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JOSEPH A. HOLMES, DIRECTOR

# THE SMOKE PROBLEM AT BOILER PLANTS

## A PRELIMINARY REPORT

BY

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# THE SMOKE PROBLEM AT BOILER PLANTS.

By D. T. Randall.

## INTRODUCTION.

Several years ago investigations were begun by the United States Government to determine the most efficient methods of utilizing the coals of the United States. These investigations, which were continued along several different lines, are now being carried on by the Bureau of Mines, in accordance with the provisions of the act creating this bureau.

It was because of the need for more complete information concerning the conditions under which coal could be economically burned in boiler furnaces without objectionable smoke that tests were made at the Government fuel-testing plants at St. Louis, Mo., and Norfolk, Va. In addition to this experimental work a number of commercial plants in the larger cities were inspected to ascertain what were the best methods then in use for abating smoke. The results of these investigations were reported in Bulletins 334 and 373 of the United States Geological Survey. Because of the continued demand for the information contained in these bulletins, the original editions of which are exhausted, they are reprinted by the Bureau of Mines. The text of this bulletin, particularly the information relating to smoke ordinances, was revised in the latter part of 1910 and the early part of 1911 by S. B. Flagg, engineer, who has charge of the steaming tests being conducted by this bureau.

## GENERAL CONDITIONS IN THE UNITED STATES.

The prevention of objectionable smoke in the manufacturing and business centers of large cities is a problem that can not be easily solved. At present no city in which a considerable quantity of bituminous coal is burned is free from smoke. The cities of the East have avoided this problem by a general use of the smaller sizes of anthracite coal. For this reason it is not surprising that the greatest improvement in the methods of burning bituminous coal has been made in the Central and Western States.

Stoves, ranges, house-heating boilers, and hot-air furnaces are as a rule intended for the use of anthracite coal or coke. Whenever bituminous coal is burned in such furnaces all the principles of combustion are violated and smoke results. The supply of anthracite coal is limited, and except for domestic purposes such coal is little used outside of the territory adjacent to the mines. The larger cities of the Eastern States, which consume practically all the available supply of the smaller sizes of anthracite coal for power and heating purposes, now find it necessary to supplement this fuel with a considerable tonnage of bituminous coal. Except the power generated by waterfalls, nearly all the heat and power used in the United States are obtained from the burning of coal. It is evident, then, that for the most part this country must depend on its bituminous coal for manufacturing, railroad, and power-plant purposes. This means that we must improve our usual methods of burning bituminous coal or continue to suffer from the lack of economy and the smoke resulting from imperfect combustion.

There are now three general methods of utilizing coal—in steam-boiler and other furnaces, in gas-producer plants, and in by-product coke plants. Of these, the last two methods are readily operated to produce heat or power without smoke, but at the present time such plants are not numerous and consume only a small portion of the coal that is used in this country. It is predicted by persons who are enthusiastic regarding the economy and smokelessness of these methods that they will in time be used exclusively for the production of heat and power in all our large cities.

It has been demonstrated at the fuel-testing plants of the Geological Survey that bituminous coal of all grades can be burned in a gas producer without smoke, generating a gas which when used in a gas engine furnishes power with much greater economy than is usual in steam plants. With good grades of coal mined in the Eastern States one horsepower can be generated with about one pound of coal. One of the most important facts in connection with the gas-producer plant is that, besides being smokeless, it will utilize coals so high in ash as to be unsuitable for boiler furnaces. The lignite coals of the West are also particularly well adapted for use in the producer, though they are considered much inferior to bituminous coal for boiler furnaces. About 100 producer plants are now in operation in the United States, burning bituminous coal. Interest in such plants is increasing, and many new ones are being planned, ranging in capacity from 500 to 10,000 horsepower each.

That the coal supply is being wasted in many ways is a fact that has been frequently brought to the attention of the public. One kind of waste results from the ordinary methods of manufacturing coke, in which all of the gas from the coal is allowed to escape into the air. This loss has led to the installation of a few by-product coke plants in which coke is made and the resulting gas is piped to points where fuel is needed and there consumed. Other valuable products from the distillation of coal are also obtained. These plants, furnishing both coke and gas as fuel, constitute a considerable factor in the prevention of smoke in the cities near which they are located, as both fuels are burned readily without smoke for domestic purposes and for manufacturing industries requiring heat or power. The convenience and cleanliness of these fuels will probably lead to an increase of their production and use.

It is reported that there are 39 by-product coke plants in this country, with a total of 4,000 ovens, using about 23,000 tons of coal a day. It is estimated that these plants manufacture daily more than 50,000,000 cubic feet of gas. The following are some of the cities near which they are located: Chicago and Joliet, Ill.; Milwaukee, Wis.; Duluth, Minn.; Detroit and Wyandotte, Mich.; Ensley and Tuscaloosa, Ala.; Chester, Dunbar, Glassport, Johnstown, Lebanon, Sharon, and Steelton, Pa.; Wheeling, W. Va.; Buffalo, Geneva, and Syracuse, N. Y.; Cleveland and Hamilton, Ohio; Camden, N. J., and Everett, Mass.

In many manufacturing plants furnaces that were formerly fired with coal are now using crude oil, natural or manufactured gas, coke, or coal burned on automatic stokers. All these methods are giving good results in preventing smoke.

## CITY ORDINANCES FOR SMOKE PREVENTION.

With the knowledge that smoke can be prevented, there has come an increasing demand from the people of the large cities that it shall not be allowed to pollute the atmosphere. This is true not only of the United States, but also of most European countries. For example, the importance of burning bituminous coal economically and without smoke led the Prussian Government some time ago to furnish, at an expense of about $10,000 a year, traveling instructors for the training of firemen throughout the State, licenses being given to competent firemen. There are also in Prussia a number of boiler-supervision societies, which employ skilled firemen to direct the work done by the regular employees of the plants owned by members of the society.

In nearly all cities of the United States efforts are being made to abate the smoke given off by manufacturing, steam-boiler, and the larger domestic furnaces in which bituminous coal is burned. As a result of the demands of the public the ordinances of some of these cities require that all new plants be equipped properly and that old ones be remodeled, and permits are now necessary for the installation of all boilers and furnaces. Most ordinances define the degree of blackness of smoke which constitutes a violation of the law. In general, it may be said that in this country the only excuse recognized for black or dense gray smoke is that the fires are being built or cleaned, but no such excuse is valid in many of our cities. The conditions in a number of the larger cities of the United States in the early part of 1911 were about as follows:

*Baltimore.*—The Baltimore ordinance contains a clause that practically excepts the manufacturing plants of the city, and for this reason little can be done at present toward abating smoke. There is no smoke inspector, and the records as to the number of boilers in use and the kinds of equipment are incomplete. There are on record in Baltimore about 660 steam plants, not including heating plants; of this number only 12 are equipped with automatic stokers.

*Boston.*—The city of Boston for five years had an ordinance prohibiting the emission of "dark smoke or dark-gray smoke" from the stack or chimney of "any building or premises, except locomotive engines and plants furnishing power for public-service corporations and plants burning wood exclusively." The smoke-inspection work was carried on by the regularly appointed sanitary inspectors of the city health department, and the nuisance was abated in many plants.

A State statute which became effective July 1, 1910, provides for regulating and restricting the emission of smoke in the city of Boston and vicinity. Under the new law a smoke inspector and such deputy inspectors as may be necessary are to be appointed by the board of gas and electric light commissioners, and are to assist this board in enforcing the law. Smokestacks are now classified according to both their size and the kind of boiler furnaces they serve, and the present law provides for increasing restrictions on all of the classes each year until 1913.

The features just mentioned are of particular interest because no other city has a law or ordinance embodying similar provisions. Below is a statement defining each class of stacks, and tabulation of the permissible emission of smoke by each:

*Density of smoke, by Ringelmann chart, which may be emitted from the several classes of stacks, and the duration of such emission.*

| Year. | Class of stack. | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3[a] | | 4 | | 5 | | 6 | | Locomotives moving trains of 6 cars or more. | |
| | Chart number. | Minutes per hour. | Chart number. | Minutes per hour. | Chart number. | Minutes per hour. | Chart number. | Minutes per hour. | Chart number. | Minutes per hour. | Chart number. | Seconds in 5-minute periods. | Chart number. | Seconds in 5-minute periods. |
| 1910 | 3 | 6 | 4 | 5 | 4 | 10 | 4 | 9 | 4 | 12 | 3 | 40 | 3 | 50 |
| 1911 | 3 | 4 | 3 | 10 | 3 including 4 | 20 including 5 | 3 | 12 | 3 | 15 | 3 | 30 | 3 | 40 |
| 1912 | 2 | 8 | 3 | 6 | 2 including 3 | 30 including 10 | 3 | 7 | 3 | 9 | 3 | 20 | 3 | 30 |
| 1913 | 2 | 6 | 3 | 3 | 2 including 3 | 25 including 5 | 3 | 3 | 3 | 5 | 3 | 20 | 3 | 30 |

[a] In years 1911–1913, permissible emission of smoke includes emission for shorter time of darker smoke. Thus in 1911 the permissible limits, 20 minutes in 1 hour of smoke No. 3, include emission of smoke No. 4 for 5 minutes.

*Class 1.*—All stationary or fixed stacks having an inside area at the top not exceeding the area of a circle 5 feet in diameter.

*Class 2.*—All stationary or fixed stacks having an inside area at the top greater than the maximum in class 1, but not exceeding that of a circle 10 feet in diameter.

*Class 3.*—All stationary or fixed stacks having an inside area at the top greater than that of a circle 10 feet in diameter.

*Class 4.*—All vessel stacks having an inside area at the top not exceeding that of a circle 4 feet in diameter.

*Class 5.*—All vessel stacks having an inside area at the top greater than that of a circle 4 feet in diameter.

*Class 6.*—All stacks on steam locomotives.

*Buffalo.*—The Buffalo ordinance is not effective, since it simply declares the emission of large quantities of smoke to be unlawful. There is only one smoke inspector, so that the smoke-abatement work of the city necessarily progresses slowly. It has, however, been supplemented by the efforts of the Society for Beautifying Buffalo.

*Chicago.*—In Chicago it is unlawful to permit dense smoke to escape from the stack of any locomotive, steamboat, steam tug, steam roller, steam derrick, steam pile driver, tar kettle, or other similar machine or contrivance, or from the smokestack or chimney of any building or premises, except for six minutes of any one hour, during the time when the fire box is being cleaned out or a new fire is being built.

The ordinance provides for a smoke inspector and a chief assistant smoke inspector, both of whom shall be mechanical engineers "qualified by technical training and experience in the theory and practice of the construction and operation of steam boilers and furnaces, and also in the theory and practice of smoke abatement and prevention." Provision is made also for deputy smoke inspectors and assistant smoke inspectors, who are appointed in accordance with the civil-service requirements of the city of Chicago, their number and compensation being fixed by the city council.

On account of the difficulty of determining when fires are being cleaned on a locomotive, tug, or freighter and the further difficulty of watching a locomotive or vessel for an hour, it is considered a violation of the ordinance if a locomotive emits dense smoke (No. 3½, Ringelmann chart, or darker) continuously for a period of one minute; it is likewise considered a violation if a tug or freighter emits such smoke for one minute when running, or for six minutes when standing.

One clause in the Chicago ordinance requires that all plans for new construction or for extensive alterations of furnaces are to be submitted to the smoke inspector and be approved by him before work is started. In this way the installation of poorly designed furnaces is prevented.

Because of the number of steam plants in Chicago and the constant changes being made in them, it is impossible to give the number of installations of any one kind. It can be said, however, that much progress is being made; in fact, it is probable that no other city in this country is making as successful a fight to abate smoke as is Chicago.

*Cincinnati.*—The Cincinnati ordinance establishes a standard for permissible density of smoke, and allows a period, not exceeding six minutes in any hour, during which the fires are being started. Much work is being done by both the city smoke-inspection department and the Smoke Abatement League. The latter organization has raised by public subscription a fund sufficient to pay the salary of an inspector, who has worked under the direction of the league.

A reorganization of the city smoke-inspection department has been effected within the last two years, and many prosecutions for violation of the ordinance have followed. The records as to the number of plants and their equipment are not complete, but the latest figures show 1,938 stationary boilers in use. Of this number, the data at hand show the equipment of about 550 of these boilers to be as follows: Down-draft furnaces, 90; other furnaces, 5; inclined-grate stokers, (*a*) side feed, 113, (*b*) front feed, 56, (*c*) underfeed, 89; automatic steam jets, hand-fired, 48; steam jets, not automatic, hand-fired, 247.

*Denver.*—The smoke ordinance of Denver prohibits the emission of dense smoke at any time, but establishes no standards for grading the density. It provides that plans for alteration or new construction on boiler furnaces shall be submitted to the smoke inspector and have his approval before the work is done, and that the inspector may require alterations made where the restrictions regarding smoke are being violated. The records show that there are 1,200 boilers in Denver, but only a small percentage of these are high-pressure boilers. The following is the record of furnace equipment: Chain-grate stokers, 37 boilers; inclined-grate stokers, 4 boilers; underfeed stokers, 37 boilers; sprinkling stokers, 5 boilers; down-draft furnaces, 4 boilers; automatic steam jets, 33 boilers; miscellaneous devices, 61 boilers.

*Detroit.*—The Detroit ordinance makes it unlawful to allow dense gray or black smoke to escape from any chimney. The smoke inspector is assisted by a committee of the chamber of commerce, and good results are being obtained. The latest report shows that there are 1,143 high-pressure and 253 low-pressure boilers in use. The smoke-preventing furnace equipment is as follows: Chain-grate stokers, 7 boilers; inclined-grate stokers, 390 boilers; underfeed stokers, 170 boilers; down-draft furnaces, 14 boilers; automatic steam jets, 114 boilers; nonautomatic steam jets, 124 boilers; miscellaneous devices, Dutch ovens, etc., 7 boilers; smokeless coal used under 57 boilers; waste heat from smelting furnaces under 16 boilers; gas-fired, 1 boiler.

*Indianapolis.*—The smoke ordinance in Indianapolis prohibits the emission of dense gray or black smoke from any chimney or stack, except that of a private residence. Progress in smoke abatement is necessarily slow inasmuch as there is only one inspector.

Figures obtained from the smoke inspector's office show that there were in the city 710 power plants having 1,300 boilers therein. The equipment was as follows: Chain-grate stokers, 13 plants; inclined-grate stokers, 31 plants; underfeed stokers, 13 plants; down-draft furnaces, 1 plant; sprinkling stokers, 3 plants; automatic steam jets, 13 plants; nonautomatic steam jets, 40 plants; Dutch ovens, etc., 3 plants; smokeless coal used under 600 boilers.

*Louisville.*—The Louisville ordinance prohibits the emission of black or dense gray smoke within the limits of the city, and provides that plans for all alterations or new construction must have the approval of the smoke inspector. Exceptions are made in the case of locomotives attached to trains, either passenger or freight, which are regularly scheduled and are passing through the city or (in the case of passenger trains) are stopping at stations to receive or discharge passengers. The engines of the city fire department are likewise exempt, and also the chimneys of buildings used as private dwellings exclusively, except when the chimneys of such dwellings "become actual and continuous nuisances by reason of the emission of dense smoke or soot therefrom." The following data regarding furnaces in the city are furnished by the inspector of buildings, who has supervision of the smoke-abatement work: Chain-grate stokers, 60 boilers; underfeed stokers, 75 boilers; down-draft furnaces, 50 boilers; automatic steam jets, 100 boilers; nonautomatic steam jets, 200 boilers; miscellaneous devices, Dutch ovens, etc., 46 boilers; smokeless coal burned under 25 boilers.

*Milwaukee.*—The ordinance in Milwaukee prohibits the emission of dense smoke for more than six minutes in any one hour. All plans for alterations or new construction of furnaces must have the approval of the smoke inspector. In the report for the year 1909 the inspector gives the number of steam plants on record as 478, and the number of boilers in plants on record as 1,080. The furnace equipment is thus classified:

*Furnace equipment of boiler plants in Milwaukee.*

| Equipment. | Plants. | Boilers. |
|---|---|---|
| Chain-grate stokers | 3 | 16 |
| Inclined-grate stokers | 10 | 41 |
| Underfeed stokers | 20 | 78 |
| Sprinkling stokers | 1 | 1 |
| Down-draft furnaces | 17 | 42 |
| Automatic steam jets | 13 | 22 |
| Dutch ovens, arches, and special settings | 17 | 34 |
| Smokeless fuel used | 25 | 44 |
| Gas and oil used | 3 | 11 |

The railroads entering Milwaukee have inspectors of their own and are cooperating with the city authorities in the effort to eliminate smoke from locomotives. Much educational work is being done among the manufacturers.

*Newark.*—The Newark city ordinance, because it prohibits the emission of dense smoke containing sufficient soot or other substance to make a deposit on any surface within the city limits, is a difficult one to enforce, except against isolated stacks. The records as to the number of boilers and the kinds of equipment are incomplete, only 327 boilers being on record. The following is the record of equipment:

*Furnace equipment of boiler plants in Newark.*

| Equipment. | Plants. | Boilers. |
|---|---|---|
| Chain-grate stokers | 2 | 3 |
| Inclined-grate stokers | 5 | 25 |
| Automatic steam jets | 13 | 23 |
| Nonautomatic steam jets | 3 | 20 |
| Miscellaneous devices | 3 | 9 |
| Liquid tar burned | 1 | 3 |

*Philadelphia.*—The Philadelphia ordinance establishes a standard for density of smoke and prohibits the escape from any stack of smoke of greater density than this standard. As exceptions to this prohibition, "any locomotive or steam river craft standing with banked fires or engaged in shifting" may emit smoke of greater density than the above proscribed maximum for a period not exceeding 5 consecutive minutes, or for a period not exceeding 10 consecutive minutes while fires are being cleaned or prepared for starting. None of the provisions of the ordinance applies to "locomotives or steam river craft in continuous transit through or across the city, or while entering or departing therefrom," nor to any stacks, between the hours of 4 a. m. and 7 a. m.

*Pittsburgh.*—At present there is no city smoke ordinance in Pittsburgh, nor any city smoke inspection, owing to the fact that a decision handed down some months ago held that under the city charter then in force the city could not regulate the emission of smoke.

In the new charter recently granted Pittsburgh, one clause permits the city to pass a smoke ordinance and to regulate the emission of smoke. It is therefore probable that Pittsburgh soon will have a new smoke ordinance and that smoke inspection will be resumed.

Conditions in the city are peculiar, in that large industrial plants are close to the heart of the business district, and that smaller plants are able to solve the smoke problem by adopting the use of natural gas, coke, or anthracite coal. Statistics for the year 1910 show that the use of gas was responsible for the elimination of the nuisance in nearly 25 per cent of the installations reported as having been made satisfactory.

There has been some progress toward smoke abatement in the large industrial plants; but on account of the radical changes in design required to bring about satisfactory conditions in some of these plants the work necessarily progresses slowly.

*Rochester.*—The Rochester city ordinance establishes a color standard for smoke and prohibits the issue of smoke of greater density from any stationary stack for more than five minutes in any four consecutive hours. Locomotives and canal steam craft engaged in shifting or moving within the city limits are allowed, while fires are being prepared for starting, to make smoke of greater density, but the period of emitting such smoke must not exceed 10 minutes in 24 consecutive hours. Locomotives or canal steam craft in transit through the city, or entering or leaving it, are exempt from the restrictions of this ordinance, provided the aggregate length of the stop or stops in the city does not exceed five minutes. None of the provisions of the ordinance applies to any stack between 5 a. m. and 7.30 a. m. The latest record shows 702 stationary boilers in use in the city, and the following smoke-abating equipment: Inclined-grate stokers, 37 boilers; underfeed stokers, 143 boilers; automatic steam jets, 86 boilers; nonautomatic steam jets, 73 boilers; miscellaneous devices, Dutch ovens, etc., 22 boilers; smokeless fuel burned, 92 boilers; gas or oil burned, 4 boilers.

*St. Louis.*—The smoke-abatement department in St. Louis has been abolished, and this work is now carried on under the supervision of the inspector of boilers and elevators. A city ordinance provides a penalty for allowing dense smoke to escape into the air. According to the last report of the smoke inspector there were in the city 1,081 boiler plants using smoke-preventing devices. The total number of boilers in these plants was 2,077, and their equipment was as follows: Steam jets, 1,012 boilers; down-draft furnaces, 617 boilers; automatic stokers, 239 boilers; miscellaneous devices, 157 boilers; burning smokeless fuel, 52 boilers.

*Toledo.*—The Toledo smoke ordinance provides a penalty for allowing dense black or gray smoke to issue from any stack or chimney other than that of a private residence. The records show 334 stationary boilers with equipment, in use in Toledo, as stated below:

*Furnace equipment of boiler plants in Toledo.*

| Equipment. | Plants. | Boilers. |
|---|---|---|
| Chain-grate stokers | 2 | 25 |
| Inclined-grate stokers | 14 | 33 |
| Underfeed stokers | 14 | 33 |
| Automatic steam jets | 19 | 26 |
| Nonautomatic steam jets | 7 | 18 |
| Smokeless fuel used | 24 | 31 |

*Washington.*—The law governing the abatement of smoke in Washington and the District of Columbia makes an exception of private residences, but provides a penalty for dense gray or black smoke from all other sources. The law is rigidly enforced, and there is little smoke from bituminous coal.

## THE PRODUCTION OF SMOKE.

The term smoke as used in this paper refers to chimney gases that contain small particles of unconsumed carbon, which give the gases a dark color. Smoke may be of any degree of blackness, but what some persons would call smoke is not considered smoke by others.

Smoke is due to a lack of air at the proper temperature at the point where the volatile gases should be burned, the result being that these gases are only partly burned and the carbon is set free. The density of smoke is measured in many ways, but the most satisfactory at present is by means of the Ringelmann charts. These charts are made by drawing black lines at right angles on a white background. The lines are so spaced as to give the effect of different percentages of blackness when placed at a distance of about 50 feet from the observer. The charts are numbered 1, 2, 3, 4, and 5, and represent, respectively, 20, 40, 60, 80, and 100 per cent of black smoke. As a matter of fact, anything but a clean stack will result in a smoky atmosphere. If a stack continuously emits a small amount of smoke, it may, during the course of the day, have given off as much carbon and have had as bad an effect as another stack which has been clear most of the time, but which for three or four periods of five minutes each has emitted a dense black smoke. In localities where bituminous coal is burned exclusively a plant is considered good if the average blackness is equivalent to 5 per cent or less.

The following information, taken from the report of the committee for testing smoke-preventing appliances, Manchester, England (see p. 27), is of interest:

Observations were made for an entire day on 179 chimneys. The general averages of these stacks gave the equivalent of black smoke 102 minutes in 10 hours. The averages for the individual stack varied from the equivalent of black smoke for 423 minutes in the worst to 4 minutes in the best. The relative amount of the smoke from different kinds of equipment may be taken as follows:

Average of 36 hand fires with air admission, 81 minutes in 10 hours; average of 10 hand fires with air admission, good firing, 40 minutes; average of 4 sprinkling stokers, about 103 minutes in 10 hours; average of 21 coking stokers, about 16 minutes in 10 hours; best coking stokers, about 4 minutes in 10 hours.

Coking stokers show best economy as well as prevention of smoke.

Sheffield association suggest that the permissible limit of smoke emission should vary with the number of boilers, as follows: For 1 boiler, 2 minutes per hour; for 2 boilers, 3 minutes per hour; for 3 or more boilers, 4 minutes per hour.

The following are reasons why furnaces sometimes smoke:

1. The furnaces and the grates are not properly designed to burn the coal available. There is almost no equipment on the market that will handle equally well all the fuels found in the United States.
2. There is a lack of sufficient draft.
3. The firemen are unskilled.
4. There is not enough combustion space.
5. Wood, paper, and other refuse are burned.
6. The load is changed quickly.
7. Excessive overloads are maintained.

## THE PREVENTION OF SMOKE IN BOILER PLANTS.

### FEASIBILITY.

Within the last few years there has been a remarkable development in the utilization of coal under the steam boiler. To-day many steam power plants in the United States are burning bituminous coal practically without smoke. This has been brought about by improving the design of the furnaces and by careful attention on the part of the firemen.

It is now possible to design and operate boiler plants burning a high-volatile coal which will be practically smokeless under usual operating conditions, giving off no black or dense gray smoke except when a fresh fire is being built. Banking the fire, shutting dampers, etc., cause smoke of a light or gray shade only. This has been demonstrated at the engineering experiment station of the University of Illinois, where a boiler has been installed, properly equipped with a furnace for burning Illinois coal. Under ordinary conditions this plant makes no smoke whatever. This equipment is not suitable for burning low-volatile coals such as are largely used in the East. In experimenting with this furnace an effort was made to produce smoke, but it was found impossible to make black smoke, the worst being about 50 per cent black.

In many of our larger cities large commercial plants having properly designed furnaces are now operating daily without smoke. Reports on some of these plants inspected by engineers connected with the technologic branch of the Geological Survey were published in Bulletin 373, and are republished in Bulletin 40, Bureau of Mines.

### THE PRINCIPLES OF SMOKELESS COMBUSTION.

Coal can be burned smokelessly, the same as gas, gasoline, or kerosene oil, if the equipment is properly designed and adjusted. Each of these fuels will give off smoke if conditions are not favorable. All the authorities on the subject of combustion and smoke prevention agree upon the following conditions as requirements for a smokeless furnace:

1. The coal should be supplied to the furnace in small quantities at frequent intervals. The more nearly the feed approaches a continuous and uniform supply the better the results.

2. The air supply should be slightly in excess of the theoretical amount required and be admitted principally through the fuel bed, with an auxiliary supply admitted at the front or rear of the furnace to burn gases from the coal.

3. The temperature in the furnace should be sufficiently high to ignite the gases given off from the fuel bed.

4. There should be a fire-brick combustion chamber of sufficient dimensions and so designed as to cause the thorough mixture of the gases and air, permitting complete combustion before the mixture reaches the boiler surfaces.

Much has already been written on the theory and chemistry of combustion. "Steam-boiler economy," by William Kent, and "Steam boilers," by Peabody and Miller, are both good works on this subject. (See p. 25.)

It has been found in this country, as well as in Europe, that when smoke is given off there is also a loss of carbon monoxide (CO) and other combustible gases. The loss due to the carbon which we see and call smoke is seldom more than 1 per cent, but the loss due to the escape of the combustible gases may amount to an additional 3 to 10 per cent.

The steam-engineering section of the technologic branch has found, as have other investigators, that, contrary to general opinion, with extremely high temperatures more smoke is produced and more unburned gases are lost up the stack. High temperature is of course due to a supply of air approaching the theoretical amount, and on account of the difficulty of obtaining a complete mixture of the gases and air some gas is allowed to escape unburned. (See Table 1.)

The combustible gas most frequently found in the flue gases is carbon monoxide (CO). This gas is nearly always present when the stack gives off black smoke, indicating imperfect combustion. Hydrogen and hydrocarbon gases may also be expected in connection with the CO, but on account of the difficulty of determining the small percentages of these gases they are seldom recorded, though the loss due to their escape is considerable. In confirmation of these statements, the accompanying tables are submitted. Table 1 gives a summary of the relation of smoke to unburned gases and combustion-chamber temperatures as determined from more than 200 boiler tests made at the St. Louis fuel-testing plant.

TABLE 1.—*Relation of smoke to CO and combustion-chamber temperatures.*

| | Per cent of black smoke. | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 0 to 10 | 10 to 20 | 20 to 30 | 30 to 40 | 40 to 50 | 50 to 60 |
| Number of tests | 37 | 18 | 56 | 51 | 36 | 17 | 4 |
| Average per cent of smoke | 0 | 7.1 | 15.5 | 24.7 | 34.7 | 43.1 | 52.9 |
| Average per cent of CO in flue gases | 0.05 | 0.11 | 0.11 | 0.14 | 0.21 | 0.33 | 0.35 |
| Average per cent unaccounted for in heat balance | 9.14 | 10.60 | 9.46 | 10.93 | 11.41 | 13.41 | 13.34 |
| Number of tests [a] | 26 | 16 | 48 | 45 | 32 | 17 | 4 |
| Average combustion-chamber temperature (° F.) | 2,180 | 2,215 | 2,357 | 2,415 | 2,450 | 2,465 | 2,617 |

[a] Temperatures in combustion chamber were not determined on all tests.

Table 2, from the Manchester report (see p. 27), gives analyses of chimney gases, including determinations of hydrogen ($H_2$) and methane ($CH_4$), which occur in small percentages.

TABLE 2.—*Analyses of chimney gases.*

| Boilers. | Smoky. | | | | | | Clear. | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $CO_2$. | $O_2$. | CO. | $CH_4$. | $H_2$. | $N_2$. | $CO_2$. | $O_2$. | CO. | $CH_4$. | $H_2$. | $N_2$. |
| No. 1, hand-fired | 11.00 | 6.90 | 0.90 | ...... | ...... | 81.20 | ...... | ...... | ...... | ...... | ...... | ...... |
| | 10.65 | 6.45 | 2.15 | ...... | ...... | 80.75 | ...... | ...... | ...... | ...... | ...... | ...... |
| No. 1, with smoke-prevention device | ...... | ...... | ...... | ...... | ...... | ...... | 7.00 | 13.50 | 0 | ...... | ...... | 79.50 |
| | | | | | | | 9.00 | 9.75 | 0 | ...... | ...... | 81.25 |
| No. 2, hand fired | 10.25 | 8.60 | .50 | 0 | 0 | 80.65 | ...... | ...... | ...... | ...... | ...... | ...... |
| No. 3, hand fired | 13.25 | 3.50 | .05 | 0.25 | 0 | 82.95 | ...... | ...... | ...... | ...... | ...... | ...... |
| No. 4, fire under caustic pot, hand fired | 10.95 | 1.30 | 3.00 | .70 | 3.23 | 80.82 | ...... | ...... | ...... | ...... | ...... | ...... |
| No. 5, split bridge, hand fired | 8.75 | 7.00 | 3.25 | .40 | 1.00 | 79.60 | ...... | ...... | ...... | ...... | ...... | ...... |
| No. 6, with smoke-prevention device | ...... | ...... | ...... | ...... | ...... | ...... | 7.25 | 12.00 | 0 | 0 | 0 | 80.75 |
| No. 7, with smoke-prevention device | ...... | ...... | ...... | ...... | ...... | ...... | 7.15 | 12.15 | 0 | 0 | 0 | 80.70 |
| No. 8, with smoke-prevention device | ...... | ...... | ...... | ...... | ...... | ...... | 8.15 | 11.10 | 0 | 0 | 0 | 80.75 |

Table 3, compiled from results obtained at the fuel-testing plant, shows that the losses due to the escape of CO and other combustible gases may be considerable and that they are of more importance than the gain from a corresponding increase in carbon dioxide ($CO_2$). It is evident that the prevention of smoke and the efficiency of the plant are very closely related.

Calculations showing the theoretical losses due to the presence of combustible gases in the flue gases have been made and the results published in "A study of four hundred steaming tests." [a]

[a] U. S. Geol. Survey Bull. No. 325, 1907, pp. 100–101.

TABLE 3.—*Relation of CO to efficiency.*

| Number of tests. | 15 | 11 | 29 | 25 | 21 | 28 | 42 | 32 | 34 | 49 | 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Average per cent of $CO_2$ in flue gases | 7.69 | 9.46 | 9.29 | 9.09 | 9.48 | 9.48 | 9.90 | 9.60 | 9.57 | 10.22 | 10.94 |
| Average per cent of CO in flue gases | .63 | .53 | .27 | .22 | .17 | .19 | .13 | .16 | .12 | .15 | .10 |
| Average efficiency (72*) [a] | 52.96 | 56.73 | 59.56 | 62.08 | 63.43 | 64.58 | 65.55 | 66.41 | 67.48 | 69.10 | 71.73 |

[a] For discussion of efficiency 72*, see A study of four hundred steaming tests: U. S. Geol. Survey Bull. No. 325, 1907.

## PROPER FURNACE EQUIPMENT.

Numerous inventions for preventing smoke have been made, based, according to the inventors, on the recognized principles discussed in the foregoing section. Most of them have not been properly designed to meet the severe service to which a boiler furnace is subjected.

The proper design of the furnace and settings, including the breeching and stacks, is a subject of much dispute. All authorities, however, agree that sufficient air must be admitted to allow complete combustion. This means that ample draft must be provided. Stacks less than 125 feet high are usually unsatisfactory, but steam or electrically driven fans are now very commonly used to produce either forced or induced draft in connection with stacks shorter than would otherwise be required.

Provision should be made for the admission of air above the fuel bed. It is also now generally conceded that there should be a fire-brick chamber of sufficient length to allow time for the gases and air to mix and burn. Numerous observations made on power plants show that it takes an average of 12 seconds for the gases to pass from the furnace to the top of a stack 125 feet high. This allows but 1 second for combustion to take place before the gases leave the combustion chamber. These conditions have been so successfully met in some plants as to permit the use of low-grade coal without the production of objectionable smoke. These plants are few when compared to the total number in operation, but they indicate the possibilities of securing practically perfect combustion.

In general, furnaces designed for burning coal may be divided into two classes, as follows:

I. Those into which coal is shoveled at intervals by hand:
   - (*a*) Plain or rocking grates, with no fire-brick arch.
   - (*b*) Same as *a*, with steam jet under a small combustion space.
   - (*c*) Plain or rocking grates, with a fire-brick arch, large combustion space, and provision for admitting air over the fire either at the front or at the bridge wall.
   - (*d*) Plain or rocking grates, with large or small combustion chamber and with or without fire-brick arch, equipped with steam jets and air-admission dampers which close automatically after each firing.

(*e*) Combinations of any two or more of the above.

(*f*) Down-draft furnaces, consisting of two grates, the upper one of water tubes to prevent its destruction by the heat, and the lower one like the common hand-fired grate. The fire is built on the upper grate, and coal is fed or shoveled on top of the fire. The furnace is so arranged that the gases and flame pass down through the upper grate and over the lower one, on which a fire of coke, supplied from the upper grate, is maintained.

II. Those to which coal is fed continuously by an automatic device:

(*g*) Powdered-coal devices, in which particles of coal are thrown or blown into the furnace and burned before reaching the bottom of the combustion chamber, which must be of fire brick.

(*h*) Sprinkling stokers, or devices for automatically feeding and distributing small sizes of coal as evenly as possible over the entire grate surface. Automatic shaking grates are usually installed with this apparatus.

(*i*) Coking stokers:

1. Overfeed stokers, in which the coal is fed continuously and coked under a fire-brick arch. Special provisions are made to admit air to mix with the volatile gases. These may be further subdivided into front-feed and side-feed stokers.
2. Traveling chain-grate stokers, in which the coal is fed at the front under a fire-brick arch and the entire surface of the grate moves toward the bridge wall at a rate which allows all the coal to be consumed.
3. Underfeed stokers, in which the coal is automatically fed at frequent intervals beneath the bed of hot fuel, air is forced through the burning coal by means of a fan, and as the volatile gases are given off from the fresh coal they mix with the air and pass up through the fire. Under favorable conditions combustion is completed within a short distance from the surface of the fuel bed.

### DIFFICULTY IN OBTAINING PERFECT COMBUSTION.

With so great a variety of furnaces from which to choose it seems at first thought that there should be no difficulty in abating smoke. It is, however, difficult to construct a furnace that will be smokeless under any and all conditions of operation. Some furnaces now in operation are practically so, conforming to every requirement outlined for smokeless combustion, but there is no type of grate or stoker on the market today which does not give off offensive black smoke in some of the plants in which it is installed. This may or may not be due to faults in the furnace. It may be due to lack of combustion space or to improper handling.

The efficiency of the furnace and the degree of success attained by any equipment in the prevention of smoke depend on the following factors: Skill of the fireman, proper design of the furnace and boiler setting, character of the coal, capacity of the boilers and furnaces, and load carried.

The skill of the fireman is the most important element in connection with the ordinary equipment. As a matter of fact, the personal element is the greatest hindrance to progress in the abatement of smoke. Both the owner and the fireman must be interested to obtain the best results. Intelligent supervision in the boiler room to secure proper air admission and care in firing will result in the saving of the losses due to smoke or unconsumed gases and to heating an excessive amount of air. At many plants such supervision has reduced the coal bills by 5 to 20 per cent, depending on the coal and the methods formerly in use.

It is a generally conceded fact that intelligent men trained in boiler-room practice could save 10 per cent of the fuel used in 50 per cent of the plants of the United States, and that in another 25 per cent of the plants such men could save 5 per cent of the fuel. It is the practice of nearly all large power plants to employ a boiler-room expert, and many of them have chemists who make frequent tests and investigations to determine the conditions favorable to the best economy. The saving of only a small percentage of the coal consumed will make a handsome return for the cost of the experimental work. There are now in a few of our larger cities competent engineers who are making a specialty of supervising boiler plants for a number of firms.

A few examples of carelessness and indifference on the part of firemen will in a measure explain why many persons are skeptical regarding the value of mechanical stokers and other smoke-preventing devices.

At a plant which had a smoke-preventing device, but which was smoking, the fireman said a connecting chain had been broken for several days and he "didn't have time to bother with it." Not more than 10 minutes would have been required to join the two ends with wire for a temporary repair. In another plant the fireman said: "The thing takes too much steam, and I shut it off." Many other cases of willful neglect have been observed.

Very few firemen can be induced to fire regularly and frequently, because it is easier to put in enough coal to last 20 or 30 minutes at one time and have little or nothing to do in the interval between firings. In one instance the engineer took occasion to measure the draft between the grates, before and after firing, of a down-draft furnace which had a free draft. The draft before firing was 0.35 inch of water, but after the fireman had thrown on 63 shovelfuls of coal the flow of air was so seriously retarded that the draft increased to 0.62 inch. Great volumes of smoke were given off, indicating this lack of air.

Prof. Benjamin, in his paper on smoke and its abatement (see p. 26), speaking of steam and air jets, expressed himself as follows:

It is a very effective method of smoke prevention, and is used very largely in Cleveland. I have not given it very much weight in my paper, because it depends so much upon the individuality of the engineer and fireman. I have found that men who use that means had to be watched so continually and reprimanded so much that I got out of patience with that sort of prevention.

Difficulties are also encountered with stokers. One of the greatest troubles is the tendency of the firemen to poke the fires unnecessarily instead of using or adjusting the attachments provided for feeding and handling the coal. In many plants where it is possible they will shovel green coal into the stokers, instead of feeding it through the hopper, and then take a bar and stir up the fresh coal with the coke and ashes, causing smoke and wasting the coal.

It is not an uncommon experience that on inspection the boiler tubes are found to be covered with scale on one side and soot on the other. One plant with nearly 4,000 horsepower had soot hanging from the surfaces of the tubes, and an investigation showed that these tubes had not been cleaned for a period of four months, no cleaning having been done since the new master mechanic had taken charge.

The following quotation is from the Manchester report, already cited (see p. 27):

Negligent management of the self-acting damper is responsible for much of the smoke from hand firing * * *. No doubt its use obviates to some extent the necessity for constant attention, but in many cases it has been disconnected after attention has been drawn to the smoke.

The foregoing examples emphasize the facts that the management of the boiler room is a problem for properly trained men and that as the coal burned is a considerable item of expense, averaging about 50 per cent of the cost of producing power, there is more opportunity with any given equipment to save in the boiler room than in the engine room. The average boiler room is a hot, dirty, and otherwise unattractive place. For these reasons only slight attention has been paid to it by superintendents and operating engineers in moderate-sized plants. The boiler rooms are managed for the most part by men hired not so much for what they know as for their ability to do hard work, and they get comparatively small wages. There are, however, some mechanical appliances, such as the chain grate, which leave little to the skill of the fireman. (See "Suppression of industrial smoke," by A. Bement, cited in bibliography, p. 26.)

Many furnaces may be classed as smokeless when attended by careful men, but unsatisfactory when fired by ordinary firemen. In some power plants it is difficult for even a trained man to secure reasonable economy and prevent smoke. This may be due to the fact that the plant is poorly designed. It does not follow that a plant having a high chimney will have a sufficient draft. The chimney may be too small, or there may be many elbows in the flues leading from the boiler to the stack, or there may be serious leakage of air through holes in the flue, boiler setting, and breeching. A poor draft is responsible for a great deal of trouble in the boiler room. Difficulty in burning coal in some one furnace in a plant has been reported where investigation showed that the damper had turned on its shaft and instead of being open, as the fireman supposed, was nearly closed. Such difficulties can be avoided only by systematic supervision.

In many plants the grate surface is not properly proportioned to the load carried. This can be remedied in hand-fired furnaces, but not without considerable expense in stoker plants. Some plants maintain fires under too many boilers for good economy; on the other hand, there are probably more in which the furnaces are overloaded.

The hand firing of plain furnaces violates all the principles laid down for insuring good combustion. The coal is usually supplied in large quantities at long intervals, and the result is that at the times of firing the temperature of the furnace is lowered, the resistance to the flow of air through the fuel bed is increased, and consequently great quantities of combustible gas are generated which can not be burned for lack of air and the necessary amount of heat.

Hand-fired furnaces with steam and air jets may save enough by better combustion to make up for the cost of the steam used in the jets. They are looked upon as makeshifts by experienced smoke inspectors and others competent to judge them.

Hand-fired furnaces with ample combustion chambers and adjustable openings for air admission are suitable for some kinds of coal, if tended by experienced and careful firemen.

Down-draft furnaces have shown decided economy in many plants and have been fairly successful in the prevention of smoke. The principle is a good one, but few installations of these furnaces are properly fired. Whether they can be run smokelessly depends on the required capacity, the kind and size of coal, and the attention.

Mechanical apparatus for burning powdered coal in boiler furnaces has been tried in many plants and with few exceptions has been found unsatisfactory on account of the cost and difficulty of maintaining the furnace. It has, however, proved a decided success in firing cement kilns.

Sprinkling stokers have as yet made little headway in this country. Records given in the Manchester (England) smoke-prevention report show that these stokers are not as successful in preventing smoke as those of the coking type.

Furnaces with mechanical stokers of the overfeed types, including chain grates, which feed the coal gradually and coke it under a firebrick arch, are used more widely than any others except the plain hand-fired furnaces. When these stokers are properly installed in connection with ample combustion chambers, and carefully operated, they give good results and prevent smoke. Many of these furnaces are not properly installed and a still greater number are badly operated. The inclined-grate stokers will burn either high-volatile coals or coals high in fixed carbon. The chain-grate stokers are successful in burning high-volatile coals such as are found in Indiana and Illinois. They require less attention from the fireman than other types of stokers, and they can be operated smokelessly when properly installed. This stoker has not been adapted to burning low-volatile coals such as are largely used in the East.

Underfeed stokers that automatically feed the coal are usually successful with either high or low volatile fuels when properly nstalled and operated at a reasonable rate of combustion.

Many furnaces are burning coal unsuited to them, and under the load conditions smoke prevention is impossible. A change to another kind, or in some cases to another size of the same kind of coal, would prove satisfactory.

## INDIRECT METHODS OF SMOKE ABATEMENT.

There is at present a general tendency to centralize power, heating, and gas plants. In the heating of buildings it is customary under existing conditions to generate steam in the building. Where this is done, it is in general considered more economical to install engines for generating current for light and power also. However, many buildings furnish their own heat, but purchase current. Large power or light plants can now be located at any convenient place, say at the coal mines, because of the ease and economy with which electric current can be transmitted; but heating plants, whether for residence or for business districts, must be within a comparatively short distance from the section to be heated on account of the cost of installation and the losses from radiation. There are now more than 150 central heating plants in the United States, furnishing steam or hot water to residences or business buildings or to both. The greater number of these plants are located in the coal-producing States. Some of them have been built especially for the purpose of heating; others are additions to electric-lighting or industrial plants and utilize the exhaust steam from the engines. These central plants can be operated without smoke under favorable conditions, and they relieve the smoke situation in a measure. The plan of purchasing both heat and light, not only for residences, but also for business houses, is popular because it relieves the consumer of the details of operating a plant, does away with the dust of coal and ashes, and makes available for storage purposes space which would otherwise be occupied by the plant.

It has been suggested that in certain types of furnaces in which perfect combustion can not be maintained, the resulting smoke may be washed from the chimney gases in the same way as dust and soot are now removed from the air that is used in ventilating large office buildings, schoolhouses, and hospitals.

The increasing use of storage batteries by street railways and other interests has aided in the prevention of smoke. These batteries furnish the extra power needed when traffic is heavy during rush hours on the street railways and make unnecessary any sudden heavy demands on the power plants. The load on the engines being more nearly uniform, there is less change in the rate of combustion in the furnaces and less smoke, for change of load and crowding of boilers constitute a most prolific source of smoke.

## SUMMARY.

The increasing use of gas and coke for domestic, manufacturing, and power purposes and the centralization of power and heating plants tend to relieve cities of a large percentage of the smoke now given off by small and inefficient heating and power plants. Notwithstanding the fact that other ways of utilizing coal are growing in favor, it will evidently be necessary to burn coal in small boiler plants for some time to come. These coal-burning plants will continue to keep the problem of smoke abatement before the residents of large cities.

It is recommended that in order to improve the conditions in any city a record of all equipment and furnaces in the power plants be made, and that improvements, methods of operation, and the kinds of coal used be made a special study. It is only by such systematic methods that the local problem can be solved, as conditions in any one city are generally different from those in others, depending on the amount and kind of manufacturing and the character of the coal available.

The personal element is the most difficult obstacle to overcome in the fight against smoke. Study of the requirements and a desire to obtain good results on the part of the firemen will do more to clear the air in cities than any other one influence.

Being principally the result of an imperfect air supply, smoke can be prevented by providing for sufficient air and for its mixture with the gases in the furnace.

Well-designed furnaces may smoke to a greater or less degree, depending on the methods of the firemen, the kind or size of the coal, and the rate at which the coal is burned. They may be expected to give smokeless combustion when burning a suitable coal, except under the following unfavorable operating conditions:

1. When fires are built. The furnace not being heated to the required temperature, the gases cool below their ignition point and escape unburned.

2. When so much coal is burned on the grate that it is impossible to supply sufficient air without frequent poking. This condition usually results in so large a volume of gas from the coal that the gas can not be properly mixed with air and burned in the combustion chamber. On reaching the boiler surfaces it is cooled, combustion is arrested, and soot and smoke result.

3. When the rate of combustion is suddenly increased, as when more coal is added, and fires are poked to get up pressure in short time.

4. When the fires are checked by closing doors or dampers, thus cutting off the air supply. Banked fires are difficult to maintain and start up without smoke. Automatic dampers are frequently the cause of smoke when not properly adjusted or designed.

There is need of further study of coals, furnaces, and combustion, but enough is now known to enable an engineer to design and operate a steam plant without objectionable smoke.

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