growth of orchard heating as a regular practice in cold locations had established many thousands of smoky heaters in orchards by 1922. The freeze of that year brought the first realization of the seriousness of the smoke problem and of course of the value of heating. At that time attempts to develop smokeless heaters began and encouraging progress was made, but the rapid growth in number of heaters in use increased the total smoke output so much that the smoke nuisance continued to grow.

Heat, Not Smoke, Effective for Frost Protection.—The belief that the smoke itself helped to conserve the heat in an orchard was widely accepted because frosts rarely occur when low clouds are present. However, in 1920 Kimball and Young[5] found that the smoke had little if any value. According to their measurements heavy smoke decreases the rate of heat loss by radiation about 10 per cent but does not prevent temperatures from reaching a minimum as low as that reached in similar smoke-free locations.

The radiation frost has peculiar characteristics in that air, cooled mainly by contact with the ground and other surfaces which radiate rapidly on clear nights, tends to settle in low areas underrunning the warmer air, which is relatively lighter. A wind would mix the warmer air with the cold and decrease the probability of frost, but on calm, clear nights the air next to the ground will cool rapidly even with no influx from surrounding hills. This usually creates a "temperature inversion,"[6] which fortunately acts as a virtual ceiling; for the cold ground air, if uniformly heated a few degrees, will rise only a short distance before reaching the level of common density, thus limiting the volume to be warmed.

That successful frost protection depends upon heat generated from a relatively large number of small fires per acre is now well demonstrated by ample field experience. Figure 1 shows thermograph records[7] obtained in an orchard equipped with open-pail oil heaters. It should be noted that the temperature dropped rapidly in both the heated and unheated orchards at 2:45 A.M. and again at 4:45 A.M., and that safe temperatures were maintained by lighting more heaters until eventually 54 per acre were used.

Usually 50 heaters are required for fully protecting an acre of orange orchard. Figure 2[8] shows thermograph records indicating that on a severe night safe temperatures could not be maintained by burn-

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[5] Kimball, Herbert H., and Floyd D. Young. Smudging as a protection from frost. U. S. Monthly Weather Review 48:461–462. 1920.

[6] Young, Floyd D. Nocturnal temperature inversions in Oregon and California. U. S. Monthly Weather Review 49:145. 1921.

[7] Young, Floyd D., and C. C. Cate. Damaging temperatures and orchard heating in the Rogue River Valley, Oregon. U. S. Monthly Weather Review 51:617–631. 1923.

[8] Young, Floyd D. Notes on the 1922 freeze in southern California. U. S. Monthly Weather Review 51:584. 1923.

ing 25 heaters per acre (even though a gallon or more of oil was burned per heater per hour), but that with 50 heaters burning, the temperature was raised above the danger point.

Need of Relief from the Smoke Nuisance.—The protection now afforded to approximately 70,000 acres of citrus orchards is estimated to consist of nearly 3,300,000 orchard heaters, of which about 2,900,000 are oil burning. Sufficient oil for only one filling of these heaters totals 2,500 railway tank carloads.

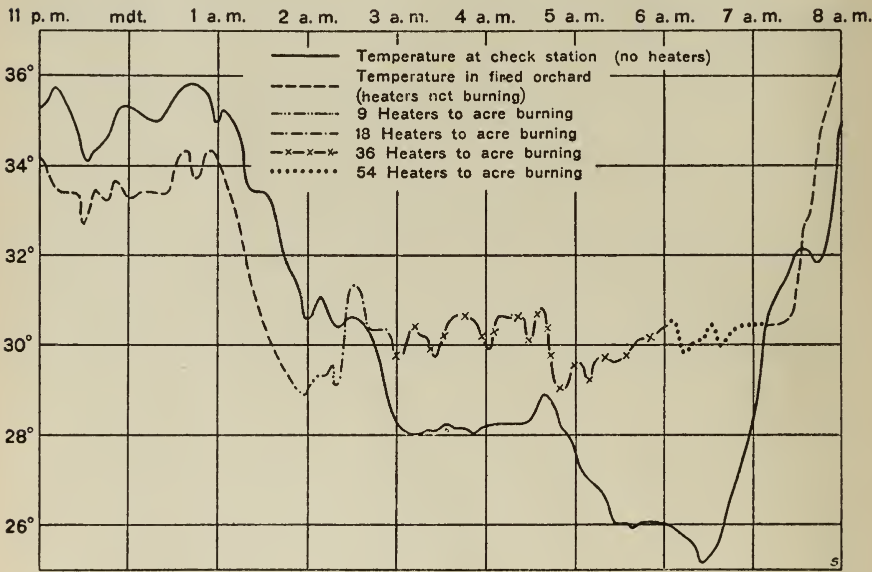

Fig. 1.—Temperature records in a heated orchard and at an outside check station on the same night. (From Ext. Cir. 40.)

If weather conditions should require general heating in all districts as much as 15,000,000 gallons of oil might be burned during a single night. No such conditions have occurred, but the burning of much smaller quantities frequently has caused the smoke nuisance to become acute.

Because of the nature of a radiation frost, there is little or no wind to blow the smoke away. This smoke pall decreases the heat from the sun and therefore necessitates longer hours of burning. Growers sustain other losses from inefficient heaters that give off unburned fuel into the atmosphere and from the added expense of washing smoky fruit. In extreme cases there are price discounts when washing has been unsuccessful.

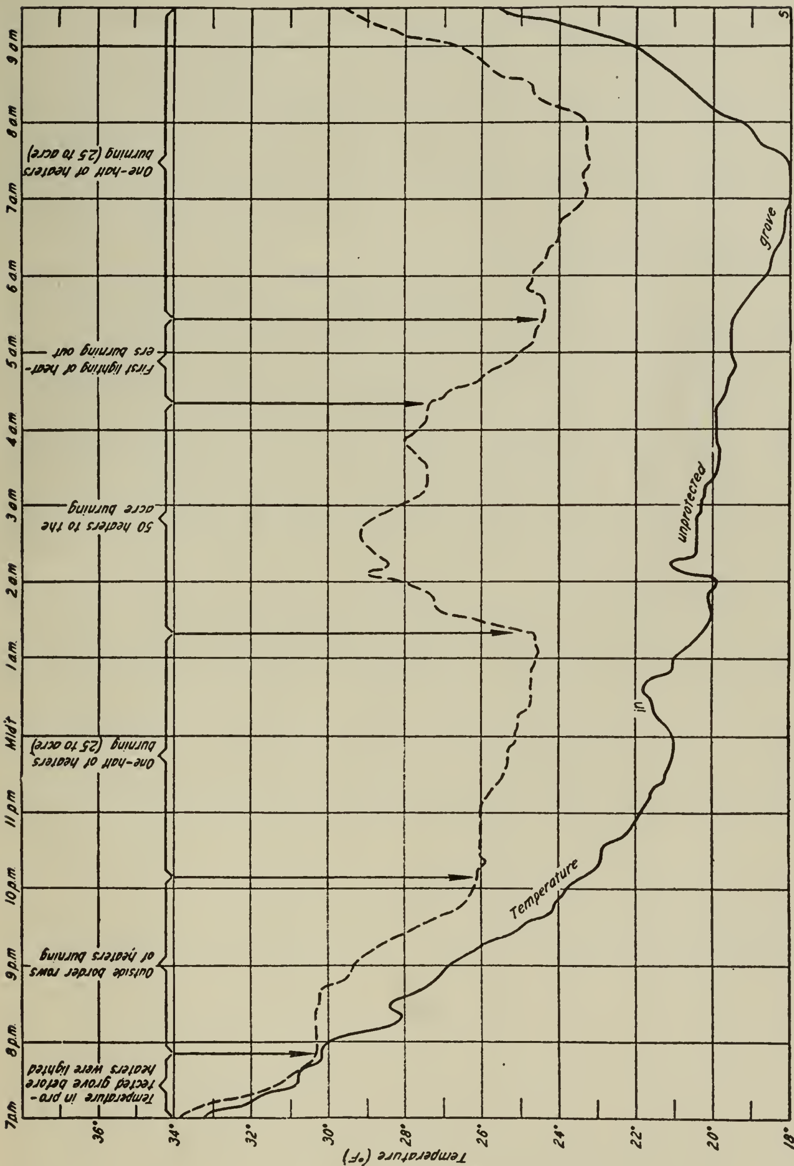

Fig. 2.—Thermograph records for the same night from neighboring heated and unheated Navel-Orange orchards. (From Ext. Cir. 40.)

The character of the soot is such that closed windows do not prevent damage to furniture, draperies, clothes, and merchandise. Under these conditions personal discomfort is, of course, intense. Highway traffic is endangered and business is interfered with generally.

It is estimated that the oil consumption in orchard heaters for the last two weeks of December, 1930, was 17,000,000 gallons. On the basis of data now available it is evident that the carbon content of orchard-heater smoke discharged into the air during this 14-day period is to be reckoned in millions of pounds. It was generally acknowledged that the smoke damage was considerable.

Economic Importance of Orchard Heating.—The citrus industry brings into California about $100,000,000 a year,[9] and this income, which supports many industries besides the actual growing of the fruit, is in constant danger of reduction through various hazards. About one-third of the citrus acreage is in locations cold enough to make orchard heating an essential orchard practice, and there are few, if any, locations entirely free from damaging frosts. The efficient protection of the colder orchards insures a regular supply of fruit so that markets can be maintained, and also guarantees to consumers fruit of high quality undamaged by frost.

The number of heaters lighted and their burning rates vary according to weather conditions, but the average oil consumption will run about 15 to 20 gallons per acre per hour. The cost of heating at present prices of fuel and labor, varies from about $0.75 to $1.00 per acre per hour exclusive of interest and depreciation on equipment.

Despite general recognition of the fact that the economic welfare of the entire state depends in large measure upon protecting the citrus crop from frost damage, the public demands relief from the unnecessary smoke produced by orchard heaters.

Initiation of the Investigation of the Smoke Problem.—The Agricultural Experiment Station undertook to measure the smokiness of orchard heaters at the urgent request of representatives of the public, fruit packers, and growers acting principally through the "Orchard Heating Improvement Committee," organized by the Los Angeles Chamber of Commerce, January 9, 1931. L. D. Batchelor, Director of the Citrus Experiment Station of the University of California at Riverside, emphasized the need and urgency of this investigation, which was assigned priority over other engineering-research projects then under way at the University Farm.

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[9] Approximate average of recent years, California Fruit Growers Exchange, annual reports.

The questions raised by the Committee[10] in regard to orchard heaters were:

1. The value of the smoke emitted by such heaters as a frost preventive.
2. The relative value, for orchard heating, of a heater that does not smoke and one that does.
3. If it shall be determined that all such heaters issue more or less smoke, then the minimum amount of smoke, per heater, necessary for operation.
4. Ways and means of elimination, by entrapment or otherwise, of the smoke emitted from such heaters.

On January 30, Mr. A. H. Hoffman, Director L. D. Batchelor, and Mr. W. R. Schoonover of the College of Agriculture, met with Mr. R. L. Willits and W. K. Beattie of the Orchard Heating Improvement Committee and Mr. Floyd D. Young of the United States Weather Bureau. At this meeting it was agreed that the Agricultural Experiment Station would undertake the investigation in cooperation with the Committee. The claim that smoke was of value as a frost preventive was considered adequately disproved by the experiments of Kimball and Young.[11] It was agreed also that smoke from oil-burning orchard heaters constituted the main problem because oil is the only fuel obtainable under present conditions in adequate quantities at a reasonable price, and because approximately 90 per cent of the heated acreage is equipped with oil-burning heaters.

The project was restricted to an investigation of the smokiness of oil-burning orchard heaters and does not include a study of the value of orchard heating, or the efficiency of heaters. These two subjects have been reported previously.[12]

Outline of the Problem.—The problem then was to study the smoke output of the oil-burning heaters in common use, using the grades of fuel most readily obtainable, and also, if possible, to determine the

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[10] Anonymous. Orchard heating regulations considered at mass meeting. California Citrograph **16**:145, 180, 181. 1931.

[11] Kimball, Herbert H., and Floyd D. Young. Smudging as a protection from frost. Monthly Weather Review **48**:461–462. 1920.

[12] Webber, H. J., *et al.* A study of the effects of freezes on citrus in California. California Agr. Exp. Sta. Bul. **304**:243–321. 1919. (Out of print.)

Schoonover, Warren R., Robert W. Hodgson, and Floyd D. Young. Orchard heating in California. California Agr. Exp. Sta. Bul. **398**:1–69. 1925. (Out of print.)

Hoffman, A. H. Laboratory tests of orchard heaters. California Agr. Exp. Sta. Bul. **442**:1–37. 1927. (Out of print.)

Schoonover, Warren R., Robert W. Hodgson, and Floyd D. Young. Frost protection in California orchards. California Agr. Ext. Cir. **40**:1–73. 1930.

factors influencing smoke output. Large variations in smoke output were expected because the heaters burn any kind of fuel oil whose pour point is below 30° F, and, furthermore, at any bowl level, with large variations of bowl and stack temperatures, with almost no control over air-fuel ratio, and with secondary combustion sometimes above the stack. Nevertheless, to control the smoke nuisance a practical method of smoke measurement was required that would yield significant test results with all heaters in question.

The subcommittee on research of the Orchard Heating Improvement Committee agreed to choose the heaters to be tested, furnish used specimens for the tests, supply the required amounts of the proper fuels, secure a suitable location for field trials, supervise the regulation of heaters, and formulate a decision as to what might be considered a reasonable limit of smoke tolerance. The Agricultural Experiment Station agreed to supply apparatus for making carbon determinations and for determining fuel-consumption rates, make oil analyses for comparison of fuels used in tests with regular run of fuels used by the growers, and supply personnel to conduct tests.

The purpose of the work was to assist in eliminating the smoke nuisance by:

1. Furnishing data to be used as the basis for legislation.
2. Furnishing information for the guidance of manufacturers in improving their heaters.
3. Developing subject matter to be used by the Agricultural Extension Service for guiding growers in better heater operation.

METHODS USED IN MEASURING SMOKE

Methods Available.—Industrial smoke is usually measured by making visual comparisons of its blackness with black and white color standards such as the Ringelmann chart.[13] This method is not directly applicable to orchard-heater tests because it cannot be used at night. Furthermore, its grading in five steps of 20, 40, 60, 80, and 100 per cent black is too coarse to register minor variations in orchard-heater smoke, which are of considerable interest in determining the causes of smokiness. Other methods considered for smoke determinations were:

1. Direct-weight methods such as the collection of a soot sample on a weighable filter, or the electrical precipitation of smoke particles.

[13] Faust, H. M. Smoke and its prevention. Ohio Engin. Exp. Sta. Cir. 24:12. 1931.

2. Indirect-weight methods such as the collection of a sample on an asbestos filter for making carbon determinations by chemical methods.
3. Measurement of the opaqueness or apparent smoke density of the products of combustion by a light-interception method.
4. Measurement of blackness by collecting a sample on a white filter and determining the magnitude of the blackening effect by photometric methods.

All of these methods were used and are discussed later.

Fig. 3.—Taking smoke sample by aspirator from tip of flame.

Tests in the Field at Pomona.—Mr. Young and the members of the Committee were of the opinion that the tests should be conducted under orchard conditions during cold weather. On the basis of experience available at that time a direct-weight method using paper filters seemed best adapted to a field study under orchard conditions.

Smoke determinations were made by holding a sampling tube in the stream of gases discharged by a heater just above the tip of the flame (see fig. 3). The attempt to use this simple method to obtain weighable samples on light paper proved unreliable and the method was abandoned for three reasons: (1) the smoke deposit could not be determined because even when weighings were made in an air-controlled chamber with complete reconditioning for moisture content, the final weights of the filter papers were both greater and less than the original (owing to change in composition of the paper itself because of exposure to the flue gases, and to variable loss of oil processed in the paper); (2) the samples were not dependable because it was impossible to draw them from the exact center of the waving flame tip; and (3) occasional breezes disturbed the weighing of fuel consumption and affected stack combustion. These difficulties forced the complete reframing of the project and the development of new test methods.

Laboratory Methods Developed at Davis.—In order to get away from the errors in the filter-paper method it was decided to estimate the smoke on a light-interception basis, which is a standard method of smoke determination.[14] The essential feature of the method is that a beam of light from a constant source is passed through the smoke stream and the light which is not intercepted falls upon a light-sensitive photo-electric cell or a radiation pyrometer. Proper electrical instruments, indicating the intensity of the light transmitted, measure the relative opaqueness of the smoke. Then by measuring the total volume of the smoke stream passing the light, per pound of fuel burned, the relative quantity of smoke emitted by different heaters can be determined.

This method avoids the previous error in weighing filter papers, eliminates the sampling error by dealing with the entire smoke stream discharged from the heater, and avoids errors due to occasional breezes because of its location indoors. The dilution of the smoke stream with extra air simultaneously affects both the opaqueness and total volume of air flow and thus does not influence the determination of relative smokiness. The values of smokiness obtained with such an apparatus do not represent actual weight or quantity of smoke no matter how accurate the opaqueness and volume determinations may be. However, for comparing different heaters the method is adequate—in fact goes one step beyond the usual basis of smoke-abatement ordinances, which grade by blackness without the volumetric determination.

If a reasonable correlation could be found between the opaqueness of smoke and the density of its carbon particles, the light-interception results might be interpreted in terms of weight within the limits shown by the correlation. This, of course, was highly desirable, and the necessary auxiliary apparatus for correlation data was added to the light-interception equipment without sacrificing its advantages over all other methods in being continuous, quick, and reliable.

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[14] American Society of Mechanical Engineers. Power test codes; instruments and apparatus, Part 20, smoke-density determinations. Amer. Soc. Mech. Engin., 29 W. Thirty-ninth Street, New York City. 1930.

Figure 4 shows the apparatus used in making the smoke tests. The orchard heater, at the extreme right, is placed on automatic self-balancing scales, which measure the loss of weight as the fuel is burned. The centrifugal blower at the left creates a gentle suction, drawing the smoke and some surrounding air into the hood, past the light, and through the main orifice where the rate of flow is measured. Two small orifices each with an area $1/100$ of the total orifice area divide the total smoke stream to obtain 1 per cent samples for carbon weight determinations. The sample from one orifice flows through an electric precipitator which collects the solid particles for direct weighing. The

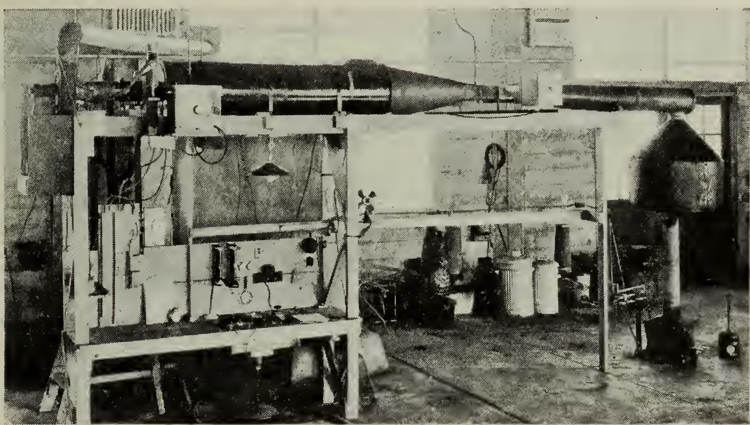


Fig. 4.—Laboratory apparatus for measuring orchard-heater smoke.

other sample flows through an asbestos filter which retains the solid and liquid particles for chemical analysis. A felt filter also can be used to obtain a deposit for comparison of blackness. Detailed description of this apparatus is given in Appendix A.

Smoke Units Used for Comparative Results.—The correlation between smoke opaqueness determined by light interception, and carbon weight determined electrically and chemically is fully discussed in Appendix B. In early tests with three fuel oils in the standard heaters there appeared to be a reasonable correlation between the opaqueness-quantity unit and weight such that one "pound-smoke" unit as defined below was approximately equivalent to 1 gram of carbon per pound of fuel burned. However, tests with seven other orchard-heater fuel oils indicate that the correlation between smoke opaqueness and density of carbon particles is not generally satisfactory even at high burning rates, and is unusable at low burning rates.

The correlation between opaqueness determinations and felt filter blackness appears to be reasonably satisfactory as shown in figure 35. Both methods are very fast. The light-interception method has the advantage of reading directly, continuously, and instantaneously while the felts offer the advantages of simplicity and semipermanent record. Each of these methods depends largely on the blackness of the smoke. Either method gives accurate, comparative results which can be interpreted in terms of the other method. If the invisible vaporized carbon compounds in the smoke are to be measured, another basis, such as the determination of the weight of carbon particles would be required. However, this characteristic of the smoke is not of general interest.

It therefore seems best to report the data on the basis of a quantity unit representing the product of the average smoke-opaqueness units (apparent density) times the total air flow (volume) during the period of burning one pound of fuel. This unit has been designated as a ''pound-smoke'' unit.

Accuracy of the Method.—Since the weight-correlation problem is avoided by comparing test results in pound-smoke units, the method as a whole is subject only to the following small errors:

1. Error in weighing the loss of fuel as burning proceeds. For short ½-pound runs this might amount to 5 per cent, but the average error is very small owing to the electric contact signals and the operating of two stop watches by independent observers. The automatic balance developed later reduced this error to a negligible amount.

2. Error in reading millivoltmeter because the smoke comes in puffs. This error may amount to 20 per cent in the case of individual readings, but the average error over the usual 10 readings is small. It is greatest in percentage with the least-smoky heaters.

3. Error in determining air flow due to the assumption that dry air is being measured, while what is measured is in fact a mixture of air with products of combustion, including carbon dioxide, water vapor, and unburned or partially cracked oil. This error has been carefully estimated and is of a negligible magnitude.

4. Errors due to instruments and orifices. The instruments and orifices have been calibrated, and the errors are known to be insignificant.

All of these errors are relatively unimportant. The determinations are of such accuracy that all heaters show distinctive characteristics of smokiness in spite of large momentary deviations in most heaters from their average performance.

Figure 5 shows graphically typical results obtained with the present apparatus when testing a heater of unusually smooth-burning characteristics. The upper line shows that the burning rate (shown as a 3-minute moving average) is rarely constant. This irregularity largely results from the distillation cycle in the heater bowl. Some heaters even show regularly spaced smoke peaks. The bottom line is the record of opaqueness, as observed each minute, corrected for temperature. The abrupt

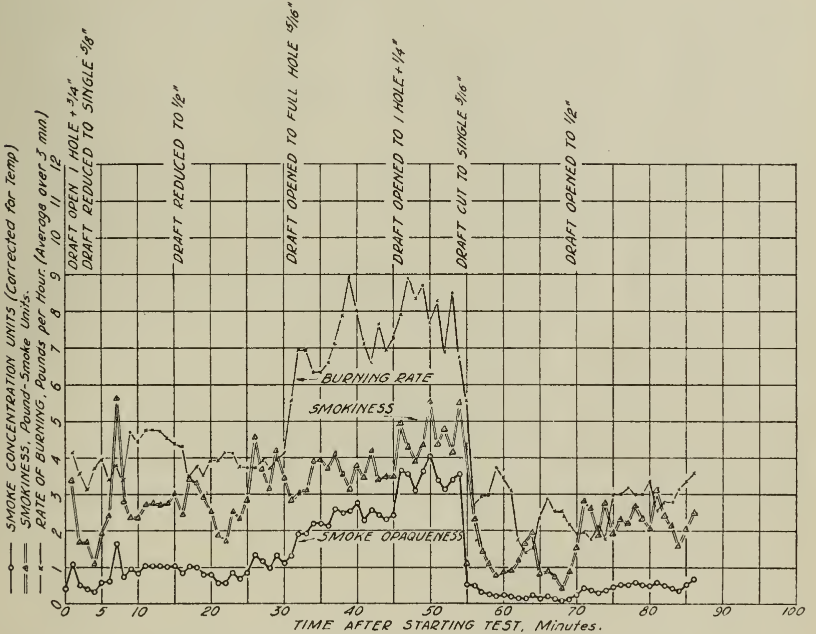


Fig. 5.—Continuous smoke test of heater No. 32, Hy-Lo 1929 Model.

return to smokeless readings when the draft was cut down after a high burning rate shows the sensitivity of the apparatus. The middle line of smokiness (in pound-smoke units) is derived from the other two by using the volume of total air flow during the period of burning one pound of fuel.

LIST OF ORCHARD HEATERS TESTED

Table 1 lists the orchard heaters and stacks tested. Photographs of many of these are given in the bulletin so that readers may identify definitely the models used. The figure numbers in which these photographs appear are given in column 2. Graphs of the smoke-test records and diagrammatic cross sections of the heaters and stacks will be found in the figures listed in column 3.

TABLE 1

List of Heaters Tested and their Photograph and Curve Numbers

No.	Photograph fig. No.	Smoke test fig. No.	Heater name
1	*2*	*3*	*4*
1	18, 21, 22	15, 28	National Jumbo Cone
2	....	6	Garbage Pail
3	20	....	Hy-Lo, Double Stack, square bowl
4	20	12	Hy-Lo, single short stack, round bowl
5	....	17	Smith-Evans
6	18	17	Kittle
7	22	....	Citrus, Olsen Stack
8	19	15	National Baby Cone
9	20	8, 24, 25	Citrus Regular
10	....	....	Canco 5 gal.
11	....	7	Dunn
12	19	13	National, Exchange model, 5½-inch stack
13	....	6	Hamilton Bread Pan with stack
14	....	13	Wheeling
15	....	....	Canco 3 gal.
16	....	....	Chinn
17	....	6	Hamilton Bread Pan
18	....	....	Hamilton, oblong with stack and down draft
19	....	7	Hamilton, square bowl with down draft
20	19	10	National Double Stack
21	....	17	Bothwell
22	20, 21	8	Citrus, 15-inch stack
23	20	12	Hy-Lo Double Stack, round bowl
25	20, 22	....	Hy-Lo, single short stack, square bowl
26	19, 22	9, 29	Citrus, high stack
27	20	....	Citrus Gas Flame
29	18	17	Fugit
30	19	11	National Junior Louver, 15 inch
31	18	14	National, Exchange model, 7-inch stack
32	18, 21	5, 16, 24, 25	Hy-Lo 1929 Model
34	19	14, 29, 30	National, Exchange model, 6-inch stack
			New stocks
52	26	27	Lamco Gyradiant
60	26	27	Hy-Lo Giant
61	....	28	Hy-Lo Giant Junior
62	26	28	Hy-Lo Drum Stack
63	....	32	Hy-Lo, straight stacks
75	....	32	Hy-Lo, tapered stacks
76	....	32	National Junior Louver, 18 inch, holes spaced spirally
80	26	29	Hinchcliff, 36-inch
81	....	29	Hinchcliff, 30-inch
90	26	32	National Junior Louver, 18 inch, holes spaced in rows
91	26	32	O'Keefe and Merritt, 6-inch straight stack
91A	....	31	O'Keefe and Merritt, 7-inch straight stack
100	....	27	O'Keefe and Merritt Corrugated
148	26	32	Hy-Lo, tapered stack

TEST RESULTS OF STANDARD MAKES OF ORCHARD HEATERS

The heaters were tested in the regular runs over the entire range of burning rates permitted by the draft regulators. The average burning rate in the field is from 4 to 5 pounds of fuel an hour. The normal operating range is from 2½ to 7 pounds an hour.

Figures 6 to 17 show the detailed results obtained with the various heaters. The marked points indicated by crosses, triangles, circles, etc., show the estimated smokiness in pound-smoke units as calculated from four to ten light-interception readings taken at 40-second intervals while burning ½ pound of fuel at the rate indicated. Development of the automatic balance permitted a continuous determination of burning rates, so that smokiness could be determined for each minute as shown in figures 5 and 30. Where such continuous observations were made, they are shown on the smoke-test graphs by single checks (√). Each curve indicates the line of trend of smoke production as the burning rate is varied. The curve shown does not indicate the exact smokiness but merely the probable center of a band of variable width. It is to be expected that any single reading might deviate from the line of trend by as much as 25 per cent. Occasionally a reading may deviate to a much greater extent from the line of trend because of unstable burning conditions.

Effects of Incomplete Combustion.—The field trials at Pomona, supplemented by orchard observations and laboratory tests, indicate that many factors influence the smokiness of an oil burner, but that the only factor of great importance is the degree to which complete combustion is approached. If oil is completely burned the products will be carbon dioxide, water, and very small amounts of ash and sulfur dioxide. Substantially complete combustion occurs under the following conditions: (1) oil thoroughly atomized and mixed with the proper amount of air for combustion; (2) high combustion-chamber temperature to sustain combustion; and (3) combustion completed before the gases are chilled. The best conditions result in a blue smokeless flame. If there is a less favorable admixture of air with the combustible gases arising from the bowl of a heater the flame may be yellow and either smokeless or smoky. A flame is yellow because it contains particles of incandescent carbon which did not come into contact with enough oxygen for complete combustion at the instant of reaching the ignition temperature. Under favorable temperature conditions these particles may be consumed before leaving the flame and there will be practically no smoke. If such a flame is cooled many unburned carbon particles will escape to form smoke. For example, the flame from a kerosene lamp or a candle may be smokeless, though yellow, but if a cold object is held in the flame it will become coated with soot or if a puff of cold air disturbs the flame it will become smoky.

Smoke may be caused also by the cracking of the complex hydrocarbons at such a distance from the region most favorable to combustion that carbon atoms can agglomerate to form particles too large to be burned readily. ''Cracking'' is the name given to a process extensively used today for the purpose of breaking up the more complex hydrocarbons into the simpler ones, either in vapor or liquid phase. Fuel oil produces simpler hydrocarbons when heated between 525° and 650° F. A representative type of reaction for such a mixture might well be $C_{14}H_{30} + \text{heat} \rightarrow C_7H_{16} + C_6H_{14} + C$. During the cracking process, which occurs when oil vapors are superheated, the larger molecules are broken down, producing lighter hydrocarbons and leaving a residue of carbon. In the refinery the process is carried on in a still and the carbon is left in the still as a hard coke. In a heater partial cracking may take place if the oil vapors are sufficiently heated to break the molecules while the air supply is insufficient for complete combustion. Carbon resulting from cracking appears as soot accumulations in the bowl and stack or as smoke.

Smoke Tests of Open-Container Smudge Pots.—Figure 6 shows the performance of what are essentially open containers with no regulation except control of the size of the fire by sliding covers on or off. The oil is vaporized and burns at the surface, producing a flickering, smoky flame. Air is deficient in the mass of flaming gases and temperatures are favorable for some cracking. No. 13 has a short stack, which, however, has little effect, because the sliding cover permits free burning from the surface.

Smoke Tests of Short-Stack Heaters.—The next stage in the development of heaters was the addition of drafts for regulating burning rates. Heaters 10, 15, and 16 fall in this class. In addition they have short stacks, which also aid in controlling the burning rate. The stacks were intended to improve the combustion, but these heaters are little if any less smoky than open containers. The smokiness varied between 16 and 28 and averaged about 24 pound-smoke units.

Figure 7 shows the performance of short-stack heaters of larger capacity having down-draft tubes designed to concentrate a generating fire in a hot spot on the oil so as to facilitate burning the entire charge even though low-grade oil is used. Hamilton down-draft heaters of other models but similar to No. 19 were tested with results nearly like those shown on the diagram. The points determining the curves were obtained at air temperatures of about 90° F, and those indicated by checks at

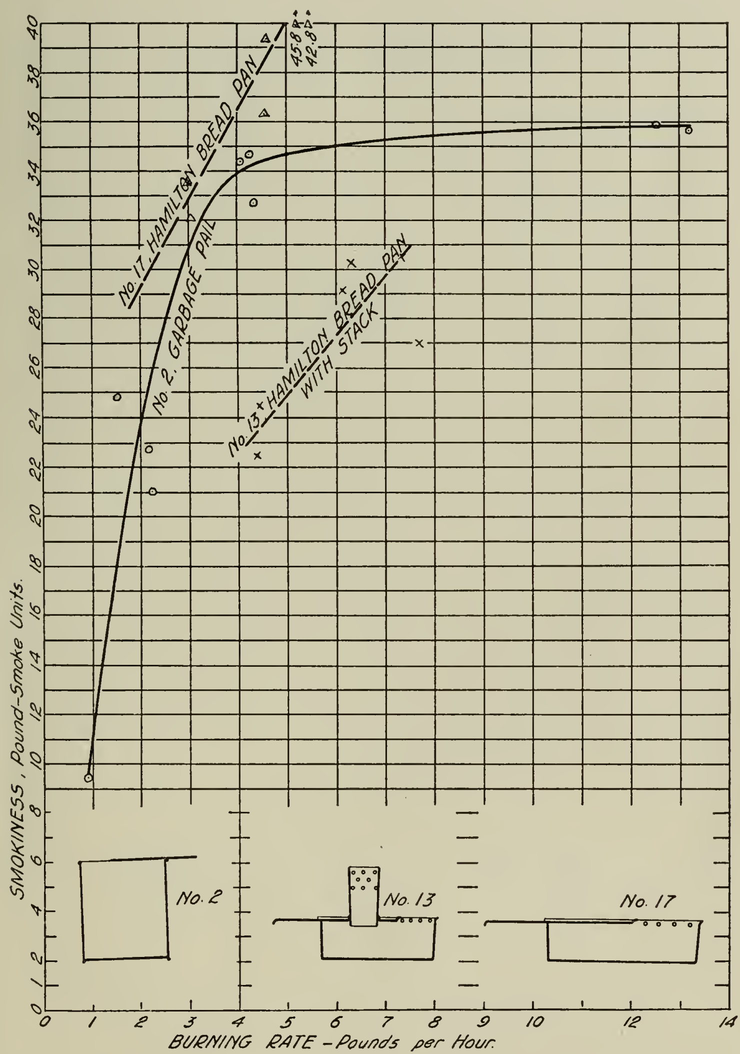


Fig. 6.—Smoke tests of open-container smudge pots, heaters 2, 13, and 17.

46° to 50° F. The determinations are too scattered to permit an accurate study of the effect of temperature, but they do show that the classification of the heater is not changed.

These heaters are more smoky than open containers. Apparently the nature of the combustion is such that more of the hydrocarbon gases are cracked and there is nothing in the construction to cause effective mix-

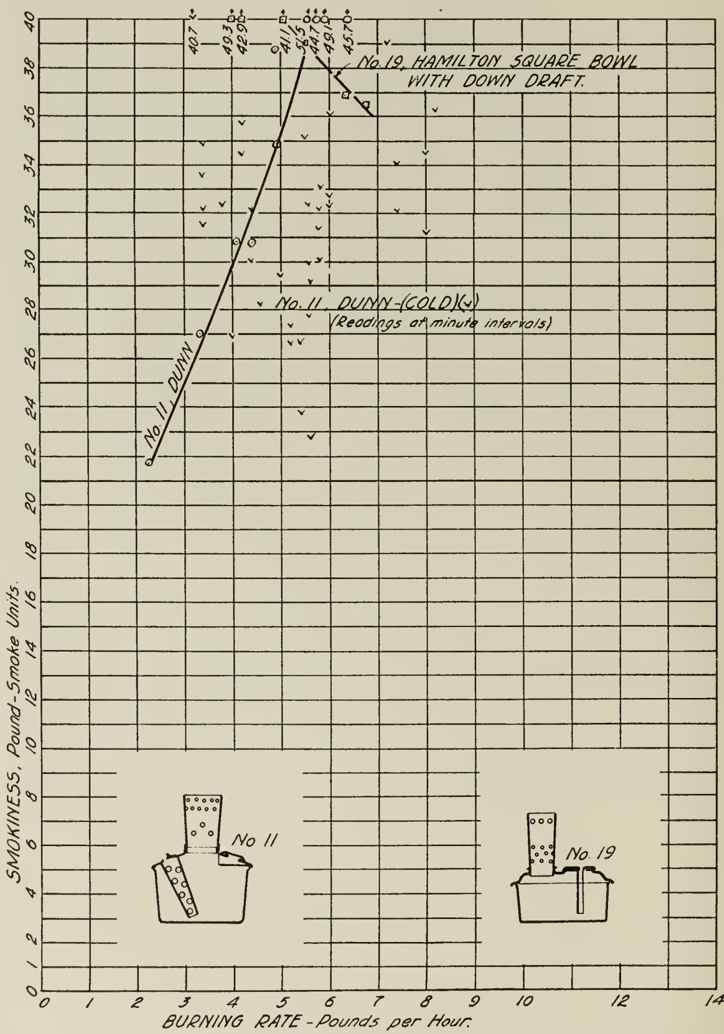


Fig. 7.—Smoke tests of short-stack orchard heaters, Nos. 11 and 19.

ing of air with the burning gases. In fact the air is admitted in such a manner that it probably chills the flame to below the most favorable combustion temperatures.

Figure 8 shows the performance of two models of Citrus heaters—the short-stub stack or Regular, and the perforated 15-inch stack. Warm and cold-weather tests are shown. From a smoke standpoint these

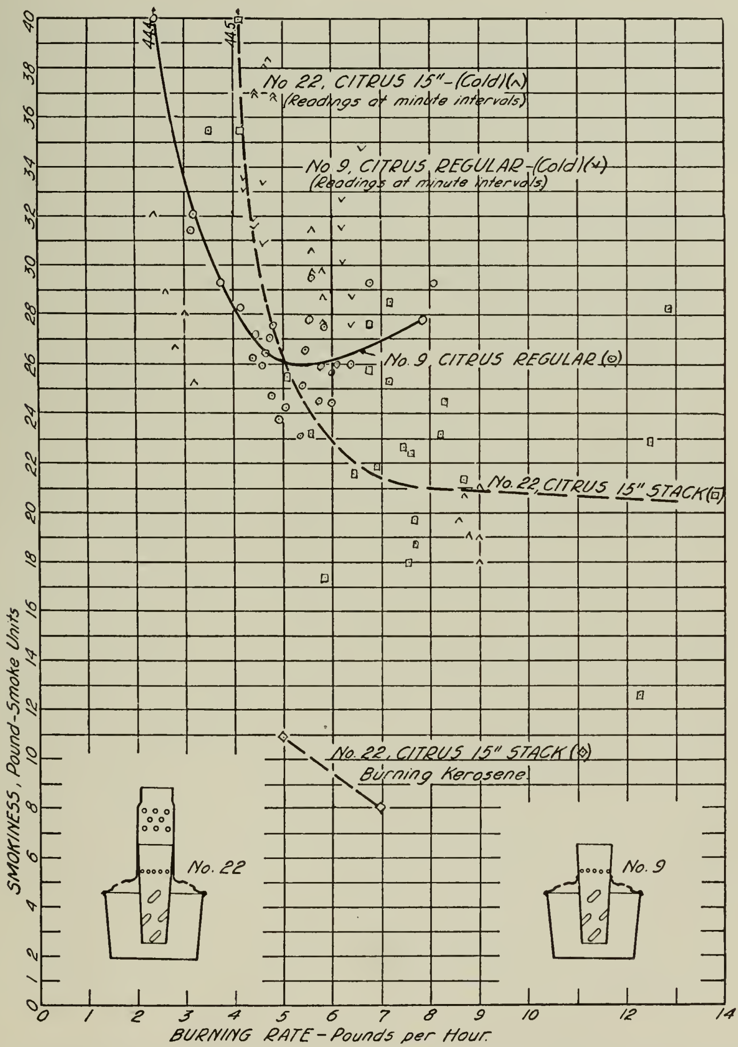


Fig. 8.—Smoke tests of Citrus Regular and Citrus 15-inch heaters, Nos. 9 and 22.

heaters are little better than ordinary smudge pots. The 15-inch stack increases the smokiness at low burning rates, probably because of stack temperatures more likely to cause cracking. It is to be noted that the use of kerosene reduced the smoke output to less than half the usual amount.

Influence of Stack Height on Smokiness.—In order to meet the demand for a tall stack and less smoky heater the manufacturers of the Citrus heater sold a top stack to be put on above the 15-inch stack. This

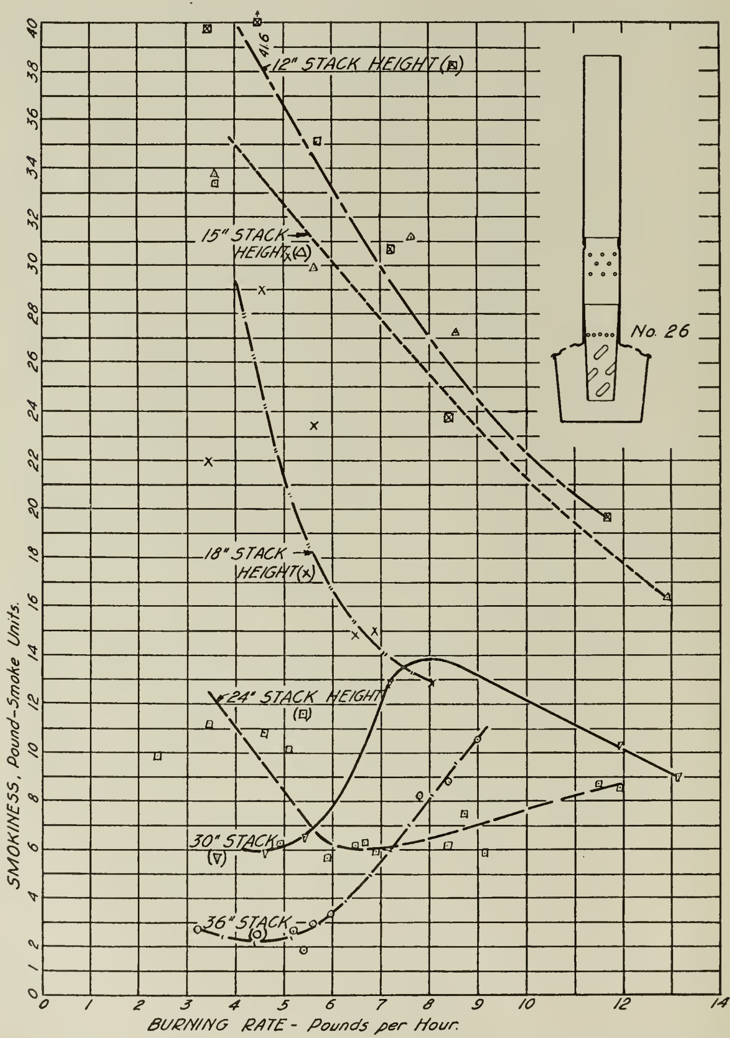


Fig. 9.—Influence of stack height on smokiness of Citrus high-stack heater, No. 26.

stack has been sold in 30, 24, and 18-inch lengths. Figure 9 shows the effect of stack height on this type of heater tested with various lengths of top stack varying from 12 to 36 inches.

The 12 and 15-inch top stacks do not produce enough draft to increase the air intake into the lower stack sufficiently to give improved combustion. On the contrary they promote cracking. The 18-inch top stack provides slightly better combustion than the 15-inch bottom stack alone. The 24-inch top stack improves combustion noticeably at low burning rates and gives reasonably good results at high rates. However, there seems to be some instability in the lower range, where a slight change in conditions causes cracking to take place and the smokiness may rise to as high as 35 pound-smoke units.

Many other heaters show unstable combustion at certain burning rates, the most pronounced effect being found in heater No. 7 (Citrus heater with Olsen Stack) in which the smokiness varied between 6 and 36 pound-smoke units with little change in burning rate and rose to 51 units during one test. Similar performance may be expected from the Apollo heater, which varies from scarcely visible smoke at 4 pounds an hour to 75 pound-smoke units at 5 pounds an hour.

The Citrus heater can be made fairly satisfactory by use of a 30-inch or 36-inch top stack above the 15-inch section. The stronger draft pull of the high stack draws in sufficient air for practically complete combustion over the burning range to 3 to 6 pounds of fuel per hour. These tall stacks can be used only on models of recent construction which have tight-fitting covers. The draft is so strong that burning rates cannot be controlled with heaters having loose-fitting covers. It is also difficult to extinguish the fires in these tall-stack modifications of the Citrus heater.

Smoke Tests of Open-Flame Heaters.—The open-flame stack (sometimes called "lazy-flame" stack) is very popular because of ease of lighting and regulation, the release of the hot products of combustion near the ground, and the low cost and depreciation. No stack parts are heated excessively. In this type the mixing of air and gases takes place in the stack and most of the combustion occurs at the top of the stack. The proportion of total heat in radiant-energy form is greater with the open-flame than with tall-stack heaters. Figure 10 shows the performance of the National Double Stack heater (No. 20) belonging to the open flame type. This stack is not very satisfactory in regard to smoke but it offers interesting possibilities, some of which are shown in the lower curves, which indicate the effect of introducing extra air at various points. These experiments with extra air were continued on newer types of open-flame stacks and will be discussed in another section.

Figure 11 shows the smokiness of a heater (No. 30) with a Junior Louver stack, an open-flame type, on both round and square bowls. Tests were made with clean and dirty stacks during warm and cold weather. The performances of these stacks on the two types of bowl are similar and there is little difference between the 15-inch and 18-inch heights. This type of stack, as well as the one shown in figure 10, admits just enough air along the stack to burn fairly well at a low rate, but at average rates and higher it tends to cause cracking, and consequently smokes.

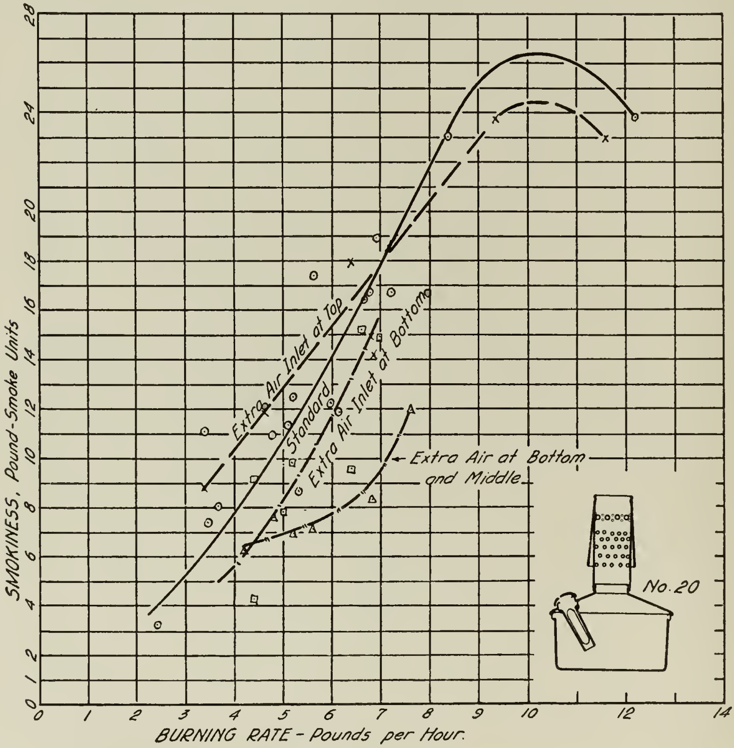


Fig. 10.—Smoke tests of National Double Stack open-flame orchard heater, No. 20.

Heater No. 27, the Citrus Gas Flame, was tested clean and dirty and with and without the baffle usually supplied with the bowl for use with this stack. With the baffle this heater will not operate practically in the field. Without the baffle its smokiness was above 20 pound-smoke units in tests at all burning rates.

Figure 12 shows the performance of the low-stack or open-flame models, heaters 4 and 23, manufactured by the Scheu Products Company. The stacks of these heaters have a great many small holes uniformly distributed from the top nearly to the bottom. As combustible gases rise in the stack, air is admitted through each hole and a small tongue of flame shoots from the hole into the stack. The remaining unburned gases burn with a smoky flame at the top of the stack. Some of the smoke is probably caused by cracking within the stack. The performance of this heater is greatly improved by a new bottom collar providing for air intake near the base of the stack.

Similar results were obtained with square-bowl heaters, No. 3 and No. 25, using the same stacks. The heaters manufactured by this com-

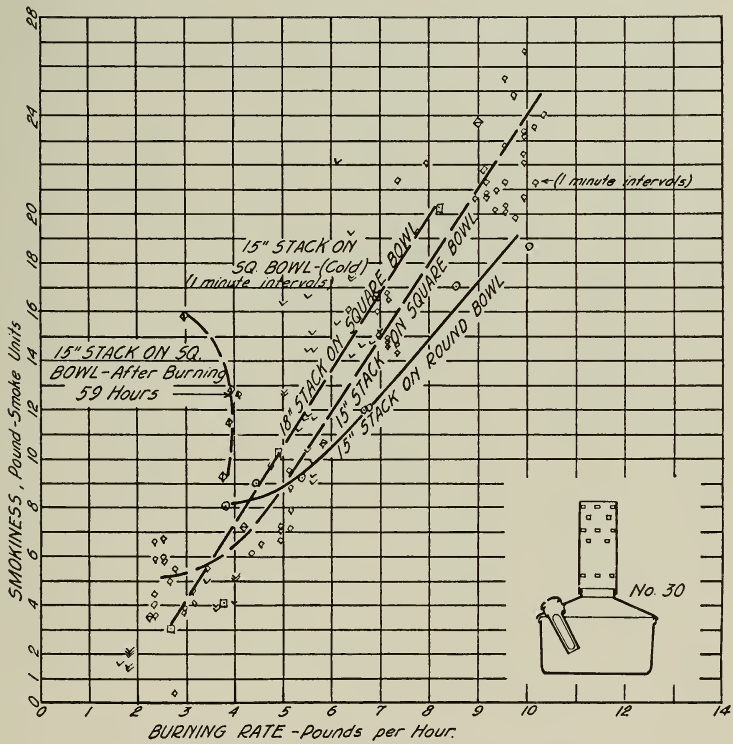


Fig. 11.—Smoke tests of National Junior Louver stack heater, No. 30.

pany have had numerous changes in attachments for improving combustion and gas generation within the bowl. Most of these have only a minor influence on smoke output. Lack of time has prevented a study of all the possible combinations.

Smoke Tests of Heaters with Straight Louvered Stacks.—Figures 13 and 14 show results with heaters having tall stacks with louvers in the lower section. Stack diameters range from 5 inches in No. 14 to 7 inches in No. 31. The curves represent the characteristics of each stack when properly cleaned. When the air intakes become partially clogged by soot the smokiness increases as shown by the upper curve for heater No. 34 (fig. 14). When this record was taken the soot accumulation had decreased the stack diameter to approximately that of heater No. 14.

A study of the curves and of the heaters in operation indicates certain causes for the performance as illustrated. In the case of heater No. 14 the smallest possible gas-generating fire in the bowl results in the

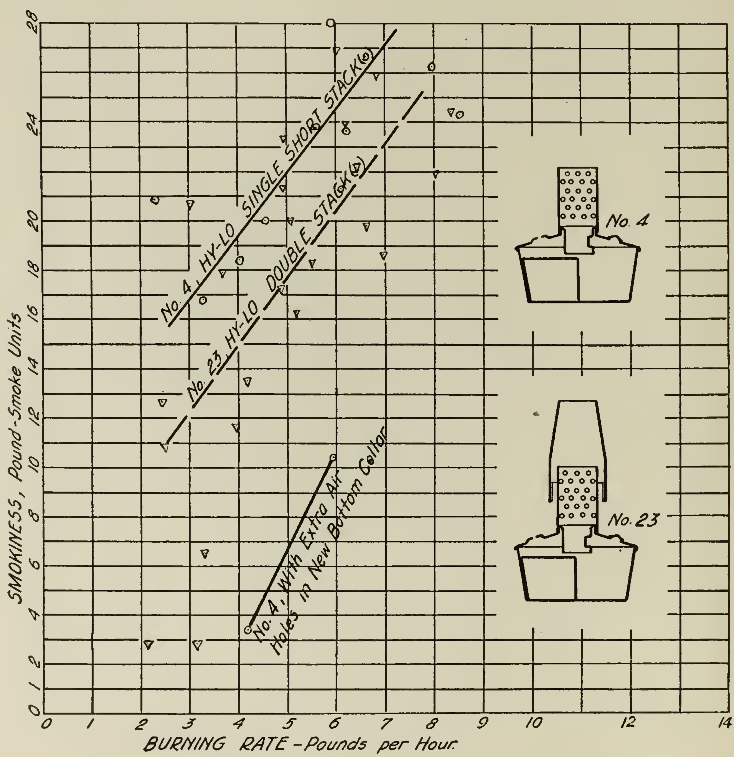


Fig. 12.—Smoke tests of open-flame heaters, Nos. 4 and 23, manufactured by the Scheu Products Company.

production of a hydrocarbon-air mixture too rich to burn in the small-diameter stack except at the topmost of the rows of louvers. The primary combustion at this point seems to crack part of the gases and cause a heavy smoke output. As the supply of combustible gases is increased a smaller percentage of the combustion occurs in the stack and less cracking takes place. There is also an increase in the secondary combustion above the top of the stack. As the heat is increased at this point some of the elementary carbon formed during the cracking is consumed and the smoke output decreases as the burning rate is increased. Stacks of diameter larger than 5 inches admit enough air to permit practically complete combustion in the louvered section at low burning rates. At the points where the air enters, the air-fuel mixture is lean enough to

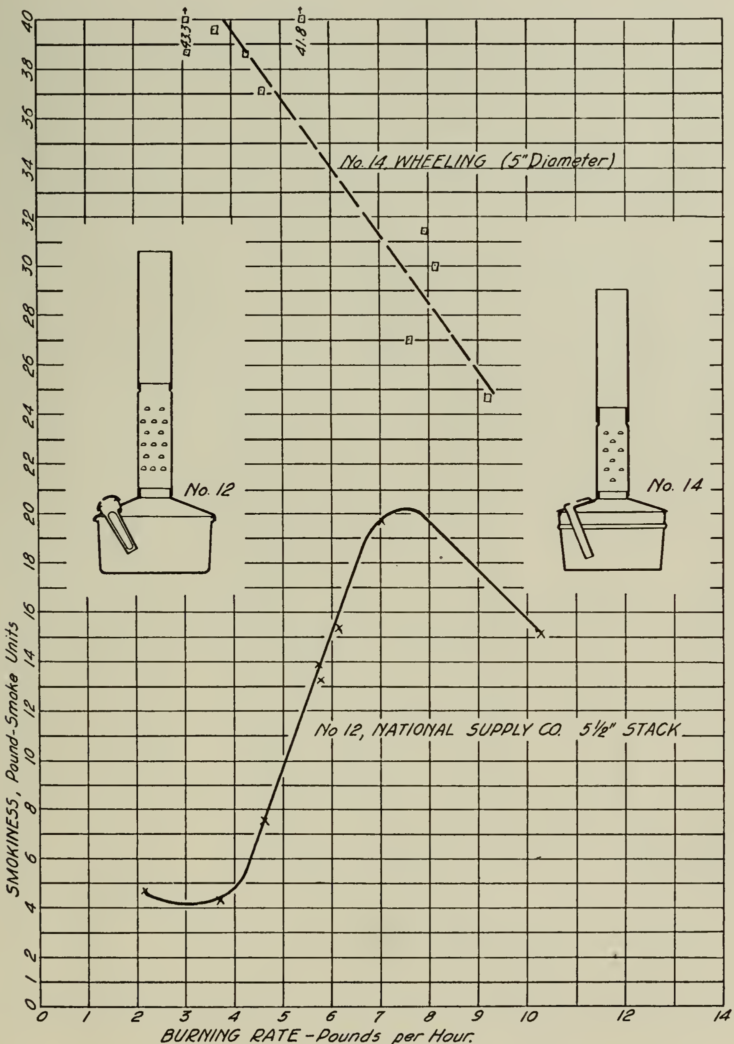


Fig. 13.—Smoke tests of 5 and 5½-inch louvered-stack heaters, Nos. 14 and 12.

burn explosively; growers call this "louvering." These small explosions increase turbulence and cause better mixing of air and gas, which improves the combustion. For each size of stack there is a burning rate at which the air-fuel ratio is satisfactory and combustion is apparently completed in the lower part of the stack. Under these specific conditions the smoke output is small. The range of burning rates over which air-

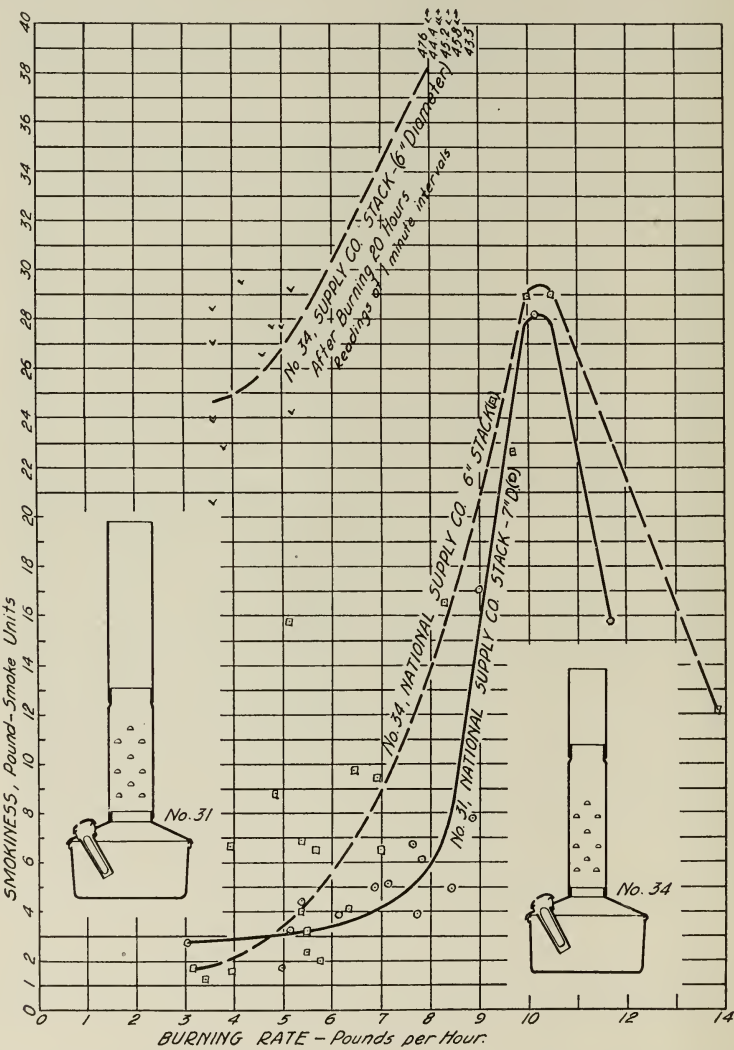


Fig. 14.—Smoke tests of 6 and 7-inch louvered-stack heaters, Nos. 34 and 31.

fuel ratios are reasonably satisfactory increases as the stack diameter is increased. With all stack diameters the smoke output increases rapidly as the generation of oil vapor in the bowl is pushed beyond the capacity of the combustion chamber, reaches a maximum, and then decreases coincidentally with the development of a secondary blaze at the top of the stack.

It is unfortunate that heaters of this type cannot be lighted without opening the drafts far beyond the amount required for normal burning. This results in excessive smokiness during the warming-up period and also perhaps later because of soot accumulation while burning at too high a rate. This same difficulty of lighting is experienced to a greater or less degree with all heaters of the lean mixture, explosive-fire type. Possibly this difficulty can be eliminated by the use of wicks to permit lighting with less draft opening.

It is apparent that heaters with straight louvered stacks are very erratic. They need careful draft regulation and frequent cleaning of stacks to give satisfactory performance. The best results are obtained when "louvering" takes place throughout the entire length of the louvered stack section. If No. 34 is burned without a top stack, "louvering" occurs at burning rates of 1 or 2 pounds an hour and the smokiness is about 4 pound-smoke units, but at a 3½-pound rate it is 36 units. With the top section on, however, "louvering" occurs at all rates between 2 and 6 or 7 pounds and good results are obtained as long as the heater is clean.

The worst over-all performance shown in any of the tests was that of heater No. 31 without a top stack. Apparently this type of stack permitted the greatest amount of cracking to take place. The smokiness at a burning rate of 3½ pounds an hour was as high as 65 pound-smoke units.

Smoke Tests of Cone-Combustion-Chamber Heaters.—Figure 15 shows the smokiness of heaters with louvered cone-shaped combustion chambers. It is similar to that with the louvered straight stacks. The National Baby Cone, heater No. 8, has a very narrow range of satisfactory air-fuel ratio. When the air supply becomes too limited there is a very sudden and steep rise in smoke output; this occurs at a 3-pound burning rate. Closing the top three rows of louvers, which can be done with a hammer, lowers the fire into the larger part of the cone and considerably improves the performance at usual burning rates. If the cone is altered in this manner a hot area develops at the top, which may result in rapid oxidation of the stack at high burning rates. The National Jumbo Cone, heater No. 1, with larger combustion chamber, is satisfactory over the entire normal operating range as long as it is clean. The upper curves show the smokiness of the same heater when using a dirty stack. The latter records were taken after burning about 14 gallons of fuel without cleaning the stack.

Smoke Tests of Hy-Lo 1929 Model Orchard Heater.—Figure 16 shows the performance of the Hy-Lo 1929 Model, heater No. 32. This heater usually gives satisfactory results over a wide range of burning

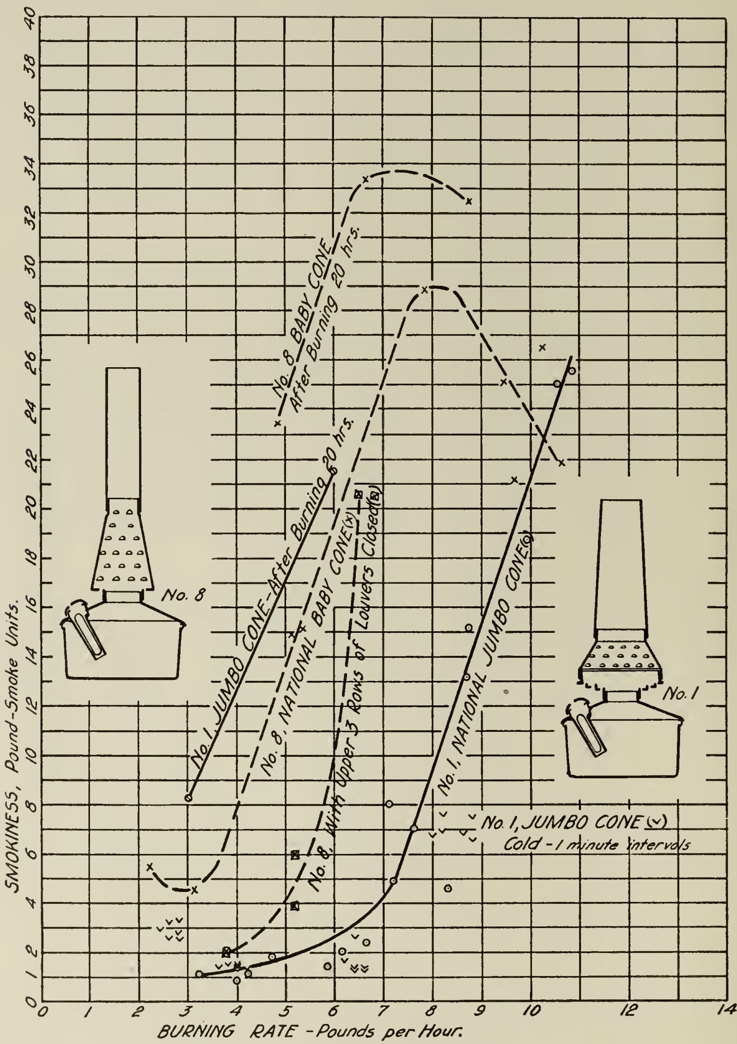


Fig. 15.—Smoke tests of cone-combustion-chamber heaters, Nos. 1 and 8.

rates as shown by the line of trend. At times it becomes very smoky, owing usually to having the fire jump back and burn at the holes in the base of the burner. When burning normally, combustion is of the explosive, lean-mixture type. This heater is the only one showing significant differences between warm and cold-weather tests. It was less smoky on the cold run. Figures 5, 24, and 25 give further test results on this heater.

Smoke Tests of "Nondistilling"-Type Orchard Heaters.—Figure 17 shows the performance of the separate-container or so-called "non-

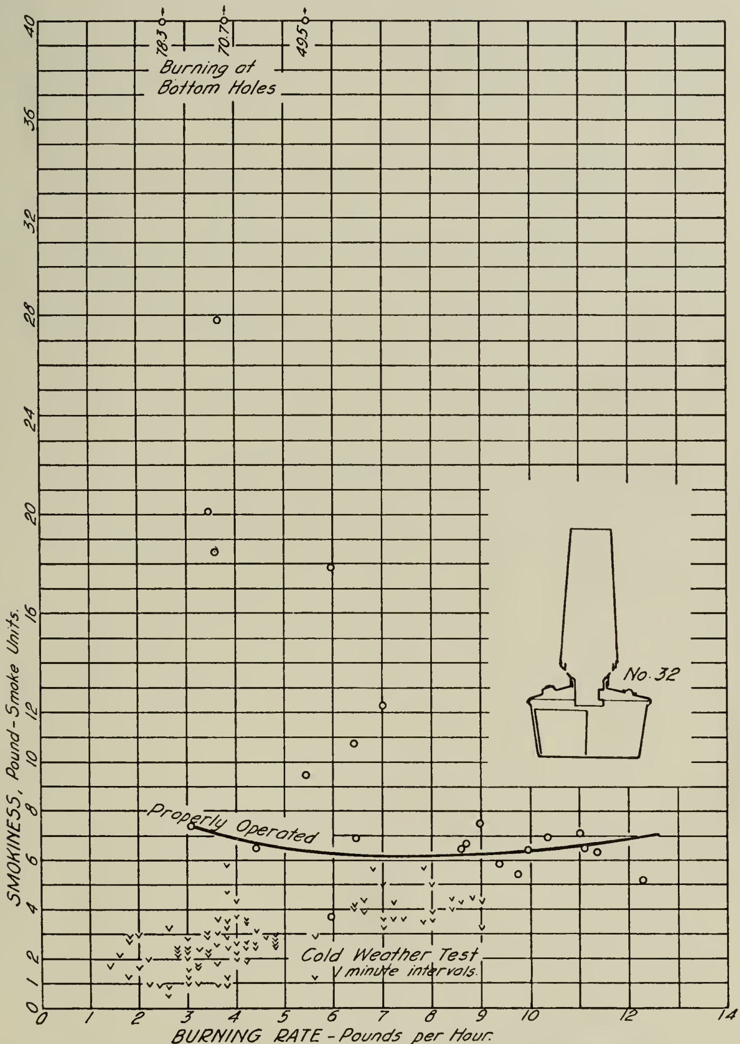


Fig. 16.—Smoke tests of Hy-Lo 1929 Model heater, No. 32.

distilling" type of heater. This type differs from the distilling types in burning fresh oil of constant composition. Kittle, heater No. 6 (gravity feed), and Fugit, No. 29 (pressure feed) require an oil of higher grade than that commonly supplied for other orchard heaters. In both of these heaters, gas is generated from the oil in a hot burner and combustion is completed at the point of gas generation without any opportunity for

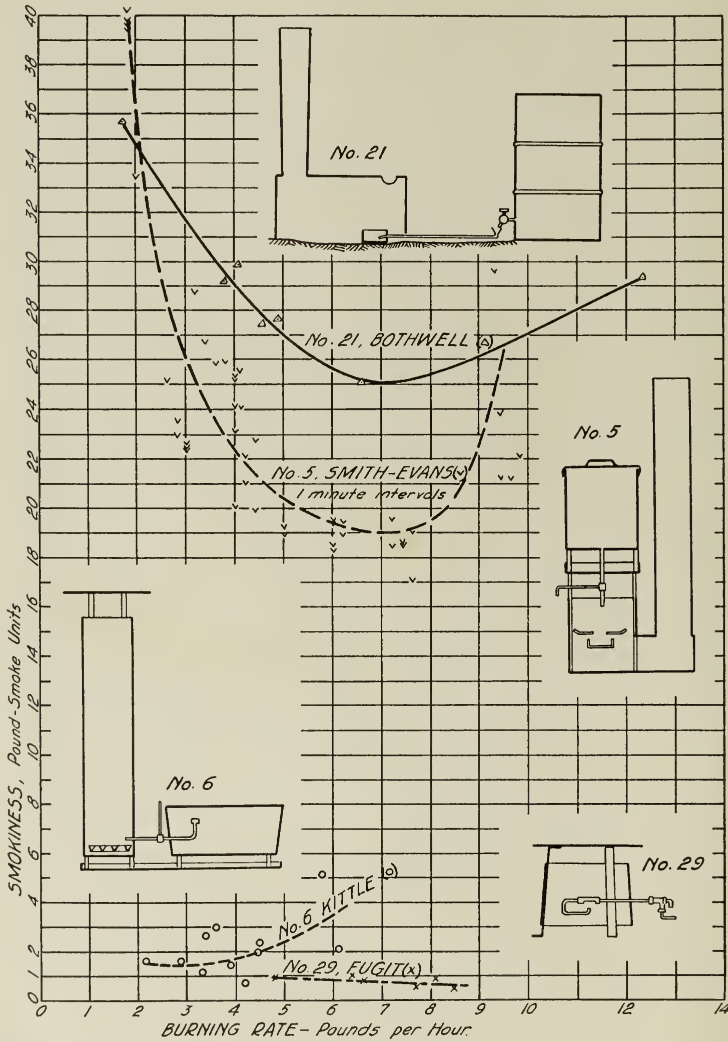


Fig. 17.—Smoke tests of "nondistilling"-type heaters, Nos. 5, 6, 21, and 29.

cracking to take place. Results are very satisfactory under proper operating conditions. No. 6 becomes smoky if the oil is fed too rapidly for the capacity of the burner.

Smith-Evans, heater No. 5, and Bothwell, heater No. 21, are similar in general design. They both drip oil onto a hot plate in a burner which admits insufficient air. A type of combustion takes place which results in considerable cracking. It is apparent that in addition to smoke these heaters discharge some unburned gases, but the quantities are not great enough to cause more than intermittent blazes at the top of the stack. It would appear that burner and stack design are more important in preventing smokiness than the method of supplying oil to the burner.

GENERAL DISCUSSON OF RESULTS

The tests show that there is great variation in the smokiness of orchard heaters, the range being from less than 1 pound-smoke unit to more than 60 at a burning rate of 5 pounds of fuel an hour. An individual heater varied from as low as 4 pound-smoke units to as high as 46 at this burning rate, the increase being due to sooting up of the air passages. Heaters vary considerably in smoke output as the burning rate is changed, usually producing more smoke as the burning rate is increased until the secondary combustion at the top of the stack becomes effective. Also when the burning rate is reduced below the critical point the smokiness usually increases, partly because the longer time consumed in burning a pound of fuel increases the accumulation of soot measured.

The tests so far conducted probably represent the best the heaters can do with the fuel used. The heaters were always cleaned before starting the regular test, filled to an average level with clean oil and placed level; covers were made tight, and drafts properly set. Furthermore, they were under constant observation while burning and were shielded from breezes. No extended studies have been made of any one heater. Repeated tests while changing only one variable at a time, such as the oil level, would probably aid in determining the exact causes of smoke production in each case.

However, a study of the results indicates the validity of certain conclusions as follows:

1. Smokiness is governed to a large extent by the design of the stack. In several tests the same stack on different bowls with different draft devices showed substantially the same characteristic.

2. The influence of air temperature on smokiness is slight and it may be expected that laboratory or summer field tests usually will be comparable with winter field tests.

3. Accumulation of soot in the heaters has no consistent influence on smokiness except on heaters having tall stacks either with or without combustion chambers. Soot accumulations in such stacks and combustion chambers greatly increases the smokiness. The smokiness of low-stack smudge pots and of open-flame heaters is not greatly influenced by soot. The principal effect is a decrease in burning rate, which may continue to the point of practically extinguishing the heater. This effect is particularly pronounced in the Citrus heaters.

4. It is possible to burn a relatively crude fuel in a very simple, inexpensive orchard heater and keep the smokiness below the level of ordinary visibility.

A *B* *C* *D* *E*

Fig. 18.—Standard heaters reasonably free from smoke: *A*, heater No. 1, National Jumbo Cone; *B*, No. 6 Kittle; *C*, No. 29, Fugit; *D*, No. 31, National, Exchange model, 7-inch stack; *E*, No. 32, Hy-Lo 1929 model.

5. Unburned carbon and hydrocarbons given off in the smoke amount to a direct fuel loss of 16 per cent in some cases and probably would average 5 per cent for all the heaters now in use. It is not correct to judge the efficiency of combustion by the blackness of the smoke because of the presence of invisible combustible carbonaceous matter. However, with the usual orchard heater the loss of unburned fuel can be considered below 1 per cent when the smoke output is not visible.

Heater Groups According to Smokiness.—It appears logical to divide the standard heaters tested into the following four groups:

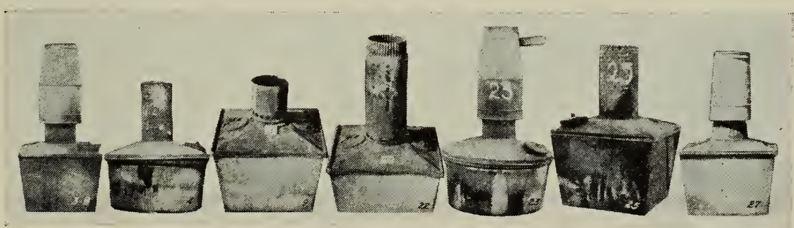
1. Heaters 1, 6, 29, 31, and 32 (fig. 18), which are reasonably free from smoke at all burning rates under good operating conditions.

2. Heaters 8, 12, 20, 26, 30, and 34 (fig. 19), which can be operated with little smoke up to burning rates used in moderately cold weather, but which may produce excessive smoke under certain conditions.

A *B* *C* *D* *E* *F*

Fig. 19.—Photographs of standard heaters which can be nearly smokeless at certain low burning rates: *A,* heater No. 8, National Baby Cone; *B,* No. 12, National Exchange model, 5½-inch stack; *C,* No. 20, National Double Stack; *D,* No. 26, Citrus, high stack; *E,* No. 30, National Junior Louver, 15-inch; *F,* No. 34, National Exchange model, 6-inch stack.

3. Heaters 3, 4, 9, 22, 23, 25, and 27 (fig. 20), which are smoky but commercially important. Nos. 3, 4, 23, 25, and 27 can be operated so as to give results similar to those in group 2, but they are erratic and as burned in the field usually would be much worse than the group 2 heaters.



A *B* *C* *D* *E* *F* *G*

Fig. 20.—Photographs of standard heaters which are smoky but commercially important: *A,* heater No. 3, Hy-Lo Double Stack, square bowl; *B,* No. 4, Hy-Lo, single short stack, round bowl; *C,* No. 9, Citrus Regular; *D,* No. 22, Citrus, 15-inch stack; *E,* No. 23, Hy-Lo Double Stack, round bowl; *F,* No. 25, Hy-Lo, single short stack, square bowl; *G,* No. 27, Citrus Gas Flame.

4. Heaters 2, 5, 7, 10, 11, 13, 14, 15, 16, 17, 18, 19, and 21 which are very smoky but which are mostly of obsolete types.

Estimate of the Number and Smokiness of Heaters in Use.—The Fruit Frost Service of the United States Weather Bureau completed in June, 1932, a survey of the numbers and types of orchard heaters now being used by citrus growers.[15]

According to these estimates the 2,900,000 oil-burning heaters may be classified into distinctive groups and the smoke output estimated from a study of the test data as follows: about 1,350,000 heaters believed to be of such a type that the smokiness will average around 12 pound-smoke units at a burning rate of 5 pounds an hour; 50,000 with an average smokiness of 4 pound-smoke units at the 5-pound burning rate; and 1,500,000 with an average smokiness of 28 pound-smoke units.

Of the 1,500,000 heaters averaging 28 pound-smoke units, 500,000 are of such a type that it will be difficult to reduce the smoke output. Most of these are obsolete heaters of very little value. This figure includes approximately 55,000 garbage pails, which can be used for orchard storage of oil. These heaters should be replaced by others having a smoke output of 8 pound-smoke units or less over the normal operating range. The remainder of the smoky heaters consist mainly of about 200,000 Dunn heaters and about 800,000 Citrus heaters with short or 15-inch stacks. It is believed that stacks can be put on all of these at a relatively small expense and the smoke output can be brought below 8 pound-smoke units.

If changes as indicated were made and if the 1,350,000 heaters mentioned above as averaging 12 pound-smoke units were cleaned regularly and adjusted so as to cut the smoke output down to an average of 8, the total smoke output of the community might be cut to less than half its present amount.

It should be pointed out that the smoke nuisance will not be eliminated until it is feasible to keep the smoke production of all heaters below the limit of visibility. This limit is from 3 to 5 pound-smoke units at a burning rate of 5 pounds an hour. If a pound-smoke unit be considered equal to 1 gram of smoke carbon, such a limit would still allow smoke particles to be discharged from an orchard heater at the rate of 0.4 grams a minute at the above average burning rate.

Operation Methods for Reducing Smoke Output.—It is evident that considerable improvement in smoke production may be obtained by grower cooperation without the necessity of turning to other fuels or the purchase of large quantities of new and expensive equipment.

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[15] Unpublished data furnished to the Orchard Heating Improvement Committee by Floyd D. Young, Senior Meteorologist, United States Weather Bureau.

The most important suggestions for growers are:

1. Not to burn oil in open pails and other obsolete heaters such as most of those manufactured prior to 1915. Figure 6 shows the performance of heaters in this class.

2. Clean soot from stack and drafts, particularly of heaters with combustion chambers or louvered stacks. Figure 21 shows how drafts and stacks become clogged. Frequently stacks become sooted up during the warming-up period.

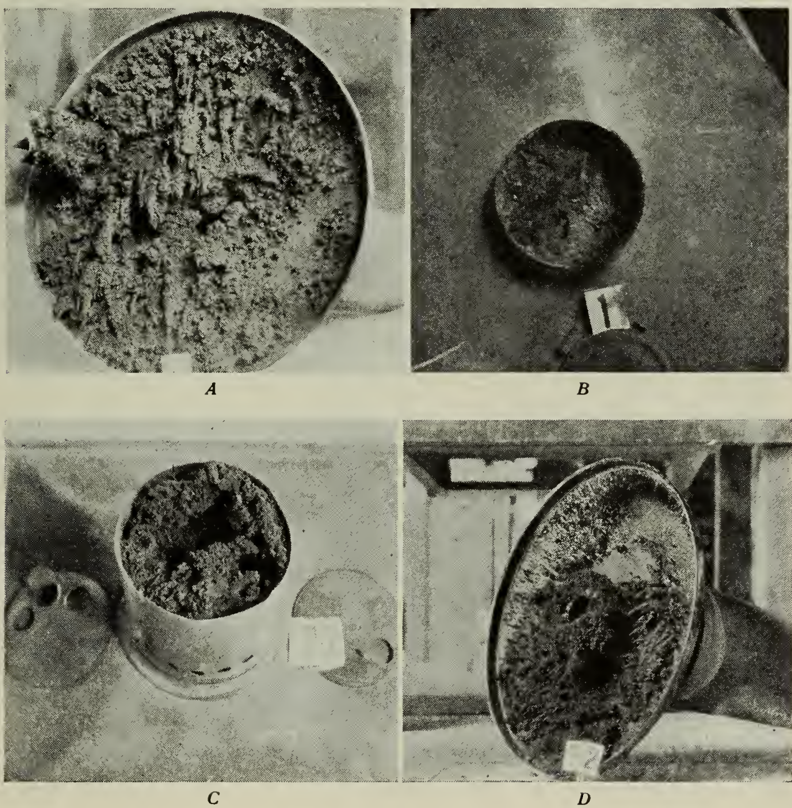

Fig. 21.—Photographs of soot collection on covers and stacks of orchard heaters: *A*, on underside of cover of heater No. 1, National Jumbo Cone; *B*, in throat of heater No. 1, National Jumbo Cone; *C*, in throat of heater No. 22, Citrus 15-inch stack; *D*, around thimble in heater No. 32, Hy-Lo 1929 model.

3. Regulate heaters systematically so as to maintain the best combustion rate for each type of heater. Figure 22 shows how smokiness varies as burning rate is changed. Most heaters smoke more at high rates.

4. Study the recommendations of the Fruit Frost Service of the United States Weather Bureau with regard to temperatures at which to begin to light heaters. Have an adequate supply of tested and properly sheltered thermometers. Be careful not to burn more oil than is necessary to maintain safe temperatures.

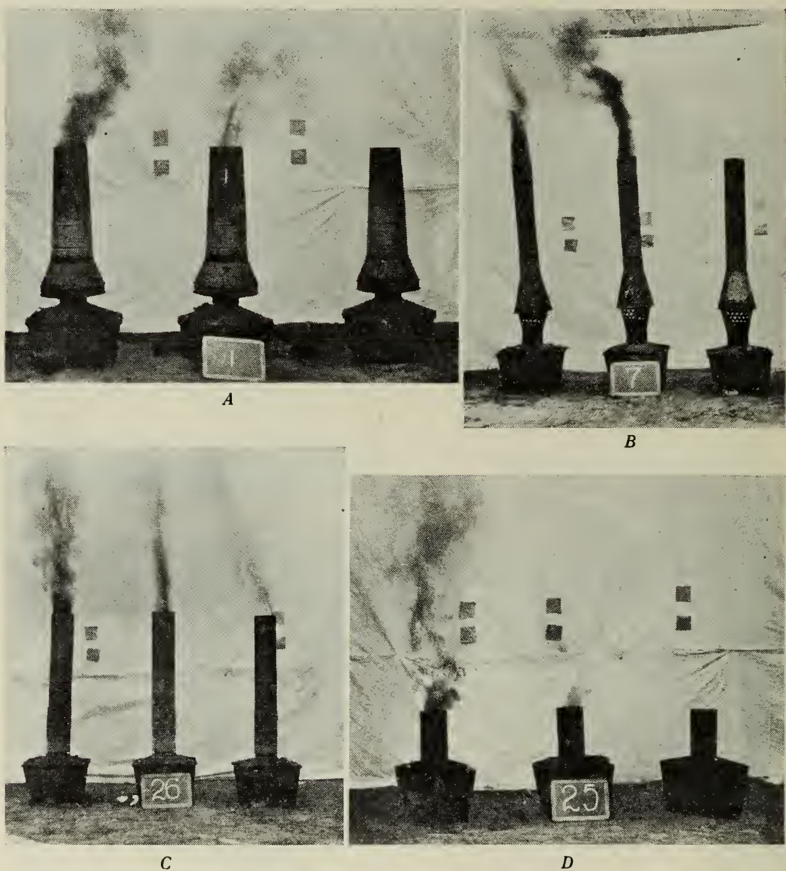

Fig. 22.—Photographs of smokiness at different burning rates: *A*, heater No. 1, National Jumbo Cone; *B*, No. 7, Citrus, Olsen Stack; *C*, No. 26, Citrus, high stack; *D*, No. 25, Hy-Lo, single short stack, square bowl.

TEST RESULTS WITH DIFFERENT FUEL OILS

The Fruit Growers Supply Company has found that it is not feasible to place rigid specifications on the oil used for orchard heating. Growers have storage facilities for 35,000,000 gallons, which is only a little more than enough for one filling of the heaters. Therefore they have to buy on short notice grades of oil normally carried in storage at the refineries.

The oil formerly used was a straight-run distillate of from 32° to 34° Baumé gravity. At present no regular cut is made between Diesel engine fuel oil of 27°+ and kerosene base of 38° to 40° Baumé gravity. Most growers use the Diesel engine fuel. During rush periods it is the only satisfactory fuel oil available in large quantities because kerosene base is not normally carried in storage by the refineries. However, there is some opportunity to choose between various lots of Diesel fuel. The specifications ordinarily used are:

1. Sulfur content less than 0.75 per cent (some samples have shown as high as 3 per cent but the normal content is about 0.25 per cent).
2. Carbon residue less than 0.50 per cent.
3. Pour point below 15° F (some samples have run from 30° to 40° F pour point).

TABLE 2

SOURCE OF OILS USED IN STANDARD TESTS

Oil No.	Description and source	Amount used
1	Kittle fuel as used in Los Angeles County (Pomona)	Sample
2	Orchard heater fuel used in Los Angeles County (Pomona)	Sample
3	Orchard heater fuel—30 gravity—Woodland	100 gals.
4	Orchard heater fuel—30 gravity—Cooks Oil Co., Emeryville. Delivered from Suisun, California	100 gals.
5	Orchard heater fuel—35 gravity—Cooks Oil Co., Emeryville. Delivered from Suisun	35 gals.
6	Orchard heater fuel—30 gravity—Cooks Oil Co., Emeryville. Delivered by Sheldon Oil Co., Suisun	100 gals.
7	Orchard heater fuel—30 gravity—Cooks Oil Co. Shipped from Emeryville, 9-9-31	200 gals.

TABLE 3

ANALYSES OF HEATER OILS*

Oil No.	Flash point (Cleveland Open tester)	Viscosity (Saybolt Universal 100° F)	Distillation test			Pour point	Carbon residue (Conradson method)	Sulfur† (Parr Sulfur Bomb)
			10 per cent over at	90 per cent over at	End-point			
	°F	*sec.*	*°F*	*°F*	*°F*	*°F*	*per cent*	*per cent*
1	149	36	395	495	510	Below 12	0.047	0.62
2	230	43	435	615	627	Below 12	.301	57
3	158	33	360	490	515	Below 12	.020	.26
4	195	39	405	620	632	Below 12	.160	.43
5	222	40	444	616	630	Below 12	.075	.47
6	190	39	400	600	622	Below 12	.283	.49
7	221	43	438	640	652	Below 12	0.028	0.53

* Analyses reported by H. W. Allinger, Division of Chemistry.

† Corrected for NaCl occlusion.

TABLE 4

ANALYSES OF ORCHARD-HEATER OILS BEFORE AND AFTER BURNING*

Oil No.	Burned in heater No.	Gravity at 60° F	Flash point	Fire point	Asphalt	Wax	Carbon	Sulfur	Viscosity: At 100° F	Viscosity: At 25° F	Pour point	Water	Sediment	Distillation test: Initial boiling point	Distillation test: 10% over at	Distillation test: 95% over at	Distillation test: End point	Distillation test: Recovery	Oil used	Residue after burning: Amt.	Residue after burning: Per cent	Average burning rate
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
		°API	°F	°F	per cent	per cent	per cent	per cent	secs	secs	°F	per cent		°F	°F	°F	°F	per cent	lbs.	lbs.	per cent	lbs. per hour
1	Before burning	33.7	190	230	0.07	0.97	0.12	0.47	38	74	−10	0	T‡	420	458	680	718	98.0	...	...	...	...
	9	...	...	...	0.12	5.00	0.37	...	...	...	+40	...	T	460	508	720	¶	¶	86.00	25.25	29.4	5.00
	22	...	...	...	0.14	4.43	0.34	...	...	...	+35	...	T	452	495	722	¶	¶	86.00	33.00	38.4	3.98
	20	...	...	...	0.15	4.72	0.37	...	...	...	+40	...	T	448	494	721	738	98.0	86.00	38.00	44.2	3.65
	1	...	...	...	0.20	4.27	0.48	...	...	...	+40	...	T	465	527	714	¶	¶	86.00	21.75	25.3	5.47
2	Before burning	30.3	...	...	T‡	0.49	0.05	...	40	90	+15	0	T‡	434	508	657	693	99.0	...	...	...	...
	9	...	...	...	0.07	3.49	0.42	...	...	...	+35	...	T	480	530	702	727	98.0	87.25	20.50	23.5	4.95
	22	...	...	...	0.04	3.41	0.37	...	...	...	+35	...	T	494	528	705	726	98.0	87.25	22.00	25.2	4.28
	20	...	...	...	0.06	3.38	0.36	...	...	...	+35	...	T	480	520	702	716	98.0	87.25	26.00	29.8	3.95
	1	...	...	...	0.11	4.02	0.43	...	...	...	+35	...	T	486	521	705	718	98.0	87.25	19.00	21.8	5.81

* Analyses made by Smith-Emery & Co., Los Angeles, through the courtesy of the Fruit Growers Supply Co. Order No. X1487.
‡ T=trace.
¶ Cracked.

Tests used in determinations:
Col. 2: Pensky-Martens Closed Cup A.S.T.M. D93-22.
Col. 3: Cleveland Open Cup A.S.T.M. D92-24.
Col. 4: Holde test.
Col. 5: Kansas City Testing Laboratory method.
Col. 6: Conradson test, A.S.T.M. D189-27T.
Col. 7: Bomb test A.S.T.M. D129-27.
Cols. 8 and 9: Saybolt Universal Viscosimeter, A.S.T.M. D88-26.
Col. 10: A.S.T.M. D97-28.
Col. 11: A.S.T.M. D95-27.
Col. 12: By extraction; after burning; filtered sample.
Cols. 13-17: A.S.T.M. D158-28.

Analysis of Oils Used in Tests of Standard Heaters.—In testing the smokiness of standard heaters an average grade of 30° Baumé gravity orchard-heater oil was used. It was not possible to reorder the fuel oil as required and receive exactly the same kind used in the previous tests. Table 2 shows the source of the oils used in the standard tests and table 3 shows the analyses. Oils 3, 4, and 6 have been used in most of the tests except for the Kittle and Fugit heaters in which oil No. 5 was used. Kerosene was burned in a few tests (see fig. 8) and was shown to produce considerably less smoke than ordinary orchard-heater oil.

It was noted in connection with the tests of standard heaters that when return was made to a given burning rate after operating several hours at various other rates, the smokiness reading was approximately the same as earlier in the run, indicating that smokiness was not changed appreciably as a result of changes taking place in the oil as burning progressed.

Analyses of Oils Before and After Burning.—Specific data on the changes in two oils after burning are shown in table 4. Four heaters were used and the oils analyzed before and after burning down to residues of approximately 0.2 to 0.4 of the original weight. The composition changes in the oil as a result of burning were marked but were less than the natural differences occurring between the various fuel oils available to growers. It is to be noted that the original pour points (–10° F and +15° F) of the two oils both rose to 35–40° F, and the initial boiling points rose on the average 36° F and 51° F, respectively. Furthermore, the percentages of wax and Conradson carbon residue were increased to a greater value than can be accounted for by the reduction in oil volume due to burning.

TABLE 5

SOURCE OF OILS USED FOR TESTING INFLUENCE OF OIL CHARACTER ON SMOKINESS

Lot No.	Gravity, ° Baume	Source
20	30	Blended from Standard Oil Co. 27°+ and 32°+, Cooks Oil Co., Emeryville
21	32+	Standard Oil Co., El Segundo
22	27+	Standard Oil Co., El Segundo
23	27+	General Petroleum Corporation
24	27+	Shell Oil Co.
25	30+	St. Helen's Petroleum Corporation
26	27+	Union Oil Co.

Analyses of Oils Used for Testing Influence of Oil Character on Smokiness.—Six lots of oil were furnished by the Fruit Growers Supply Company for testing the influence of the chemical and physical characteristics of the fuel oil on smokiness. These were compared with oil

TABLE 6

ANALYSES OF OILS USED FOR TESTING INFLUENCE OF OIL CHARACTER ON SMOKINESS

Oil No.	Flash point (Cleveland Open tester)	Viscosity (Saybolt Universal 100° F)	Engler distillation test*			Pour point	Carbon residue (Conradson method)	Sulfur†
			10 per cent at	90 per cent at	End point			
	°F	*sec.*	*°F*	*°F*	*°F*	*°F*	*per cent*	*per cent*
20‡	181	39	382	580	620	Below 12	0.305	0.209
21	180	36	380	560	600	Below 12	.027¶	.125
22	228	44	450	590	600	Below 12	.034¶	.188
23	243	49	485	650	680	30	.375	.151
24	206	37	420	540	550	Below 12	.081	.433
25	245	44	475	630	645	12	.028	.298
26	190	37	410	560	600	Below 12	0.213	0.302†

* On distilling No. 23 the condensed distillate congealed between 80 and 90 per cent, and on No. 25 between 86 and 90 per cent.

† Sulfur determined from oxygen bomb rinsings following calorific valve determinations at Berkeley. The sulfur on No. 26 is an estimate made from part of the rinsings.

‡ Analyses made by H. W. Allinger.

¶ Carbon residues analyzed by W. B. Dye.

TABLE 7

VACUUM DISTILLATION RANGE AND HEAT VALUES OF ORCHARD-HEATER OILS NOS. 20 TO 26

Per cent over	No. 20	No. 21	No. 22	No. 23	No. 24	No. 25	No. 26
	Vapor temperature, °F (pressure 10 mm mercury absolute)						
Start	108	125	173	185	160	170	156
5	160	160	228	234	194	232	184
10	180	176	244	254	204	250	194
20	212	192	260	284	216	268	206
30	234	208	270	304	226	278	216
40	250	220	279	320	235	290	224
50	258	230	290	338	248	300	234
60	264	246	308	......*	257	316	242
70	275	254	328	......*	268	336	254
80	312	280	......*	424	280	362	276
90	376	322	406	470	302	398	324
95	440	......*	444	518	326	434	352
End point	476	416	468	535	365	462	418
	Per cent recovery						
	97	98	99	96	98	98	98
	Heat values as B. t. u. per lb. (to an accuracy of ±25 B. t. u. per lb.)						
	19,000	19,200	18,800	19,050	19,300	19,700	19,100

* Determination uncompleted.

No. 20, which was used for most of the tests run during the winter of 1931–32. Table 5 shows the source of these oils.

These oils were carefully analyzed by the Division of Chemistry, according to the standard methods of the American Society for Testing Materials. The vacuum distillation range and heat values were determined by the College of Engineering. Table 6 shows the results of the oil analyses. Table 7 (plotted in fig. 23) gives the vacuum-distillation data and heat values.

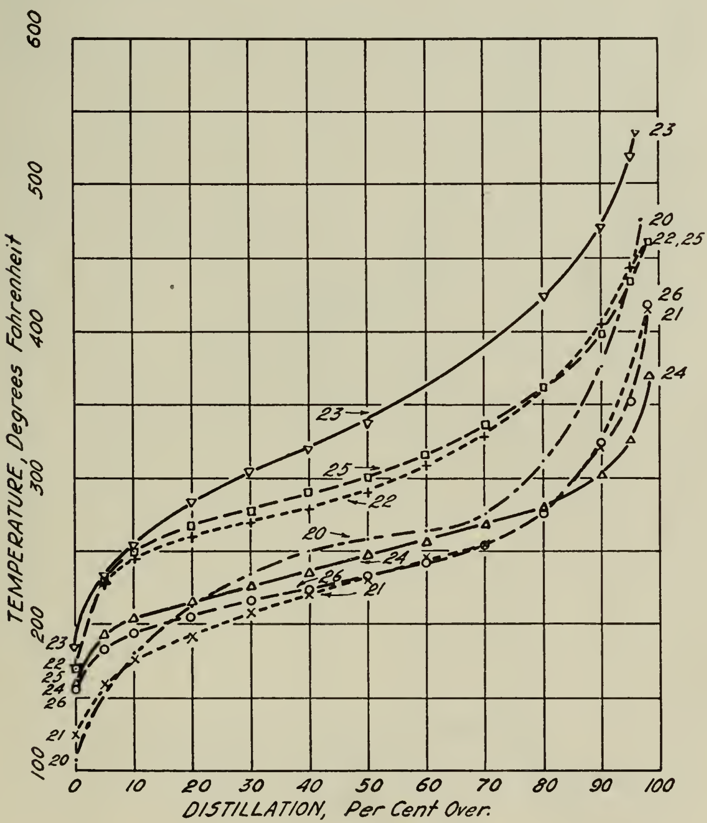

Fig. 23.—Vacuum distillation range of orchard-heater oils 20 to 26 inclusive (see table 7).

Method of Testing Influence of Oil Character on Smokiness.—Tests were run using heater No. 9, Citrus Regular, as typical of a smoky heater and No. 32, Hy-Lo 1929 Model, as typical of a relatively smokeless heater. These heaters were chosen because in the standard tests their smokiness had been exceptionally steady, which is of considerable advantage in determining small differences between fuels. The procedure in running the tests was as follows: Heaters were cleaned thoroughly between tests. Heater bowls were filled uniformly to a level 3 inches

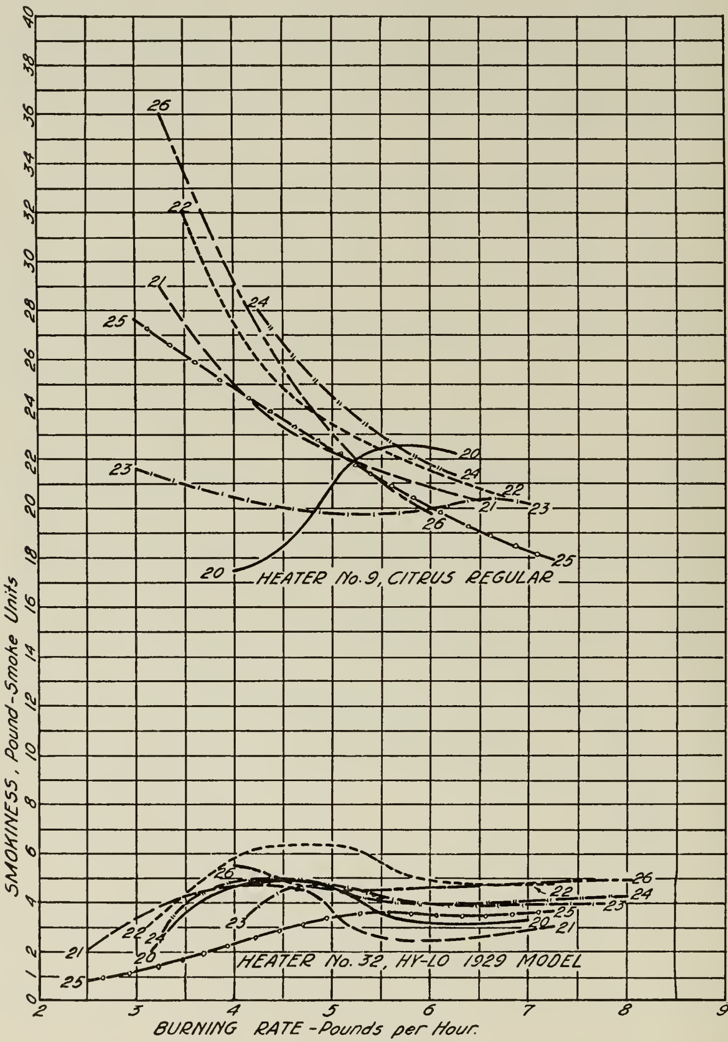

Fig. 24.—Influence of oil character on smokiness of heaters No. 9 and No. 32.

from the top at the start of each test. Each test included four burning rates. At the beginning of a test the heater was warmed up by burning at a high rate and then reduced to a rate of 3 pounds an hour or less. When the burning rate had become steady twenty-five or more readings of smokiness and weight change were taken at one-minute intervals. Then the drafts were opened, and aftér conditions became steady the tests were repeated for each of the three other burning rates.

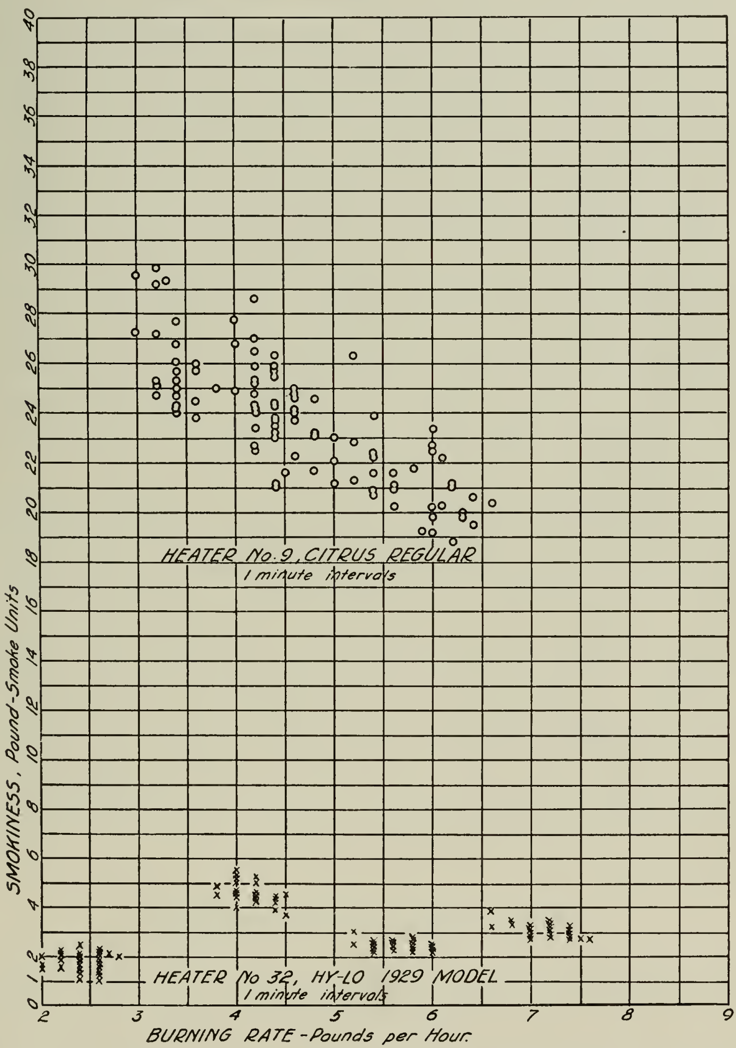

Fig. 25.—Smoke-test observations of heaters No. 9 and No. 32, burning oil No. 21

Variation of Smokiness Not Consistent with Oil in Different Heaters. —Figure 24 shows the results of the oil studies. The curves are based on averages of ten consecutive smokiness determinations for each burning rate. Figure 25 indicates the spread of the individual smokiness determinations for oil No. 21. This figure shows results typical of those obtained with the other oils. The scale of burning rate used in figures 24 and 25 is twice that used in reporting the standard tests. The oil test results indicate some difference between fuels, especially with heater No. 32, in which the smokiness from the best oil is about half that from the poorest. This degree of variability is present over the full range of burning rates but the individual oil curves cross so that there is no consistent variation between any two oils. This difference has little real value as the worst smoke was scarcely visible from this heater. When the normal spread of individual determinations is taken into consideration it can scarcely be said that the character of the oil, within the range shown by the analyses, had a significant influence upon the smokiness of either of the heaters used in these tests. This is especially true if cross comparisons are made between the two heaters. Oil No. 20, which gave the least smoke in heater No. 9 at low burning rates and the most smoke at high rates, was about average throughout the whole range in heater No. 32. Oil No. 25, which was the best in heater No. 32, was about average in No. 9.

Conceivably the divergence of the curves for heater No. 9 at low burning rates and the departure of several oils from the general performance curve for this heater as shown in figure 8 are partially caused by different rates of soot accumulation. Observations in the field and laboratory indicate that new heaters or ones which have been very thoroughly cleaned do not display their normal smokiness immediately after lighting. Probably, then, the warming-up period before the low-burning-rate tests were started caused different degrees of soot formation with different oils. The only general conclusion which seems justified is, that the smokiness of a great variety of heaters cannot be materially reduced by placing more rigid specifications on oil than those now in use.

TESTS ON STACKS OF NEW DESIGN

As soon as it became apparent that smoke-abatement ordinances would be adopted in some counties, the manufacturers of heaters began intensive study of stack design. The tests on standard heaters showed the need for improvements and in some instances suggested lines of procedure. The availability of test apparatus enabled manufacturers to make a systematic study of stack design in relation to smokiness.

No new heaters were studied in the laboratory, for it was felt that the citrus industry could best be served by aiding the development of stacks designed primarily for the improvement of heaters already in use. Manufacturers have made frequent visits to the laboratory to study stacks. More than sixty different stacks have been tested over the normal range of burning rates to determine their smokiness, and many others have received single-point tests to indicate whether or not further study might be desirable.

Requirements of a Good Orchard Heater.—The problem of developing simple new heater stacks is not easily solved. Smokelessness is only one of many requirements all of which a heater must meet as closely as possible in order to be useful. According to the generally accepted ideas as to the more important specifications of a heater, it should :[16]

1. Hold sufficient fuel to burn all night without refueling, even though 7 pounds or more of oil an hour be burned at times.
2. Be capable of sufficient regulation to give its greatest heat just before sunrise even though the fuel in the reservoirs is low by this time (ordinary burning rates are from 3 to 5 pounds an hour).
3. Be able to burn any of the ordinary grades of heating fuels on the market without smoking and without leaving a heavy residue.
4. Be rain-tight.
5. Deliver the heat and products of combustion near the ground, but without heating the ground unnecessarily.
6. Be easy to light and regulate by inexperienced labor under all weather conditions.
7. Be capable of being lighted with the draft opening set as required for normal burning.
8. Be readily extinguished by merely closing the regulator and capping the stack.
9. Be arranged for filling and for soot removal without taking off the stack or cover.
10. Be so designed that if it burns dry the bottom of the heater will not be damaged.
11. Avoid oil condensation on the stack or cover.
12. Be of reasonable cost.
13. Be made of good material and show small annual depreciation.
14. Be easy to take apart, clean, and store.

Interpretation of Test Results on New Stacks.—All of the standard heaters tested were known to have reliable burning characteristics in the field. An observer could also notice differences from usual operation if for instance a cover happened to be loose. However, in testing a new

[16] Schoonover, Warren R., Robert W. Hodgson, and Floyd D. Young. Frost protection in California orchards. California Agr. Ext. Cir. 40:1–73. 1930.

design one cannot be familiar with its normal characteristics, and of course a new stack has not been subject to the ordinary orchard operating practice. *The new stacks have been tested for smokiness only. A season's use in an orchard might increase the smoke output. Field trials alone can prove their practicability for general orchard use.* However, the great improvement in test results of most of the new designs in comparison with the standard heaters is so encouraging that it appears advisable to report the results in spite of the limitations.

Not all of the new experimental results can be reported, but the smokiness of the better stacks developed in each group is shown in figures 27, 28, 29, 31, and 32. These are so much better than most of the standard heaters that smokiness and burning rate are shown on scales twice as

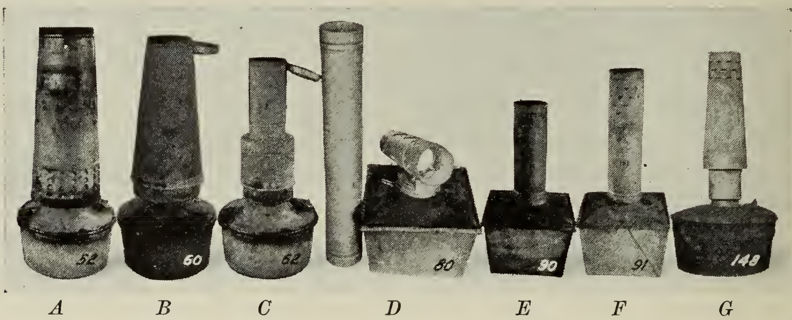

Fig. 26.—Photographs of new smokeless stacks for orchard heaters: *A*, No. 52, Lamco Gyradiant; *B*, No. 60, Hy-Lo Giant; *C*, No. 62, Hy-Lo Drum; *D*, No. 80, Hinchcliff 36-inch; *E*, No. 90, National Junior Louver, 18-inch; *F*, No. 91, O'Keefe and Merritt, 6-inch straight stack; *G*, No. 148, Hy-Lo tapered stack.

large as before. The photographs in figure 26 show a number of the new stacks. All types have been studied including simple, slip-on stacks for use with the Citrus heater to stacks much larger than any heretofore in use and giving complete combustion within the stack over a wide range of burning rates.

Smoke Tests of Annular-Combustion-Chamber Stacks.—Figure 27 shows the smokiness of stacks which have large annular or ring-shaped combustion chambers. In these stacks the gases rising from the bowl come into contact with excess air at the base of the stack. Conditions in the burner at the bottom of the stack are favorable for complete and practically smokeless combustion. Because this involves high temperatures the stack must be made of high-grade material. A large surface for radiation serves to deliver considerable heat close to the ground.

Smoke Tests of Enlarged-Combustion-Chamber Stacks.—Figure 28 shows the smokiness of three models of Hy-Lo stacks with medium-sized

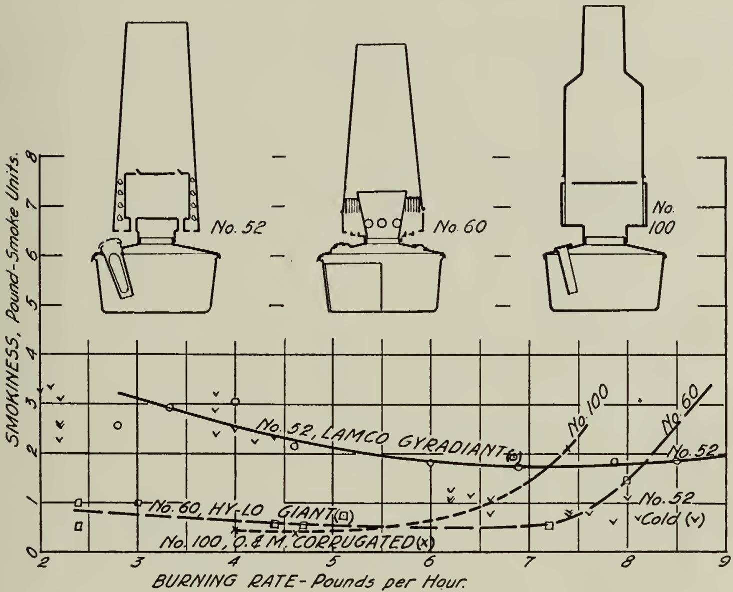

Fig. 27.—Smoke tests of annular-combustion-chamber stacks, Nos. 52, 60, and 100.

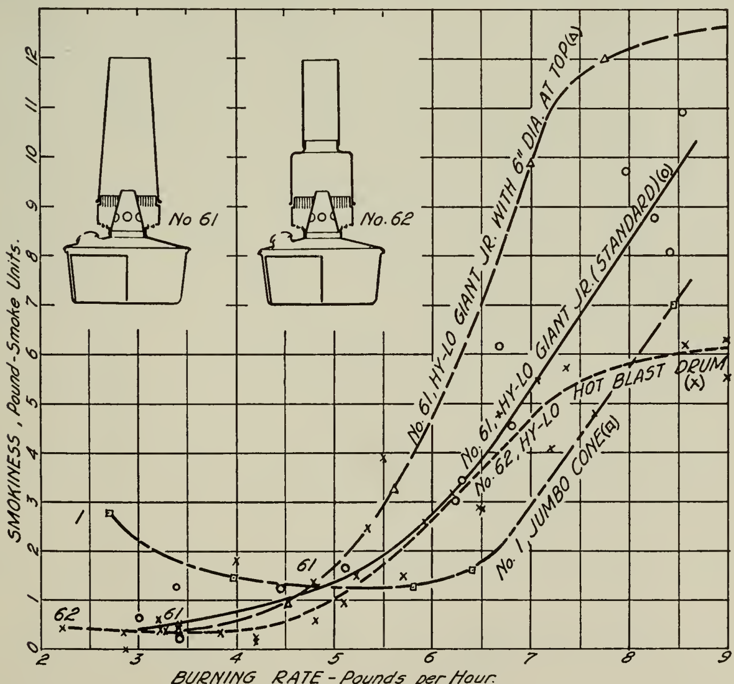

Fig. 28.—Smoke tests of enlarged-combustion-chamber stacks, Nos. 1, 61, and 62.

combustion chambers. Their prototype, the National Jumbo Cone, is also shown for comparison. These heaters are similar in burning characteristics to the heaters with larger ring-shaped combustion chambers

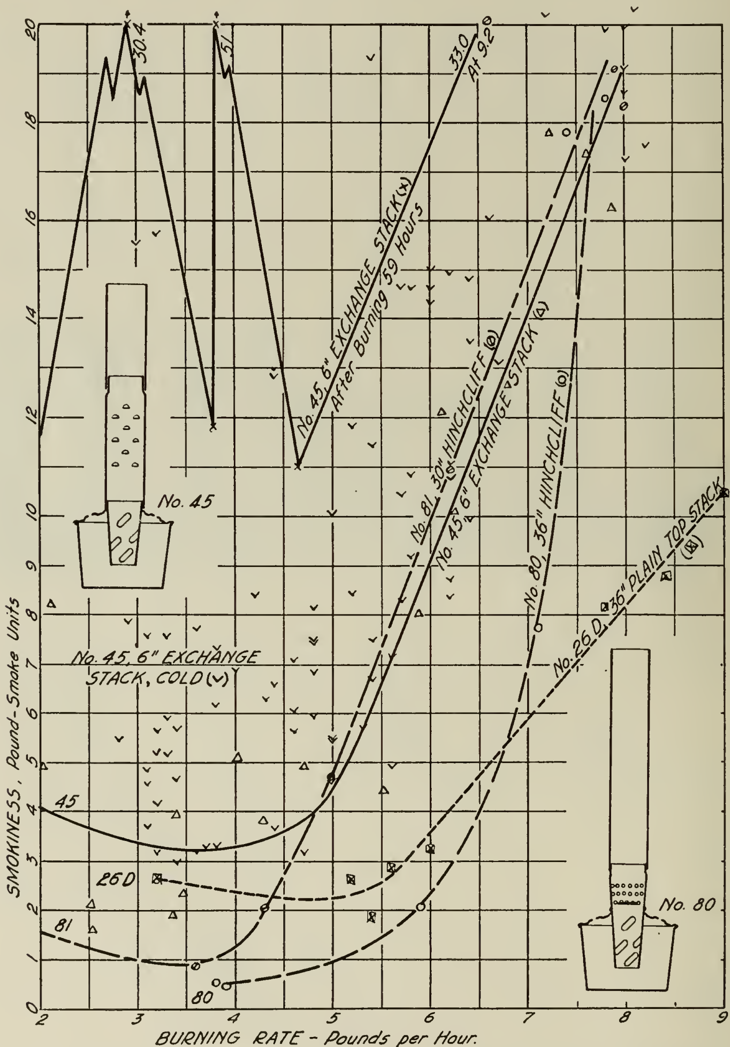

Fig. 29.—Smoke tests of straight tall stacks on Citrus bowls: stacks 26D, 45, 80, and 81.

and are excellent at burning rates permitting completion of combustion in the burner or lower part of the stack. The smokiness increases greatly when the capacity of the burner is exceeded. Stack No. 61A had a smaller stack diameter at the top than No. 61 and although the burner was the same the performance was not as good, and this experimental design was dropped.

These stacks are all of the lean-mixture type requiring warming up before being adjusted to normal burning rates.

Smoke Tests of Straight Tall Stacks.—A number of attempts have been made to improve the Citrus heater by equipping it with some sort of a tall stack. Figure 29 shows the results of such attempts. The best

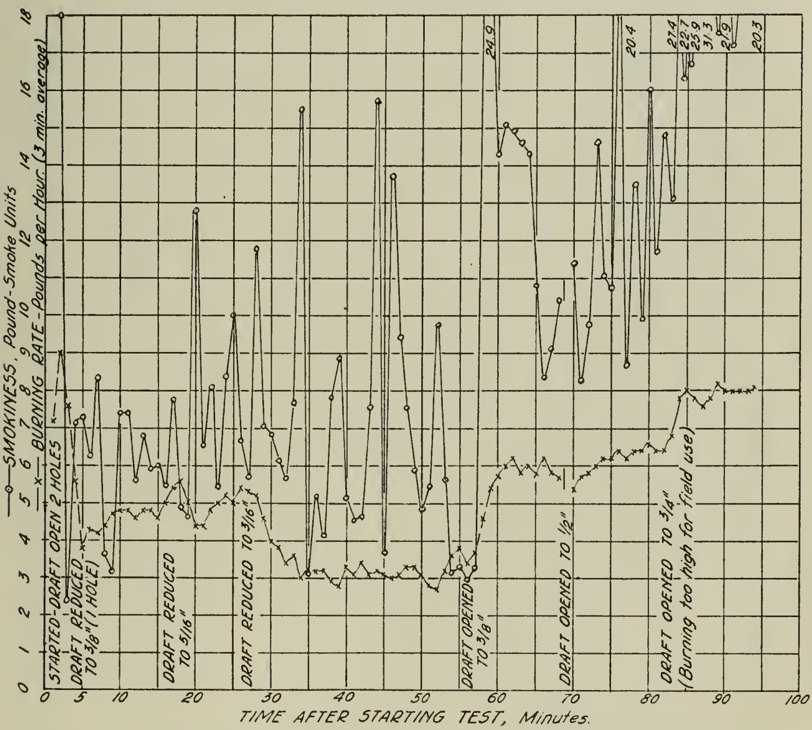

Fig. 30.—Continuous smoke test of 6-inch Exchange stack on Citrus bowl.

results were obtained with a 36-inch top section placed on the 15-inch stack of heater No. 26 and with the Hinchcliff stack of 36-inch length. With these stacks combustion is practically completed in a limited portion of the lower stack much as in the enlarged-combustion-chamber stacks. The straight stacks lack the large radiating surface of the latter and develop local hot spots. Field experience will be required to determine if the stack life is long enough to make them practical.

The 6-inch exchange stack is even more erratic on the Citrus bowl than on the round bowl with a down-draft tube. Curves show clean and dirty runs and checks indicate cold-run smokiness. The peculiar performance of this stack is well illustrated in figure 30, which shows a continuous record of the cold-weather run with smokiness plotted at minute intervals. A periodicity in smokiness peaks is indicated at all burning rates.

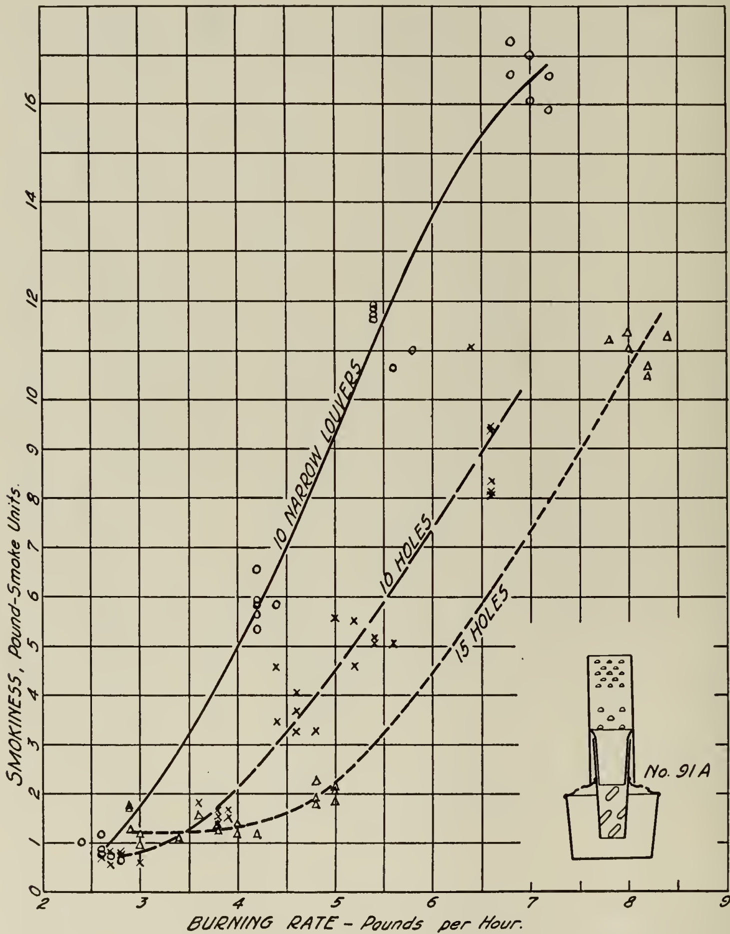

Fig. 31.—Influence of bottom air openings on smokiness of open-flame stack, No. 91A.

Principles of Combustion in Open-Flame Stacks.—Combustion in a good open-flame stack should be similar to that in an ordinary Bunsen burner. That is, sufficient air for a good air-fuel ratio should be mixed thoroughly with the combustible gases at the base of the stack and the flame should be at the top. If anything causes the fire to "strike back" and burn at the air-mixing holes the gases are cracked and the smokiness is greatly increased. In a Bunsen burner using gas under pressure the normal blue flame changes when ''striking-back'' occurs to a yellow

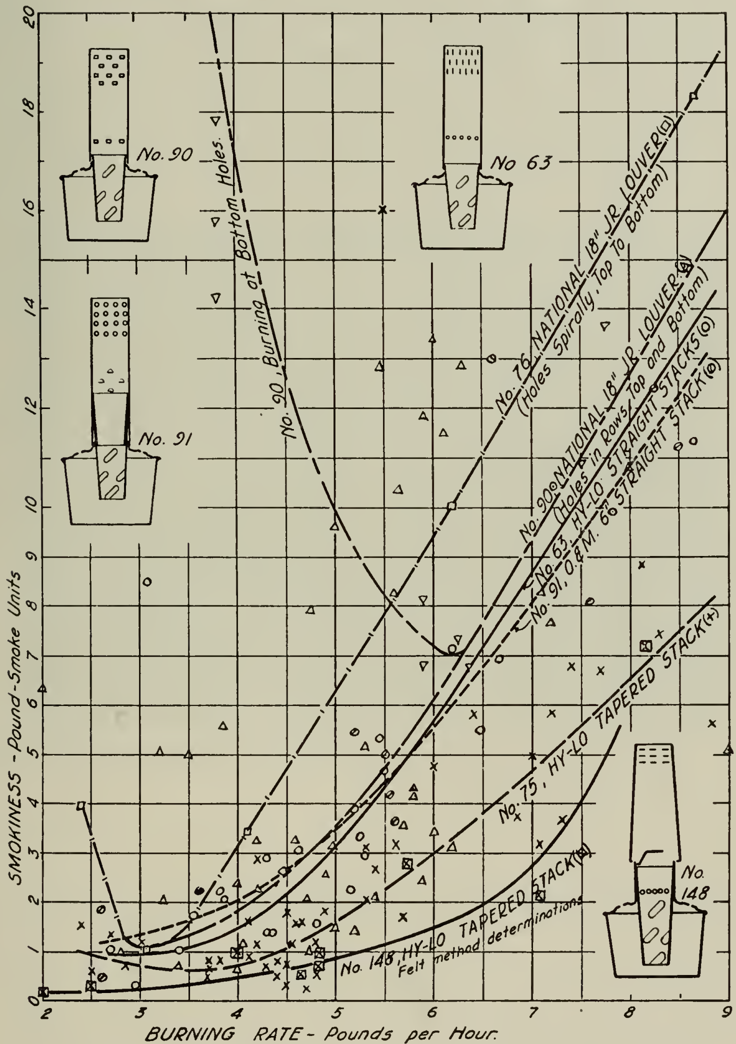

Fig. 32.—Smoke tests of new open-flame stacks on Citrus bowl.

somewhat smoky flame. In a heater burning oil vapors under natural draft the change is from a yellow smokeless flame to a reddish-colored very smoky flame.

Apparently it is relatively easy to design an open-flame stack which will burn without smoke at a single fixed burning rate, but very difficult to design one which will be satisfactory over the whole range of burning rates desired by citrus growers. The problem of air mixing is not simple. If adequate air is admitted for complete combustion at high burning rates it will be too much for low burning rates. The mixture then will be very lean and there will be a tendency for the fire to drop below the air-intake zone and burn the rich oil vapors in the collar, thus producing a smokiness like that of the old smudge pots. A lean mixture, furthermore, tends to burn explosively, which may cause the generating fire in the bowl to blow out. If the air intake is correct for low burning rates it will be insufficient for higher burning rates and the stack will show characteristics similar to early models of lazy-flame heaters such as Nos. 4, 20, 23, and 30. Figure 31 shows the effect on smokiness of changing the bottom air openings.

Smoke Tests on New Open-Flame Stacks.—The manufacturers have worked constantly to develop successful stacks of this general type, with results which have sometimes been exceptionally promising. Figure 32 gives data from tests on various experimental models. The repeated efforts made in the development of stacks of this general type are indicated by the progressive lowering of the smoke curve. The data from all the tests on new open-flame stacks are now being used by manufacturers as the basis for developing the models they expect to sell.

The new production models have not been tested, but tests on experimental stacks indicate the possibility of making open-flame stacks the smoke of which is scarcely visible over burning rates of from 2.5 to 6 pounds of oil an hour. It also seems probable that such stacks can be both practical and inexpensive.

FIELD MEASUREMENT OF THE SMOKINESS OF ORCHARD HEATERS

During the early winter of 1931 field measurements were made with the electrical precipitator in connection with a portable smoke-collecting device mounted on a truck. The portable apparatus was similar to the laboratory apparatus in all basic principles with the omission of the light-interception parts. One per cent of the total smoke discharged was passed through the precipitator while burning ½ pound of fuel. Although dependable results were obtained, the method is not well adapted to field studies, for it is cumbersome and expensive. Technically trained operators are required.

Visible Records of Smokiness.—In the course of field demonstrations conducted by the Agricultural Extension Service, visible records of relative smokiness were made by pulling 1 per cent of the total smoke stream for 1 minute through a 5-inch square of white filter paper. This method was very effective in demonstrating smokiness and it appeared to offer possibilities of development into a simple, accurate, and portable means of measuring orchard heater smoke.

After experimenting in the laboratory, it was found that satisfactory records could be made on a white filtering felt, such as is used in some automobile air cleaners. The smoke sample was collected on a felt

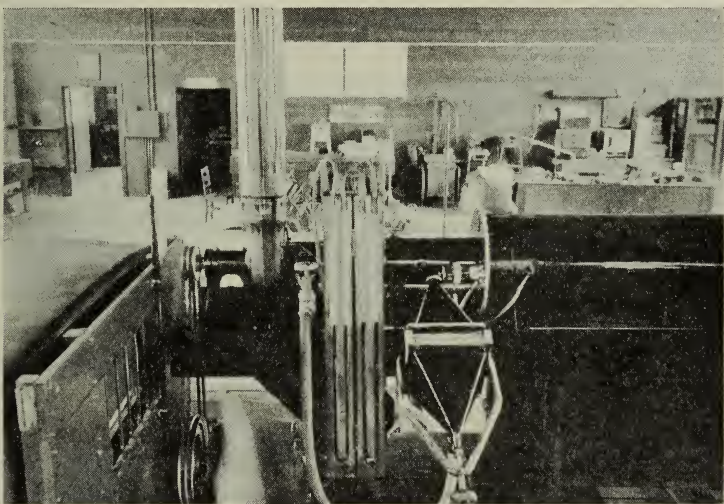

Fig. 33.—Felt sampling apparatus. The felt is held in the square frame between the two rectangular funnels (to the right of the manometers).

9 inches square with ¾-inch margin, giving an exposure of 56.25 sq. in. This size was chosen because preliminary studies indicated that this area was sufficient to permit taking the sample while using the suction normally developed by the centrifugal fan. (See fig. 33.) A large number of tests were run to determine the sensitivity of the method and also the amount of smoke which could be collected on the felt in order to give good comparisons between all of the heaters to be tested. The whiteness of the felt, the depth of penetration of the soot, the degree of dispersion of the carbon, the presence of filterable vapors, etc., influence the blackness of the deposit. It finally appeared that a satisfactory record would be obtained by collecting on this white felt the soot from 0.1 per cent of the total smoke produced by burning 1 pound of fuel. Such a record shows a light gray with the good heaters and still is not too black with

the bad heaters for accurate calibration of the smokiness. For the very best heaters it is advisable to collect 0.5 per cent and for the worst 0.05 per cent in order to obtain measurable records.

The grayness of these felt samples can be measured electrically by reflected light with the same equipment used for the light-interception method in measuring the opaqueness of smoke. However, the standard color wheel is more commonly used because of its simplicity. The nature of the felt smoke records and the method of grading them by the color wheel are illustrated in figure 34. The color wheel used has one disk covered with black velvet and the other with a piece of the same white felt material used in making the tests. The areas of black and white exposed can be varied, and when the wheel is spun to blend the black

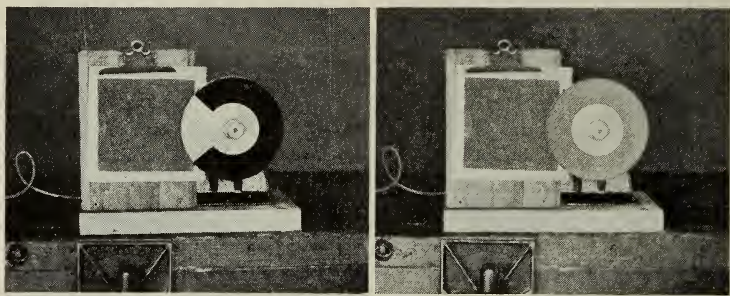

Fig. 34.—Photographs of color wheel (stationary and running) used to measure blackness of felt sample.

and white into a gray, an exact match can be obtained from any smoked felt sample. The relative smokiness is expressed in the terms of the percentage of black required.

Correlation with the Light-Interception Method.—This felt method provides another quantitative means of evaluating the relative smokiness of orchard heaters. Furthermore, one can compare the results with tests made with the light-interception method and thus interpret them in pound-smoke units. The correlation between percentage of blackness and pound-smoke units is shown in figure 35. The curve is based on simultaneous determinations of smoke opaqueness and sample collection by the felt. Opaqueness readings were taken at 5-second intervals while the smoke was being drawn through the felt and burning rates were determined on the automatic balance. The curve indicates a very high degree of correlation between the smokiness as determined from percentage of blackness on the color wheel and the smokiness as determined in pound-smoke units by the light-interception method. This is to be expected, for both methods depend upon the quantity and blackness of the soot. If the accuracy of the color-wheel determinations is not required, quick and dependable comparisons of the grayness of the felt smoke records can be made with properly prepared gray color standards.

According to the correlation shown in figure 35, the very best heaters would produce felt smoke records less than 30 per cent black, or a smokiness under 3 pound-smoke units. A good heater, that is, one which would give off smoke scarcely visible to the eye at a 5-pound burning rate,

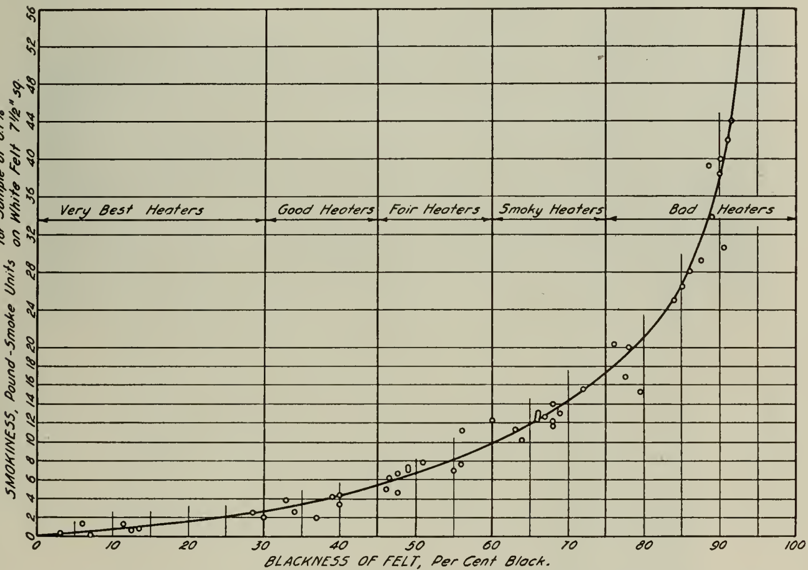

Fig. 35.—Correlation between blackness of felt sample and quantity of soot collected.

would produce records from 30 to 45 per cent black or a smokiness of from 3 to 5 pound-smoke units. The fair heaters burning under favorable conditions would produce records from 45 to 60 per cent black, or a smokiness of from 5 to 10 pound-smoke units. A smoky heater would produce records from 60 to 75 per cent black, or a smokiness of from 10 to 17 pound-smoke units. The bad heaters would produce records blacker than 75 per cent, or above 17 pound-smoke units.

The above grades of blackness are only slightly different from the Ringelmann chart, which has been adopted by many cities as the official standard of comparison for the enforcement of smoke abatement ordinances.[17]

[17] Anonymous. A digest of smoke ordinances in American cities and Canada. Power **74**:447–482. 1931.

Use of Felt Method for Smoke Measurements in the Field.—The felt method appears to meet the requirements for use in the field; it is simple, inexpensive, and accurate. All the apparatus required can be mounted readily on a light truck capable of being driven into orchards while frost-protection operations are in progress. (See fig. 36.) Inexperienced operators can easily be trained to collect dependable records of the smokiness of orchard heaters. This type of apparatus is also suitable for manufacturers who wish to carry on studies leading to heater improvement.

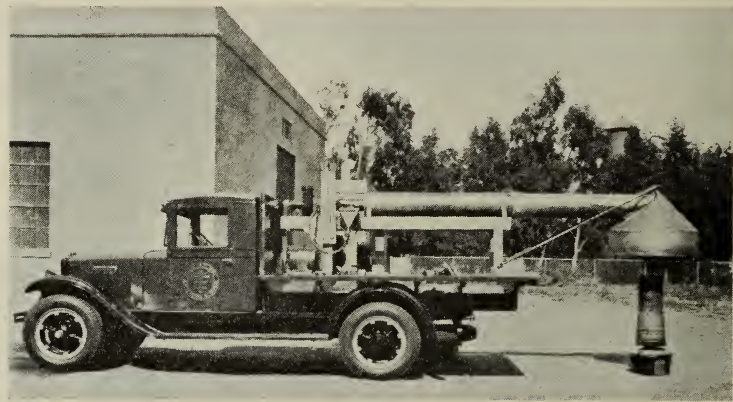

Fig. 36.—Field apparatus for measuring orchard-heater smoke.

ACKNOWLEDGMENTS

This project received very effective cooperation from many persons outside the Experiment Station. Thanks are due particularly to the Orchard Heating Improvement Committee, under the chairmanship of Mr. B. R. Holloway, for its personal attention and the equipment furnished. The California Fruit Growers Exchange has also been generous in supplying technical information and several lots of fuel oil. Mr. Floyd D. Young of the United States Weather Bureau rendered considerable assistance in starting the project and Mr. F. T. Seabern of Pomona very kindly arranged for the experimental field work to be done in his orchard.

APPENDIX A: DESCRIPTION OF APPARATUS AND TEST METHODS

Equipment for making smoke-density determinations on the light-interception basis as developed and built in the laboratories of the Agricultural Experiment Station is shown in figure 4. The work of testing standard heaters was completed before the apparatus was remodeled to increase its sensitivity in determining both opacity and burning rate.

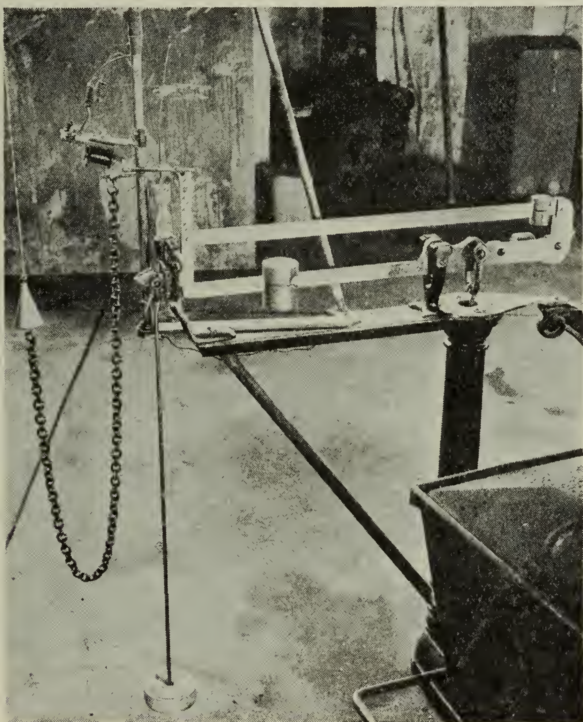

Fig. 37.—Automatic self-balancing scales used for determining burning rate.

The details of the original equipment need not be given; for all of the results reported were developed on apparatus similar in all essential details to that described below.

The heater being tested is placed on scales under the hood at the extreme right hand. The scales (fig. 37) are self-balancing; the beam carries one end of a chain (like a ''Chainomatic'' balance) and a mercury contact which operates an auxiliary device while in the low position to raise the other end of the chain, thus lightening the beam load. To increase the sensitivity of the scales an electro-magnet in series with an ordinary light flasher causes the beam to oscillate regularly. Since the frequency of the contact period is constant, its duration is what regulates the winding-up device. This duration of the contact period is governed in turn by the average position of the beam, thus keeping the scales in perfect balance. A vernier slide attached to the winding-up mechanism indicates accurately the loss of fuel weight and hence the burning rate.

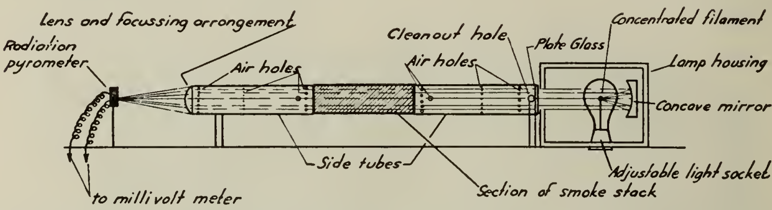

Fig. 38.—Diagram of light-interception apparatus for measuring opaqueness of smoke.

A centrifugal fan at the extreme left draws the entire smoke stream with some surrounding air into the hood and up through a 6-inch stack into a 10-inch horizontal pipe. The sudden change of section and the right angle turn serve to mix thoroughly the smoke particles and air, giving a stream of uniform opaqueness under steady burning conditions. The smoke stream is then flattened to 4¼ inches and spread horizontally to 24 inches where it crosses the path of the light beam. Small air holes in the 4-inch pipes enclosing the light beam drilled near the channel wall allow just enough additional air to seep in to prevent

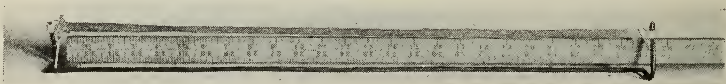

Fig. 39.—Felt strip used to check uniformity of smoke distribution and length of light path through the smoke.

the smoke from swirling out into the light tubes. (Glass screens could not be used to confine the smoke stream because they would become coated with soot.) The plan of construction of the light tube is shown in figure 38. The sharpness of boundary and uniformity of smoke spread was tested by a felt strip left in the line of light just long enough to become gray with soot. (See fig. 39.)

For a light source, a standard Balopticon 1,000 watt lamp and its concave mirror is used. On the far side of the smoke stream a condensing lens focuses the parallel rays on a radiation pyrometer (fig. 40). The voltage impressed on the source lamp is held constant at the low value of approximately 65 volts, which produces a pyrometer reading of 15 millivolts with clear air. This setting is checked before and after test. The opaqueness of the smoke is indicated by a decrease in the electromotive force (e.m.f.) of the pyrometer and is measured in concentration units.[18] Each successive concentration unit represents a reduction of 10 per cent of the original light intensity. That is, one concentration unit reduces the millivolt reading to 13.500, two units to

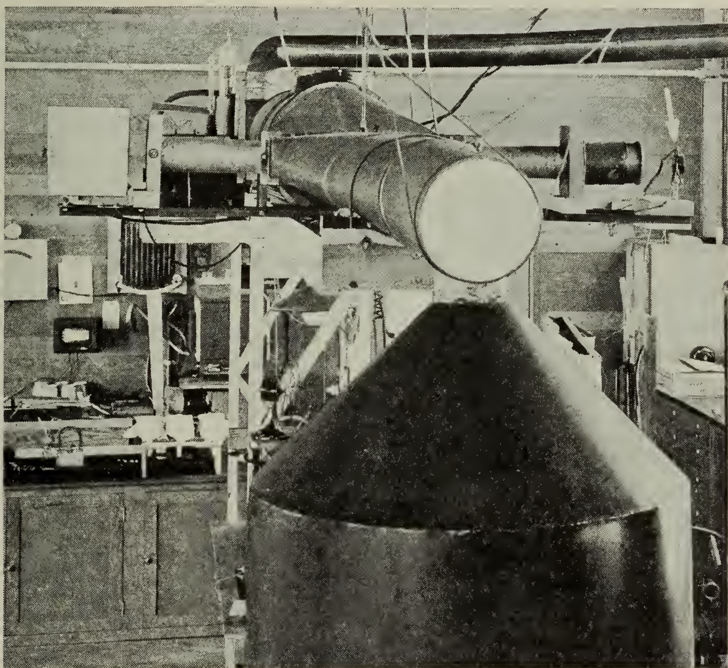

Fig. 40.—End view of laboratory apparatus for measuring smoke, showing radiation pyrometer at the end of the light path (see arrow at the right).

12.150, three units to 10.935, etc. The smoke-stream temperature at the light beam is noted and the value in concentration units is then increased by the correction for temperature to a standard-density basis.

From the light, the smoke stream passes into a large drum 18 inches in diameter through a honeycomb of ¾-inch tubes 3 inches long and slowly approaches the orifice plate. Three orifices are provided: one large central orifice (3-inch diameter) for measuring total flow and two fractional orifices to obtain 1 per cent samples for carbon collection, the

[18] Simon, A. W., L. C. Kron, C. H. Watson, and H. Raymond. A recording dust concentration meter. . . . . Rev. Sci. Instruments 2:67–83. 1931.

first by electric precipitator, and the second by a Buchner funnel for a chemical analysis or by a felt for color-wheel comparison. The pressure drop across each small orifice is balanced exactly with the main orifice by butterfly valves some distance downstream. A definite fraction of the total flow can be obtained unaffected by the temperature or pressure, which apply alike to the three orifices.[19] Calibration of the main orifice[20] was accomplished by using a special elliptically rounded approach nozzle with a Venturi expanding cone.[21] The flow through the fractional orifices was measured in a large displacement tank with a stop watch by noting the rate of discharge of water, which was regulated to balance the manometer between the downstream taps of the large and small orifices. Both the pressure differential and temperature are observed at the orifice for the calculation of air flow.

The radiation pyrometer e.m.f. readings are taken at definite and frequent intervals so as to give a practically continuous record of relative smoke density at the point of observation. The average value of opaqueness, suitably corrected for temperature (expressed as smoke-concentration units), multiplied by the number of thousand cubic feet of air (standard conditions) pulled through the stack while burning a pound of fuel gives a convenient smokiness unit. This quantity unit, which has been designated heretofore as a "pound-smoke" unit, although not actually weight, is comparable with a mass unit per pound of fuel burned.

A typical calculation is as follows:

Opaqueness (average of 6 readings)	= 13.55 millivolts
	= 0.965 concentration units
Thermocouple (average reading at light path)	= 2.18 millivolts
	= 134° F (calibrated)
Temperature correction to standard air conditions (32° F)	$= \frac{458 + 134}{490}$
Therefore, opaqueness (corrected for temperature)	$= 0.965\left(\frac{458 + 134}{490}\right)$ concentration units
	= 1.165 concentration units

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[19] Hodgson, John L. The laws of similarity for orifice and nozzle flows. Amer. Soc. Mech. Engin. Trans. 51 (FSP):303–332. 1929.

[20] Bean, H. S., E. Buckingham, and P. S. Murphy. Discharge coefficients of square-edged orifices for measuring the flow of air. Bur. Standards Jour. Research 2:561–658. 1929.

[21] Schiller, Ludwig. Hydro- und Aerodynamik. In: Wien, W., and F. Harms. Handbuch der Experimentalphysik 4(1):581. Akademische Verlagsgesellschaft. M.B.H., Leipzig, Germany. 1931.

Differential pressure (drop across orifice)	= 4.73 inches water
Thermocouple (at orifice)	= 2.04 millivolts
	= 128° F
Therefore, differential (corrected for temperature as above)	= 3.95 inches
And the air flow[22]	$= 127 \sqrt{3.95}$
	= 252 cubic feet per minute (standard conditions)
Change of fuel weight	= 0.35 pounds in 6 minutes
Therefore the burning rate	= 3.5 pounds per hour
	= 17.15 minutes per pound
The total air flow per pound of fuel burned is therefore	17.15×252 cubic feet
	= 4.32 thousand cubic feet
Therefore the smokiness	$= 1.165 \times 4.32$ pound-smoke units
	= 5.02 pound-smoke units.

In this way it is possible to calculate, on the basis of fuel consumed, the relative smokiness of different heaters at different burning rates without error due to sampling or to admixture of outside air with the products of combustion.

APPENDIX B: CORRELATION BETWEEN LIGHT INTERCEPTION AND WEIGHT OF SMOKE PARTICLES

In order to secure data for determining the weight of carbon per pound of fuel burned corresponding to one pound-smoke unit, a series of chemical determinations was run. Smoke-density readings on the millivolt meter and the necessary data for calculating air flow were taken simultaneously. In making the chemical determinations during the first part of the investigation gas samples were withdrawn from the smoke chamber through an M-shaped sampling tube introduced just downstream from the point of making the opaqueness determinations. Small holes approximately $\frac{1}{16}$ inch in diameter were drilled in the sampling tube at right angles to the direction of gas flow. The suction for removing the gas samples was created by allowing water to flow from a steel oil drum mounted on scales. The rate at which the water discharged from the barrel was controlled to collect the gas sample con-

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[22] 127 is the numerical value of the coefficient of discharge and dimensional factors of the appropriate air flow formulas given in the Bureau of Standard Journal of Research. (Bean, H. S., E. Buckingham, and P. S. Murphy. Discharge coefficients of square-edged orifices for measuring the flow of air. Bur. Standards Jour. Research 2:561–658. 1929.)

tinuously while burning a known weight of fuel. The volume of gases (approximately 6 cubic feet) withdrawn from the smoke chamber was calculated from the weight of the water which ran from the barrel. The gas volumes were reduced to standard conditions except that the correction for water vapor was not applied.

Later chemical determinations were based on the 1 per cent sample taken through one of the small orifices described above.

For making a carbon determination of a sample, the flue gases were passed through a filter mat of shredded asbestos supported in a 130-mm Buchner funnel. The weight of smoke absorbed on the filter was not determined directly; instead, its carbon content was found by combustion and weighing the carbon dioxide. The Division of Chemistry cooperated effectively in establishing test procedure, in making all chemical determinations, and in interpreting the data. Standard analytical methods were used with additional refinements which made certain that the variations observed resulted entirely from the test heater and not from the method of determination. This method gives the weight of carbon in the absorbed smoke, from which can be calculated the meaning of 1 pound-smoke unit in terms of weight of carbon per pound of fuel burned.

The smoke analyses show a mixture of carbon and unburned carbonaceous matter. Some of the smoke particles are practically pure carbon and some are rather oily. This difference in character of the smoke was determined by taking a second sample on another filter while maintaining as nearly as possible the same burning conditions. The oily matter was extracted by ether, the ether driven off, and the remaining carbon determined as before by combustion.

For the fuel oils used in the tests of standard heaters, figure 41 gives the results of the chemical determinations compared with pound-smoke units. It will be seen that the value per unit is not constant but varies between 0.81 grams and 1.58 grams per unit with an average value of 1.00 grams of carbon in the smoke for each pound-smoke unit. The greatest dependable value is 24 per cent above the average and the smallest 19 per cent below. Forty-two determinations were made, representative of three different oils and 21 different heaters operated over a range of burning rates varying between 3.5 and 15.0 pounds of fuel per hour. The dotted line drawn on figure 41 shows how the value varied with one oil in one heater over a range of burning rates. The average correlation value of 1.0 gram per pound-smoke unit applies to a light path 24 inches long through the smoke stream. For any different length the value would change in inverse proportion.[23] The above data indicate that the weight of smoke for the three fuel oils used in testing the standard heaters might be estimated from light-interception measurements if the accuracy of 25 per cent is satisfactory, but further tests with seven other fuel oils showed much wider variation, especially at low burning rates.

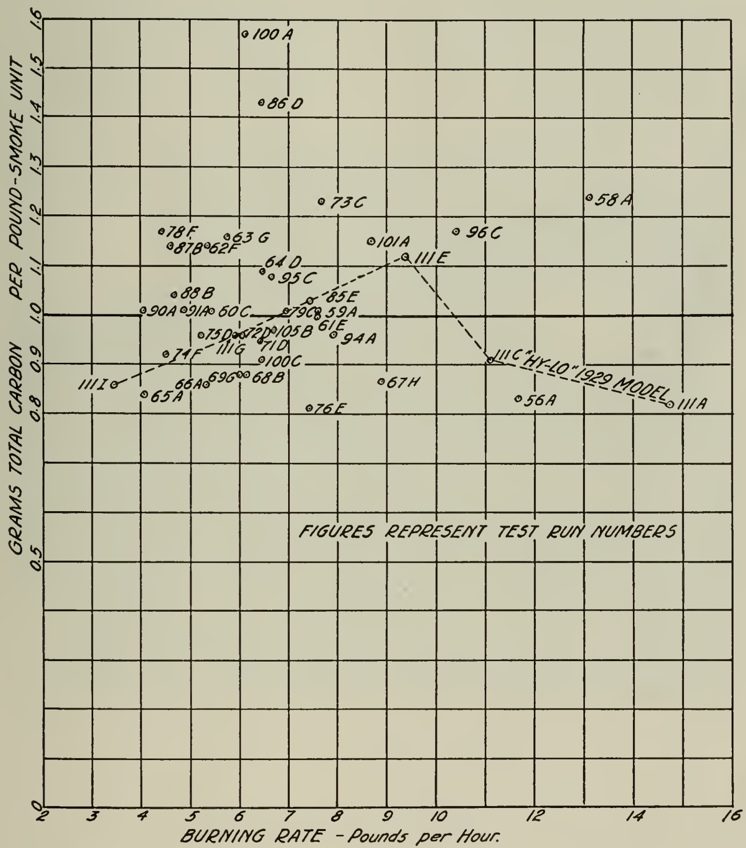

Fig. 41.—Correlation between chemical determinations of total carbon and pound-smoke units.

This variation may be explained as follows:

1. Weight of soot particles of given density varies substantially as the cube of the linear dimension of the particles, while the area for light interception varies as the square. Thus the degree of dispersion of the smoke particles influences the result.

[23] Simon, A. W., L. C. Kron, C. H. Watson, and H. Raymond. A recording dust concentration meter..... Rev. Sci. Instruments 2:67–83. 1931.

2. The smoke is not pure carbon. Adsorbed oily matter may increase the weight of individual particles without increasing their size.

3. The smoke comes from some heaters in distinct puffs. This makes it difficult to get a correct figure for the average number of millivolts even when reading at intervals of 40 seconds. The filter sample is taken continuously and represents an average.

4. Relatively transparent smokes seem to contain colorless carbon compounds, capable of being collected by the asbestos filters.

In the last three cases the felt method should show slightly better correlation with weight than would the light-interception method.

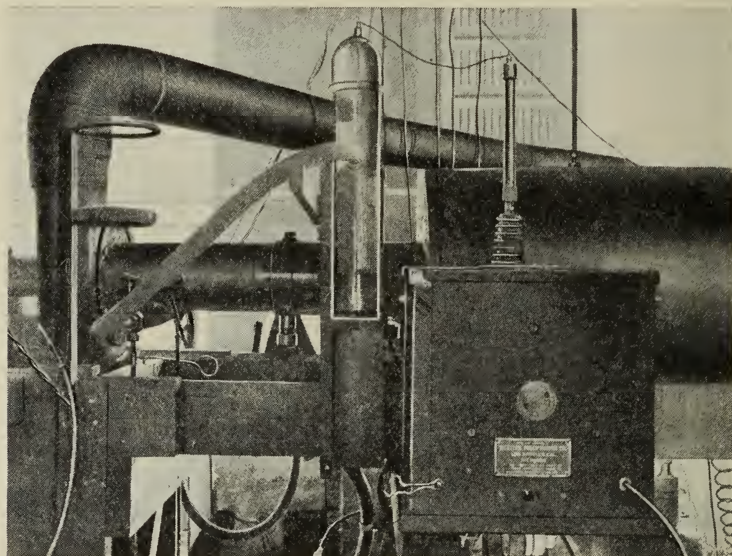

Fig. 42.—Electrical precipitator and its connections with sampling orifice and high-tension transformer.

Additional Studies on Correlation of Smoke Density and Weight.—The additional data mentioned above as bearing on the correlation between opaqueness and weight were developed in connection with studies of the influence of oil composition on the smoke output of a smoky heater and a typically good heater. Seven different fuel oils of variable characteristics were used. These data were obtained by the same chemical methods as before, by use of asbestos filters for collecting samples, and also by use of an electric precipitator to collect smoke samples which could be weighed directly and later analyzed for carbon, hydrogen, and ash content. The precipitator was developed with the cooperation of the Western Precipitation Company of Los Angeles. It is a laboratory model, alternating current, Cottrell precipitator[24] capable of handling 2 cu. ft. of smoky gases per minute (see fig. 42). The precipitating potential is 30,000 volts developed by a small transformer operating on a 110-volt circuit. Smoke is precipitated both on the central high voltage electrode and on the glass container, which is surrounded by a wire-mesh grounded electrode.

Precipitation of the smoke particles carried in the hot gases is visually complete up to a certain load. With very smoky gases some smoke may be carried over, especially if too long a run is made. The chemical studies seem to indicate that light smokes contain heavy molecules, probably compounds of carbon, hydrogen, and oxygen, which intercept very little light and are not precipitated electrically but which are adsorbed onto the asbestos filters. However, for average conditions, the direct smoke weight data correlate fairly well with weights determined chemically. The precipitated smoke contains about 10 per cent ash, which would tend to give higher results with this method because ash was not determined on the filtered smoke. For extremely light or heavy smokes the correlation between the chemical and electrical methods is not good.

For the average conditions applying to all the tests of the old heaters supplied by the committee 1 pound-smoke unit may be considered approximately equal to 1 gram of carbon in the smoke from 1 pound of fuel. Examination of the weight data obtained during the oil studies indicates that the correlation between smoke opaqueness and weight is not satisfactory at average or high burning rates, only a general trend being evident. At low burning rates, no consistent correlation was found. It varies with different oils and with different heaters as well as with the burning rate, as is pointed out in figure 41. One pound-smoke unit may represent as little as 0.75 grams or as much as 3 grams of carbon in the smoke per pound of fuel burned. This indicates that the pound-smoke unit results, if interpreted in terms of grams weight per pound of fuel burned, should be considered as minimum values.

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[24] [Anderson, E.] Cottrell processes of electrical precipitation for removing suspended particles from gases. Leaflet issued by the Western Precipitation Company, 1016 W. Ninth Street, Los Angeles.

Simon, A. W., and L. C. Kron. Electrical precipitation. Amer. Inst. Elec. Engin. Paper 32–32. Rev. in: Elec. Engin. 51:93–95. 1932.

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