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THE ILLINOIS SMOKELESS FURNACE

BY

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THE ILLINOIS SMOKELESS FURNACE

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ABSTRACT

The studies that led to the development of the Illinois Smokeless Furnace were begun in 1935, and consisted of experiments with a down-draft conversion burner installed in a hand-fired furnace. As a result of these initial studies the down-draft conversion burner was perfected. They demonstrated the practicability of the principles involved and indicated the possibility of their incorporation in a complete furnace unit. An experimental furnace, designed specifically to facilitate the study of all the factors affecting the performance of a smokeless furnace, was constructed in the Mechanical Engineering Laboratory in the summer of 1939.

The first commercial model was completed in December, 1942. It consists of an integral assembly of a number of parts, including a coking chamber, a coke-burning chamber, a baffle wall, three separate air orifices, and two forms of grates. In the coking chamber each charge of fresh coal is converted to coke, while that converted from the previous charge is burned in the coke-burning chamber at the back. The volatile matter released from the fresh coal mixes with the secondary air introduced through vertical air passages in the baffle wall. The mixture then passes over live coals in the coke-burning chamber, where it is ignited. The burning is completed in the combustion flues and the auxiliary combustion chamber located above the flues. Provision is made in the furnace for the control of the rate of gas release and the air supply for the thorough mixture of gas with secondary air, and for the ignition of the gas-air mixture. In general, the present designs are well adapted to normal production practices involving the fabrication of sheet steel. A study has not yet been made of the modifications necessary to adapt the smokeless principle to cast-iron furnaces or to boilers.

Performance tests of the furnace were conducted in the laboratory to determine the burning characteristics of a wide variety of solid fuels. In general, over a wide range of burning rates, the density of the smoke resulting from the burning of high-volatile coal was comparable with that obtained in using an underfeed stoker, and was well within the limits imposed by existing smoke ordinances.

Data are presented on the desirable proportions of the three sets of air orifices and on the operation of dampers placed over the orifices. The use of a combined check damper and draft regulator together with dampers used in connection with the orifices is recommended. The combined check damper and draft regulator limited the draft at the smoke collar of the furnace to 0.06 in. of water, which in turn limited the temperature that could be attained by the flue gases. Thus the arrangement served as a safety limit control, and it is probable that it could be equally well adapted to a conventional hand-fired furnace.

The performance of the furnace was entirely satisfactory in the Warm-Air Heating Research Residence, from the standpoint both of smokeless operation and of adaptability to temperature control.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

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THE ILLINOIS SMOKELESS FURNACE

I. Introduction

1. *Smoke Abatement.* — The widespread use of high-volatile bituminous coals in conventional hand-fired heating and cooking devices has resulted in serious atmospheric pollution in many cities, and as a consequence a general demand for smoke abatement programs has arisen. In St. Louis, for example,[1] an ordinance was enacted which prohibits the sale of high-volatile, bituminous coal in preparations suitable for use in hand-fired equipment. Other large cities confronted with acute smoke problems are considering the passage of similar ordinances.

Smoke abatement can be partly effected by the conversion of hand-fired equipment to stoker, oil, or gas firing. However, the expense of the required equipment, together with the added cost of oil or gas, makes conversion prohibitive to a large number of homeowners who must depend upon a low-cost fuel. Regardless of the popularity of oil and gas, the basic fuel for the United States is high-volatile coal, which constitutes over 98 per cent of the total fuel resources[2] and which is found in 29 of the 48 states. Undoubtedly, any feasible methods for the preparation of a smokeless fuel from high-volatile coals will assist in smoke abatement, provided that the resulting price of the prepared fuel is comparable with that of low-volatile coal. It is a fact, however, that the majority of homeowners will continue to depend upon the lowest-cost fuel available in their community. A complete solution of the smoke problem in the country as a whole, therefore, must involve the development of adequate hand-fired stoves, furnaces, and boilers that are capable of burning high-volatile coals smokelessly.

2. *Investigation of Smokeless Combustion.* — The studies that led to the development of the Illinois Smokeless Furnace were begun in 1935, and consisted of experiments with a hand-fired furnace in a private home. As a result of these studies, based on 45 experimental models, the down-draft burner described in Appendix E was perfected.

The studies on the down-draft burner demonstrated the practicability of the principles involved and indicated the possibility of their incorporation in a complete furnace unit. Accordingly, experiments on this phase of the subject were undertaken as a project of the Engineer-

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[1] R. R. Tucker, "A Smoke Elimination Program That Works," Heating, Piping, and Air Conditioning, Vol. 17, pp. 463-69. Sept., 1945.

[2] H. L. Ickes, "Coal's New Horizon," Coal Age, Vol. 48, No. 4, April, 1943, pp. 54-64.

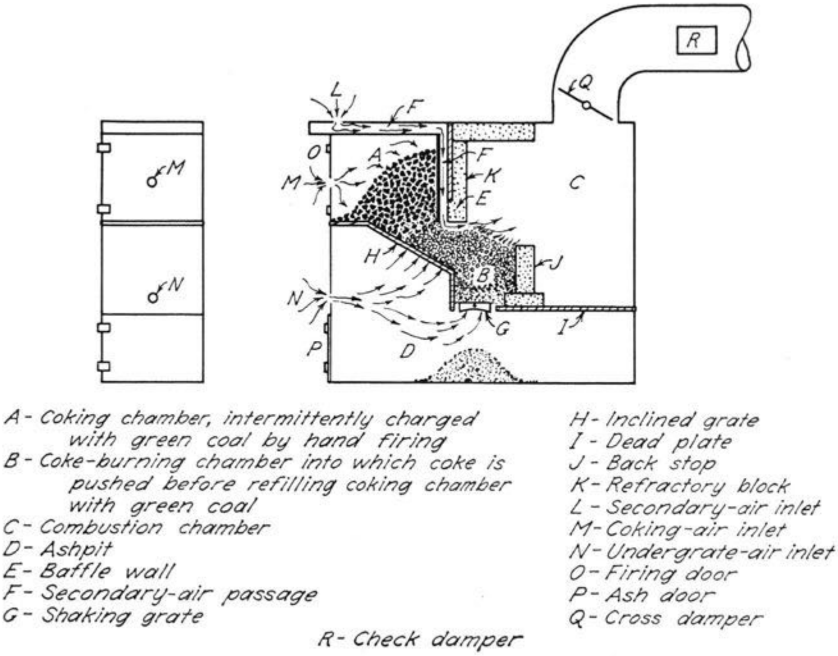

FIG. 1. DIAGRAM OF FIRST EXPERIMENTAL FURNACE

ing Experiment Station in 1939, and an experimental unit was built which was readily adapted to the study of such factors as the temperature of the baffle wall, the design of the grates, and the proportions of the various chambers and air inlets. As a result of tests[3] on this unit, which is shown in Fig. 1, it was established that owing to the high temperatures it was more practical to use a refractory baffle wall than one made of metal alloys. In addition, the tests served to determine the proper proportions for the sizes of the chambers and the air orifices.

The cooperation of an experienced furnace manufacturer was then enlisted and a new type of baffle wall was developed. The first commercial model, shown in Fig. 2, was completed in December, 1942. It was installed in the Mechanical Engineering Laboratory as shown in Fig. 3, and tests were made to determine the performance of the furnace with various fuels. For this purpose the furnace was operated over a wide range of combustion rates, varying from a minimum to

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[3] J. R. Fellows and J. C. Miles, "An Improved Hand-Fired Furnace for High-Volatile Coals," A.S.M.E. Trans., April, 1942, pp. 161-67.

the maximum that could be obtained with a draft of 0.06 in. of water measured at the smoke collar of the furnace.

During the heating season of 1943-1944 a similar model was installed in the Warm-Air Heating Research Residence for field investigations, and the furnace was subjected to a wide range of load demands in response to weather conditions. During the spring of 1944 and the heating season of 1944-1945, a larger unit incorporating the principle of the Illinois Smokeless Furnace was also tested in the Residence. The results obtained both in the Laboratory and in the Research Residence are presented in this bulletin.

Although most of the development work was done with furnaces for warm-air heating systems, the principles and many of the design features can be adapted to such fuel-burning devices as stoves, room heaters, boilers, water heaters, and ranges. Laboratory investigations in these fields are in various stages of progress. The existing patents and those which have been applied for are held by the University of Illinois Foundation, and licenses for the production of commercial units have been granted to a number of manufacturers upon a non-exclusive basis.

3. *Acknowledgments.* — This investigation has been carried on as a part of the work of the Engineering Experiment Station of the University of Illinois and as a project of the Department of Mechanical Engineering. The investigation was conducted under the general administrative direction of DEAN M. L. ENGER, director of the Engineering Experiment Station, and of EMERITUS PROFESSOR O. A. LEUTWILER, former head of the Department of Mechanical Engineering.

Acknowledgment is made to PROFESSOR JOHN C. MILES for his studies in connection with the first laboratory furnace. Acknowledgment is also made to the National Warm Air Heating and Air Conditioning Association for cooperation in providing the staff and the facilities of the Warm-Air Heating Research Residence for field investigations of the Illinois Smokeless Furnace. Credit is also due to MR. W. D. REDRUP and MR. JOHN W. NORRIS for their cooperation in adapting the principles of smokeless combustion to practical furnace construction. The data on the performance of the furnace when burning anthracite coal were taken by NWANKWO CHUKWUEMEKA, a graduate student in the Department of Mechanical Engineering during the academic year 1943-1944.

II. REQUIREMENTS FOR SMOKELESS COMBUSTION OF BITUMINOUS COAL

4. *Composition of Bituminous Coal.* — The design of any fuel-burning device must necessarily be adapted to the inherent characteristics of the fuel to be burned. Coal is a physical mixture of various chemical compounds. Largely as a matter of convenience, for the purpose of proximate analysis its constituents are usually designated as moisture, volatile matter, fixed carbon, and ash, some of which may be complex chemical structures. Although the composition of bituminous coal from different mines varies widely, the combustible portion always consists of carbon and combinations of hydrogen and carbon, together with small amounts of sulphur. Some of the carbon in the coal is present in an uncombined form, designated as fixed carbon, but the rest is united with hydrogen in the form of hydrocarbons.

These hydrocarbons constitute the major part of the gas-producing portion of the coal, or volatile matter, which is liberated from the fuel bed when the coal is heated. When the gaseous hydrocarbons are subjected to the high temperatures in the fuel bed and the combustion chamber, a complex chemical reaction takes place in which a part of the carbon may be freed from the hydrogen. Under favorable conditions of burning, the carbon will combine with oxygen to form carbon dioxide, and no uncombined carbon or smoke will be produced. Under unfavorable conditions, however, part of the carbon may fail to combine with oxygen, and will escape from the combustion chamber as soot or smoke.

5. *Requirements for Smokeless Combustion.* — In order to burn bituminous coals without the production of smoke, the volatile matter must be burned smokelessly. The basic requirements for smokeless combustion may be stated as follows:

(a) The rate at which volatile matter is released from the fresh fuel — in other words, the rate at which a charge of coal is coked — must be controlled.

(b) The gases as they are released must be thoroughly mixed with sufficient air, so that the oxygen in the air will be in intimate contact with the combustible gases.

(c) The combustible mixture of gas and air must be heated to a temperature that is above the ignition temperature for the mixture. The required temperature[4] for the instantaneous ignition of a mixture of coal gas and air is of the order of 1300 to 1500 deg. F.

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[4] J. W. McDavid, "The Temperature of Ignition of Gaseous Mixtures," Trans. Chemical Soc. (London), Vol. 3, pp. 1003-1015. 1917.

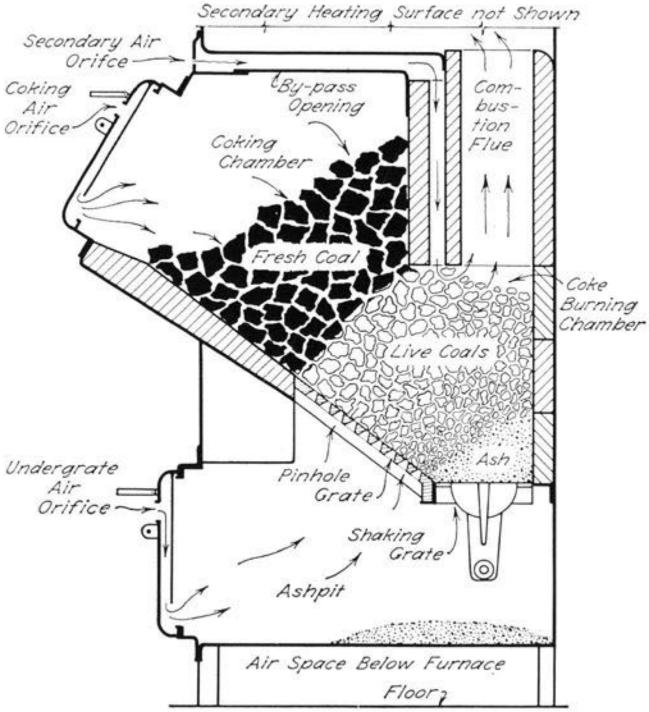

FIG. 2. CROSS-SECTION OF FIRST COMMERCIAL FURNACE

In the conventional furnace sufficient air is usually supplied over the fuel bed, but with the firing methods commonly employed by the householder the other basic requirements are not fulfilled, particularly during the period immediately after the firing of a fresh charge of coal.

6. *Operating Principles of Illinois Smokeless Furnace.*—The downdraft coking principle is employed in the Illinois Smokeless Furnace, shown in Fig. 2. In the coking chamber each charge of fresh coal is converted to coke, while that converted from the previous charge is burned in the coke-burning chamber at the back. The volatile matter released from the fresh coal mixes with the secondary air introduced through the vertical air passages. The mixture then passes over live coals in the coke-burning chamber, where it is ignited. The burning is completed in the combustion flues and the auxiliary combustion chamber located above the flues.

The rate of release of volatile gases is governed by the amount of air admitted to the coking chamber, and the rate of burning in the coke-burning chamber is determined by the amount of air admitted under the grates through the ashpit. The orifices in the firing door and the ashpit door are so proportioned that each charge of fresh coal is completely converted to coke before that from the previous charge is all burned. The furnace is ready for a fresh charge of coal when the fuel in the coking chamber is completely coked. At the time of firing, the ashes accumulated in the coke-burning chamber are shaken through the rotating grates, the newly formed coke is pushed back, and a fresh charge of coal is placed in the coking chamber. Thus, provision is made in the furnace for the control of the rate of gas release, the thorough mixture of gas with secondary air, and the ignition of the gas-air mixture.

A detailed description of the various component parts of the furnace is given in Appendix B, and performance data from both Laboratory and Residence tests are set forth in later sections of this bulletin.

III. EQUIPMENT USED

7. *Equipment in Laboratory.* — The furnace shown in Fig. 3, containing three flue sections and hereinafter referred to as the 3-section furnace, was developed subsequent to the tests on the experimental unit. Laboratory tests on this furnace were begun in December, 1942.

A cross damper was placed in the 8-in. smokepipe to facilitate obtaining low values of draft at the smoke outlet. The smokepipe, in turn, was connected to a metal stack, 10 in. in diameter and 25 ft. in height. In order that a wide range of stack drafts might be maintained steadily under all atmospheric conditions, an air jet regulated by a manually operated valve was directed upward into the stack to induce the flow of flue gas.

Measurements of smoke density were made by means of a recording smoke meter, in which a beam of light was passed through the path of the flue gas and focused on a thermopile. Smoke densities were recorded in percentage units on an arbitrary scale determined by considering the indication of the meter when the smokepipe was completely clear of smoke as zero, and the indication when the beam of light was completely intercepted as 100 per cent.

FIG. 3
THREE - SECTION FURNACE
INSTALLED IN
LABORATORY

Both an Orsat apparatus and a continuous recording CO_2 meter were used for flue gas analyses. Thermocouples were used for the measurements of temperatures of metal surfaces of the furnace, the circulating air, and the flue gas. Weights of coal and ash were determined by weighing on scales.

Tests on the 3-section furnace were made with both gravity and forced circulation of the air heated. In the forced-air arrangement, a centrifugal fan delivered air into the space between the furnace body and the casing. The fan was connected at the back of the casing by means of a short section of duct, which contained an air-measuring section. The quantity of circulating air delivered by the fan was measured by means of a Pitot tube installed in the calibrated air-measuring section. Measurements of the air volume and density, together with measurements of the temperatures of air entering and leaving the furnace, provided the necessary data for obtaining the bonnet capacity of the furnace.

8. *Equipment in Research Residence.* — The Warm-Air Heating Research Residence[5] is a three-story structure of standard frame construction, fully insulated, and equipped with storm sash and a storm door. The total space heated consisted of five rooms on the first story, four on the second, and three on the third. The calculated heat loss from the house was 51,140 B.t.u. per hr. for an indoor-outdoor temperature difference of 80 deg. F.; however, previous tests reported in Bulletin 355 indicated that the actual heat losses were probably somewhat higher.

The duct system for the forced-air heating arrangement used in these tests has been described in Bulletin 348. Three return ducts were connected to a return-air plenum, which was placed above the centrifugal fan. The furnace was in the east end of the basement, and two warm-air trunk ducts served 12 warm-air registers located in high sidewall positions in the rooms being heated. An outside brick chimney containing a 12-in. x 12-in. flue was used in this installation.

During a greater part of the 1943-1944 heating season a 3-section furnace was under test. This unit was similar in construction to the 3-section furnace installed in the Laboratory, shown in Fig. 3, except that the diameter of the smokepipe was 6 in. instead of 8 in. The arrangement of the secondary heating surface of this furnace is shown in Fig. 18, Appendix B.

In most of the tests the combustion was controlled by means of a

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[5] Described in A. C. Willard, A. P. Kratz, and V. S. Day, "Investigation of Warm-Air Furnaces and Heating Systems, Part III," Univ. of Ill. Eng. Exp. Sta. Bul. 189 (1929) and also in Kratz and S. Konzo, same monograph, Part VI, Bul. 266 (1934).

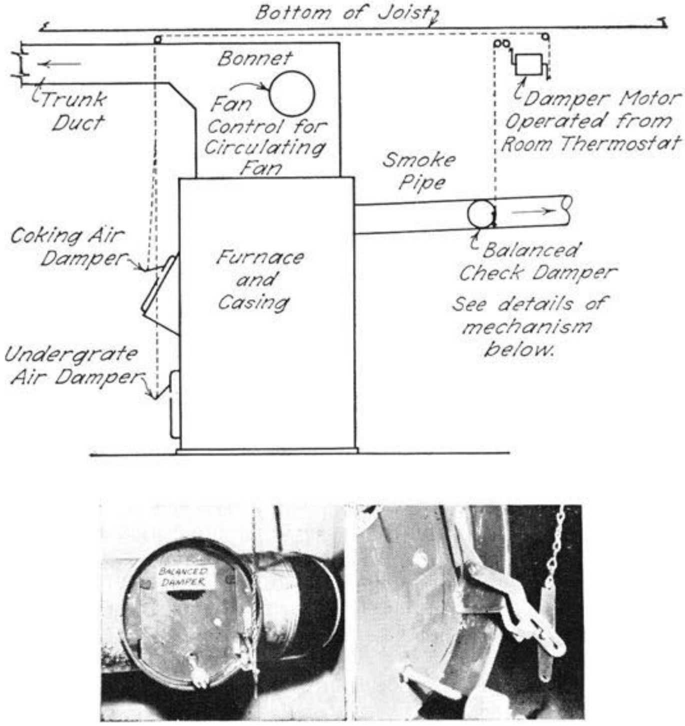

FIG. 4. ARRANGEMENT OF COMBINED CHECK DAMPER AND DRAFT REGULATOR

room thermostat and a damper motor, the latter being connected by chains to a damper in the coking-air inlet and to a combined check damper and draft regulator in the smokepipe. As shown in Fig. 4, this arrangement consisted of a barometric-type draft regulator which was fitted with a bracket and lever assembly. During periods of no heat demand the lever was raised so that the damper functioned as a check damper, but during periods of heat demand the lever was released and the damper served as an automatic draft regulator. The adjustable weights were so set that any draft in excess of about 0.06 in. opened the damper and permitted basement air to enter the chimney. Thus a definite upper limit was placed on the draft available at the smoke collar of the furnace, which in turn limited the temperature that could be attained by the flue gases. In consequence the arrangement served also as a safety limit control to prevent the attainment of dangerously high flue-gas temperatures. It is probable that this type of damper control could be equally well adapted to a conventional hand-fired furnace.

For low-fire conditions a draft as low as 0.01 in. of water at the smoke outlet of the furnace was necessary. However, the chimney in use produced a draft so high that the 6-in. check damper was not adequate to provide the desired reduction. It was therefore found necessary to supplement the small check damper with an auxiliary check damper installed in the cleanout of the chimney. In later tests on a 4-section furnace in which the smoke outlet was 9 in. in diameter, a single check damper in the smokepipe proved sufficient. It is possible that if an 8-in. smokepipe and check damper had been used with the 3-section furnace the auxiliary check damper would not have been necessary.

In a few tests with the 3-section furnace, the damper at the coking-air inlet was omitted and the draft control was obtained by means of the check damper alone. As discussed in Section 14, this arrangement of draft controls was not so satisfactory as that in which the coking-air inlet was also controlled.

In the spring of 1944 the 3-section furnace was replaced by a larger one, and the test program was continued during the rest of the 1943-1944 heating season and the entire 1944-1945 season. The larger furnace, shown in Fig. 5, had four flue sections, each with walls somewhat thicker than those used in the 3-section furnace. In addition, the fuel capacity of the 4-section furnace was larger than that of the 3-section. As shown in Fig. 18, Appendix B, the arrangement of the secondary heating surface was similar to that of a conventional, crescent-radiator type furnace. A refractory baffle was provided immediately above the vertical combustion flues in order to deflect the hot combustion gases toward the front of the furnace. The smokepipe was 9 in. in diameter and was provided with a 9-in. combined check damper and draft regulator. The control system for this furnace differed from that of the 3-section furnace in that an additional chain from the damper motor was connected to a damper placed over the undergrate air orifice. The two dampers, one over the coking-air and one over the undergrate-air orifice, used in connection with tightly fitting doors that could be clamped shut, provided a means of obtaining extremely low combustion rates during periods of low heat demand. Details of both furnaces, together with a discussion of desirable arrangements and sizes of the component parts, are presented in Appendix B.

Test equipment in the Residence included all instruments necessary for obtaining complete data relating to the performance of the furnace and the heating plant.

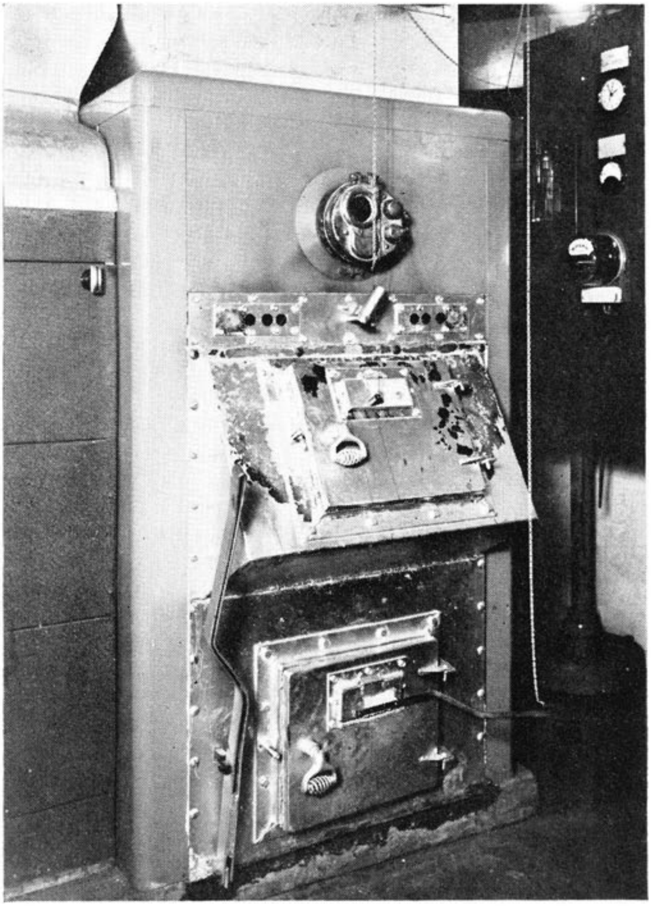

FIG. 5. FOUR-SECTION FURNACE INSTALLED IN RESEARCH RESIDENCE

IV. Test Procedure

9. *Procedure for Laboratory Plant.* — Several series of tests were conducted in the Laboratory plant to determine the performance of the furnace. For these tests sufficient fuel was fired to establish a normal fuel bed before the start of an actual test cycle. The furnace was then operated until it required refiring, and after shaking the grates and pushing the coke back, a sufficient weight of coal was fired to bring the fuel in the coking chamber to the same level as it was at the start. In general, the procedure involved performance tests conducted with maximum rates of combustion, followed by long hold-fire periods. During the tests the volume of air circulated was determined, and readings were made of the CO_2 content and temperature of the flue gas, the smoke density, and temperatures of the air entering and leaving the casing. Observations were also made of the character of the coke formed and the character of the ash. In a number of special tests, such as those to determine the proper proportions of the air inlets, the test procedure was modified to conform with the specific requirements of the test.

Before kindling a fire, necessary adjustments were made in the zero setting of the smoke recorder. In case any fogging of the glass lens had occurred, the effect on the zero reading was compensated for by slightly increasing the intensity of the light source. For those tests in which accurate comparisons of smoke density were required, the draft at the smoke collar was controlled by means of a manually operated cross damper in the smokepipe, in order to prevent any dilution of the flue gas by infiltration of air into the breeching. In some cases, however, the smoke density was of secondary importance, and the draft was more conveniently controlled by means of an automatic, draft-regulating damper attached to the breeching. Under these conditions the observed densities, as affected by infiltration of air through the regulating damper, were considered as equivalent to those which would be obtained at the top of a chimney.

For most of the studies of the performance characteristics of the furnace, Illinois coals from Franklin and Saline counties were burned. These coals, which were available in suitable preparations, represented fairly wide deviations in coking characteristics. Franklin County coal was free-burning, whereas that from Saline County had pronounced coking characteristics. Duplicate series of tests were conducted with each coal. A number of coals from other sources were also burned in the furnace. The results are discussed in Section 11. Since the available quantity of these fuels was small, each test was necessarily short.

TABLE 1

PROXIMATE ANALYSES OF COALS USED IN RESEARCH RESIDENCE

As-received basis. Analysis by Applied Chemistry Division, University of Illinois.

	Vermilion County, Illinois, Westville Mine	Saline County, Illinois
Moisture	12.33 per cent	4.94 per cent
Volatile Matter	35.05 per cent	36.19 per cent
Fixed Carbon	44.58 per cent	52.28 per cent
Ash	8.04 per cent	6.59 per cent
Total	100.00 per cent	100.00 per cent
Sulphur	1.22 per cent	1.34 per cent
Heating Value	11,441 B.t.u. per lb.	13,032 B.t.u. per lb.

10. *Procedure for Residence Plant.* — The furnaces in the Residence were hand-fired, and the ashes were removed manually. Each furnace was controlled by means of a room thermostat which operated the damper motor. The firing was done by inexperienced operators, who were given the same instructions that would normally be furnished with the furnace for use by the householder. The furnace was not fired in accordance with any definite time schedule, but was served in a manner considered representative of the methods that would be employed by the average householder. In mild weather the fuel bed was inspected once a day, and a fresh charge of fuel was added if necessary. During severe weather the furnace was fired whenever the temperature in the house became too low for comfort.

Continuous records were made of the smoke density, the CO_2 content and temperature of the flue gas, the drafts at the smoke collar and at the base of the chimney, and the temperatures of the outdoor and indoor air. Incidental data consisting of room air temperatures, hours of fan operation, electrical input to the fan motor, relative humidity, etc., were also recorded five times each day.

Nut coal, 1¼ in. by 2 in., from Vermilion County, Illinois, was used during the 1943-1944 season; Saline County, Illinois, coal was used during the 1944-1945 season. Proximate analyses of both coals are given in Table 1. Records were made of all coal fired and all refuse removed from the furnace.

A special test was conducted on the 3-section furnace, during which the furnace was operated at the maximum combustion rate obtainable with a draft of 0.06 in. at the smoke collar. The results of this test are presented in Section 16.

V. RESULTS OF TESTS IN LABORATORY

11. *Burning Characteristics Obtained with Different Solid Fuels.* — A series of tests was conducted in the laboratory to determine the burning characteristics of a wide variety of solid fuels. The samples, weighing from 200 to 400 lb., differed widely with respect to such properties as moisture content, volatile matter content, ash content, ash fusion temperature, and friability of coke formed. Each fuel was burned over a period of at least two complete firing cycles at a maximum combustion rate, and over a period of at least one long hold-fire cycle. In a few cases, the burning characteristics at an intermediate combustion rate were also observed over a period of a complete firing cycle. A brief résumé of the observations made from a representative group of these tests is given in Table 2.

Fuels of such diverse types as lignite, bituminous coal, anthracite, coke, and carbon briquets were burned with little difficulty and with practically no smoke. However, in the cases of lignite and low-volatile fuels some modifications were made in the proportionate amounts of air supplied to the three orifices of the furnace, as discussed in Appendix B, Section 7.

The following general conclusions, based on the experience obtained in these tests, may be drawn with respect to the burning characteristics obtained with different solid fuels:

(a) Fuels having a range of volatile matter of from 1.5 per cent to 41.9 per cent were satisfactorily burned. (Column 5, Table 2.)

(b) Coals having a high ash content introduced no difficulty, aside from the inconvenience of removing greater amounts of ash. From the standpoint of hold-fire characteristics, in fuels having a high ash content the ash served to insulate a small bed of hot coals and thereby tended to increase the possible length of the hold-fire period. (Column 7.)

(c) By increasing the size of the coking-air orifice, it was possible to burn lignite having a calorific value of about 7000 B.t.u. per lb. at a rate sufficient to obtain about the same heat output from the furnace as that obtained with coals having twice this calorific value. (Column 8.) The firing periods for rated output of the furnace were considerably shorter for lignite than for fuels having higher calorific values. Excellent hold-fire characteristics were observed with lignite, the fuel responding even more readily than bituminous coal after the fire had been checked for as long as 24 hr.

TABLE 2
BURNING CHARACTERISTICS OBTAINED WITH DIFFERENT FUELS*

Fuel No.	Type	Location of Mine	Characteristic Prox. Analysis as Rec'd.†					Ash Softening Range, deg. F.	Size in Inches	Type of Coke Formed	Special Precautions	Characteristics Exhibited	
			Moist.	V.M.	F.C.	Ash	B.t.u.					Advantageous	Disadvantageous
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	High Vol. Bit.	Ill., Franklin County	9.5	33.0	49.0	8.5	11 900	2100-2500	¾ x 1½, 2 x 3	Easily broken	Do not refire until charge is well coked	Good response Holds fire well	None
2	High Vol. Bit.	Ill., Saline County‡	3.5	38.2	51.6	6.7	13 040	2000-2100	1½ x 2, 2 x 3	Firm when first formed	As above	As above	None
3	High Vol. Bit.	Ill., Westville‡	12.3	35.1	44.6	8.0	11 441	1940	1¼ x 2, ¼ x ¾	Easily broken	As above	As above	None
4	High Vol. Bit.	Ill., Springfield	15.2	34.3	38.5	12.0	10 450	1900-2000	1 x 2	Easily broken	As above	As above	None
5	High Vol. Bit.	Ill., Knox County	14.5	37.2	38.6	9.7	10 970	......	1 x 2	Easily broken	As above	As above	None
6	High Vol. Bit.	Ill., Vermilion County	13.3	36.6	39.0	11.1	10 940	1940	1 x 2	Easily broken	As above	As above	None
7	High Vol. Bit.	Ind., Clay County (Brazil)	16.0	31.3	46.5	6.2	11 460	......	1 x 2	Easily broken	As above	As above	None
8	High Vol. Bit.	Iowa, Polk County	14.8	33.7	35.1	16.4	9 840	......	1 x 2	Easily broken	As above	As above	None
9	High Vol. Bit.	Ky., Perry County	3.5	37.3	54.8	4.4	13 820	2300-2800	3 x 6, ¼ x 1	Firm when first formed	As above	As above	None
10	High Vol. Bit.	Pa., Pittsburgh	3.0	35.1	54.4	7.5	13 540	2400-2700	2 x 4	Firm when first formed	As above	As above	None
11	High Vol. Bit.	Tenn., Campbell County	4.0	36.6	53.9	5.5	13 520	......	1 x 2	Easily broken	As above	As above	None
12	High Vol. Bit.	Utah, Carbon County	4.9	41.9	47.1	6.1	12 860	2400	2 x 6	Easily broken	As above	As above	None
13	High Vol. Bit.	Montana, Roundup	14.2	30.6	47.7	7.5	10 870	2400	3 x 6	Easily broken	As above	As above	None
14	High Vol. Bit.	Colorado, Pitkin	2.2	33.1	57.3	6.7	14 120	......	3 x 6	Easily broken	As above	As above	None
15	High Vol. Bit.	Canada, Nova Scotia		Information not available				......	2 x 6	Easily broken	As above	As above	None
16	High Vol. Bit.	Chile, Concepcion		Information not available				......	2 x 6	Easily broken	As above	As above	None
17	Sub. Bit.	Colorado, Boulder	20.0	30.7	44.8	4.5	9 980	2300	3 x 6	Non-coking	As above	As above	None
18	Low Vol. Bit.	W. Va., Raleigh County	2.7	17.1	74.8	5.4	14 390	2800-3000	¾ x 1	Firm when first formed	As above	As above	None
19	Lignite	N. Dak., Ward County	35.1	26.5	30.0	8.4	6 720	2100-2200	2 x 6	Non-coking	Coke will pack if unnecessarily disturbed	As above	Tendency to disintegrate and pack in coke-burning chamber
20	Lignite stored 4 yrs.	Texas	34.7	32.2	21.8	11.2	7 056	......	2 x 6	Non-coking		As above	
21	Anthr.	Pa., Pittston	4.3	3.8	82.2	9.7	12 830	3000	Chestnut	Non-coking	Do not let fire get low	Hold fire several days	Slow response
22	Metall. Coke	Ill.-W. Va. Mixture	0	1.5	88.8	9.7	13 000	2140	2 x 4	Non-coking	As above	Clean	Hard to ignite Low density
23	Carbon Briquet	Oregon, Gas and Coke Co.	0	15.0	84.5	1.5	14 800	......	1 x 2	Non-coking	As above	Little ash	May smoke at low burning rate

* See Table 4 for air proportions used. For fuel Nos. 11 and 12, coking air must be reduced slightly.

† Source of analyses:

For coal Nos. 1, 4-14, 17-19, 21:	Bureau of Mines Bulletin 446
For coal Nos. 2, 22:	Illinois Geological Survey
For coal No. 3:	University of Illinois
For coal No. 23:	Portland Gas Coke Co.
For coal No. 20:	Kent Handbook

‡ Coal Nos. 2 and 3 were used in Research Residence tests. All other coals were tested in laboratory furnace.

(d) Bituminous coals having ash-softening temperatures ranging from about 1900 to 2800 deg. F. were burned without formation of slag or clinkers. (Column 9.) Some fusion of the ash was noted when the coke sample listed as No. 22 was burned.

(e) Coals ranging in size from ¼ in. x ¾ in. to 3 in. x 6 in. were satisfactorily burned. However, coals of the types listed as Nos. 9, 10, 15, and 16 did not coke satisfactorily at the center of the coking chamber if a large proportion of the pieces was less than 2 in. in diameter. (Column 10.) Stoker coals free from excessive amounts of fines were successfully burned, but better results were obtained with preparations including pieces between 1 in. and 6 in. in size.

It is probable that the angle of the firing door and the shape of the coking chamber are well adapted to the use of packaged fuel.

(f) Most of the bituminous coals formed a coke mass that was easily broken up and pushed back by sliding the push poker, shown in Fig. 19, Appendix B, along the floor of the coking chamber. Some of the fuels — Nos. 9, 10, 15, 16, and 18 — formed a coke mass that was relatively hard when first formed but that became friable if allowed to burn to some extent before being pushed back. By using coarser preparations, such as 3 in. x 6 in. egg, a more friable type of coke was formed.

Fuels listed as Nos. 13, 17, and 19 to 23 did not coke, and the individual lumps of fuel retained their separate identities. As these fuels burned, the entire charge of fuel settled downward into the coke-burning chamber. It was, therefore, found advisable to refill the coking chamber before the fuel bed had burned too low. No difficulty was experienced when fuel was added to the coking chamber before the charge had completely coked. Since these fuels did not soften when heated, the fuel bed could be disturbed without the release of volatile matter and smoke. Although the furnace was specifically designed for high-volatile bituminous coals, the results of these tests proved that it was also well adapted to practically all solid fuels.

12. *Effect of Draft on Furnace Performance.* — The effect of draft at the smoke collar on the performance of the furnace is shown by the curves in Fig. 6, the data for which were obtained from tests on the 3-section furnace. Four tests were made with 2-in. x 3-in. bituminous coal from Saline County, Illinois, and two with chestnut-size anthracite from Pittston, Pennsylvania. After the preparation of the fuel bed at the beginning of each test cycle, no further attention was given to the furnace between firings.

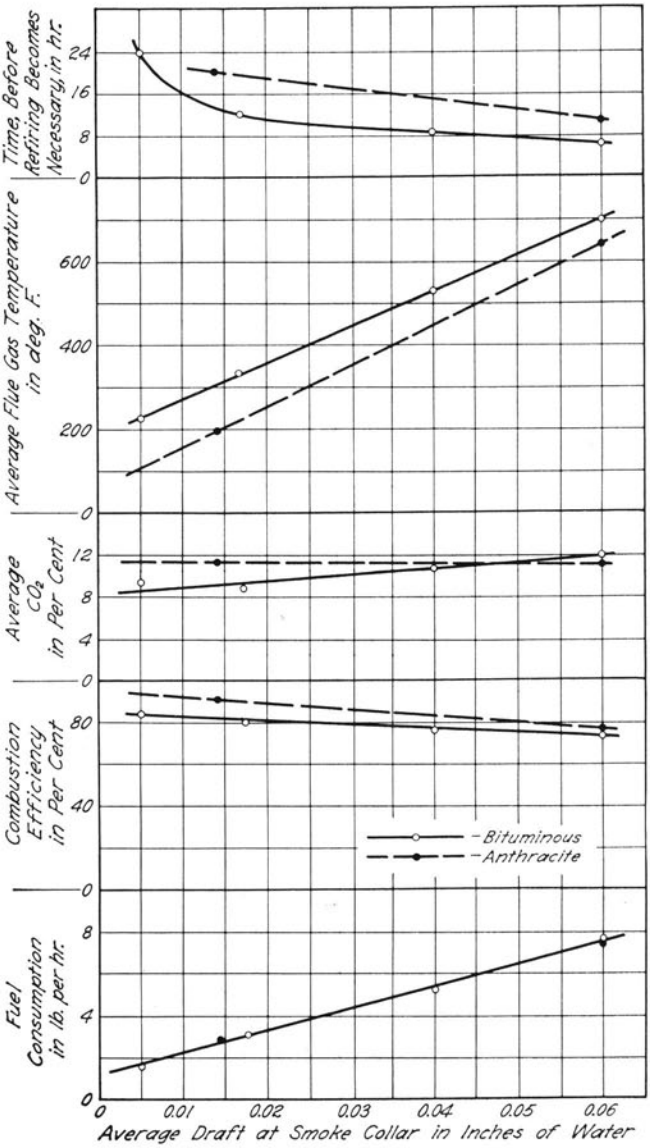

FIG. 6. PERFORMANCE OF FURNACE AS AFFECTED BY DRAFT

The sizes of the orifices used in connection with these tests were substantially the same as those recommended in Appendix B, Section 7. For the tests with Illinois coal, the orifices employed were all 1 in. in diameter. Four orifices were used for the secondary air, one for the coking air, and one for the undergrate air. For the tests with anthracite, one orifice 1 in. in diameter was used for the secondary air, one orifice ⅞ in. in diameter for the coking air, and one orifice 1¾ in. in diameter for the undergrate air. No dampers were used over any of the orifices, and the draft was kept constant by frequent adjustment of a manually operated cross damper in the smokepipe.

The tests with bituminous coal were run with drafts of 0.005 in., 0.017 in., 0.04 in., and 0.06 in. of water at the smoke collar. As shown in Fig. 6, when the draft was increased from 0.005 in. to 0.06 in. the burning rate increased from 1.5 lb. per hr. to 7.5 lb. per hr. The corresponding increase in flue gas temperature was from 220 to 690 deg. F. Between 8.5 per cent and 11.5 per cent, increases in the CO_2 content of the flue gases have relatively small effect on the flue gas loss. As a result the flue gas loss, and hence the combustion efficiency, which is defined as 100 minus the sum of the percentages of the flue gas loss and the grate loss, is primarily determined by the temperature of the flue gases. As shown in Fig. 6, the combustion efficiency varied from 84 per cent at low draft to about 72 per cent at a draft of 0.06 in. of water.

In the operation of a hand-fired furnace during mild weather, it is often necessary that burning rates of less than about 1 lb. of coal per hr. be maintained. Any significant amount of burning that occurs during hold-fire periods results in appreciably overheating the house. In the case of conventional, hand-fired furnaces, in which feed and ashpit doors and undergrate-air dampers may not be tight, even the exercise of considerable skill in the adjustment of drafts and in the firing of the furnace may not result in a sufficiently low burning rate.

In the case of the Illinois Smokeless Furnace, it may be observed from the lower curve in Fig. 6 that for a draft of 0.005 in. the burning rate was 1.5 lb. per hr. Furthermore, in order to obtain a rate of 1.0 lb. per hr., a draft of zero at the smoke collar would have been necessary. Special tests of the 3-section furnace confirmed the fact that when a zero draft was actually maintained at the smoke collar, the fuel continued to burn. Under these conditions the chimney action of the vertical combustion flues produced a draft at the level of the bottom of the baffle wall that was sufficient to induce a flow of air into the orifices even though the draft indicated at the smoke collar was zero.

The same results were observed when the smokepipe was disconnected from the furnace.

In this series of tests no dampers were used over any of the three orifices, and low burning rates could be attained only by controlling the draft by means of the cross damper in the smokepipe. Under service conditions it is probable that with this arrangement, drafts of less than 0.01 in. could not be readily achieved and that, as a result, burning rates exceeding 1.0 lb. per hr. would be attained. It was further indicated that some additional means of dampering, or checking the flow of air through the orifices, would be desirable. Results of tests conducted in the Laboratory and Residence plants and discussed in Sections 14 and 15 proved that, with the use of suitable dampers to reduce the hourly fuel consumption to less than 1 lb., the Illinois Smokeless Furnace is particularly well adapted to the prevention of overheating in mild weather.

It may be noted in Fig. 6 that when anthracite instead of bituminous coal was burned, lower temperatures of flue gases and somewhat higher combustion efficiencies were indicated. With a given draft at the smoke collar, no difference was observed between the burning rates for anthracite and bituminous coal. In this respect the performance of the Illinois Smokeless Furnace differs from that obtained when the two fuels are burned in the conventional furnace. In the latter case, at the same rate of burning, greater drafts are usually required for anthracite than for bituminous coal. With a given CO_2 content of the flue gases both of these fuels require practically the same weight of air to burn 1 lb. of fuel. In the conventional furnace, when the ashpit damper is opened the major resistance to the flow of air is in the fuel bed itself, and the resistance of an anthracite fuel bed is usually greater than that of a bituminous coal fuel bed. Hence, to burn the same amount of coal the former requires more draft than the latter. In the Illinois Smokeless Furnace, however, the major resistance is offered by the control orifices, and in order to induce the flow of the same amount of air necessary to burn equal amounts of fuel, practically the same intensity of draft is required.

The curves in Fig. 7 show the relative rates of increase of flue gas temperatures for anthracite and bituminous coal. From these curves it is evident that the response to heat demands was slower with anthracite than with bituminous coal. It was further observed, however, that when anthracite was burned, owing to the greater density of the fuel the furnace could be operated for longer periods between firings than was possible when bituminous coal was used.

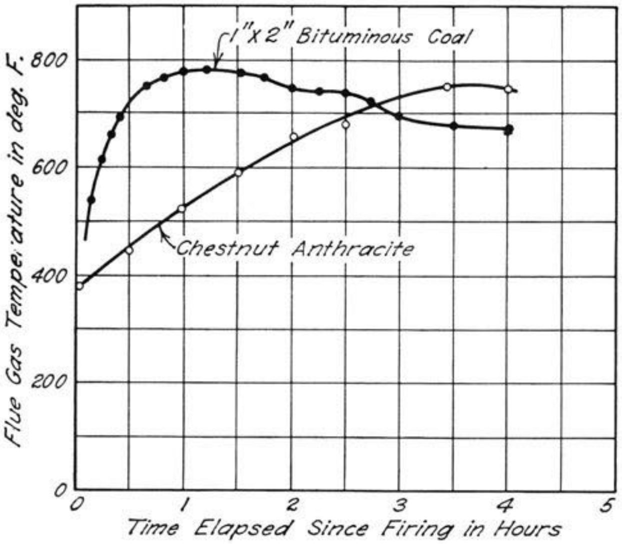

FIG. 7. RATE OF INCREASE OF FLUE GAS TEMPERATURE AFTER FIRING

13. *Smoke Density.* — Smoke records obtained from tests made on a conventional hand-fired furnace, reproduced from Engineering Experiment Station Circular 46, are shown in Fig. 8. The factors which influence the production of smoke cannot be exactly duplicated in successive firings of any furnace. As a result it was difficult to obtain a single smoke record that could be considered as typical for all conventional hand-fired furnaces. The records of smoke density shown in Fig. 8 should therefore be considered as approximate representations of average firing conditions. However, from these records, used in conjunction with other observations, it was demonstrated that the amount of smoke produced after a charge of coal was placed in the firepot was largely dependent upon the amount of ash on the grate, the amount and position of the hot coals in the firepot, the amount and location of the coal charge, the amounts of air entering above and below the fire, and the draft at the smoke collar of the furnace.

Two methods of firing were employed in the tests with the conventional furnace — the side-bank method and the spreading method. In the former the coked charge in the fuel bed was moved to one side of the firepot, and the fresh charge of coal was placed in the cleared space. In the spreading method the fresh charge of coal was spread

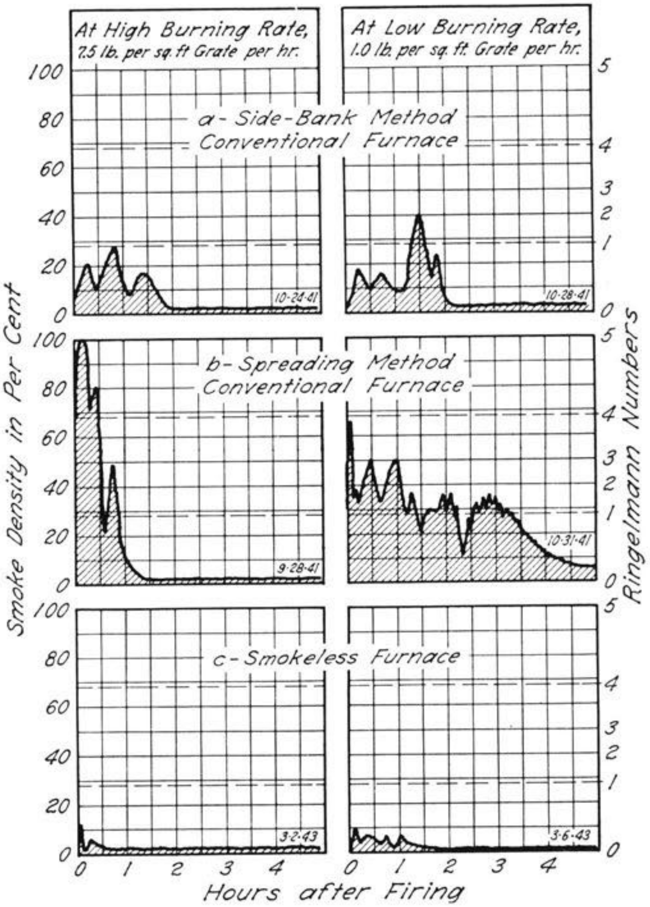

FIG. 8. COMPARATIVE SMOKE RECORDS OBTAINED WITH CONVENTIONAL FURNACE AND ILLINOIS SMOKELESS FURNACE

uniformly over the entire surface of the fuel bed. With both methods of firing, tests were made at combustion rates of 7.5 and 1.0 lb. per sq. ft. of grate area per hr. The coal burned was a high-volatile bituminous coal from Saline County, Illinois.

The records of smoke density obtained with the side-bank method of firing are shown in the upper part of Fig. 8. The ordinates at the left side of the figure show the smoke density in percentage units, as recorded by the smoke meter. The scale on the right side of the figure shows the equivalent Ringelmann Index of smoke densities, which is commonly referred to in smoke abatement ordinances. It is common practice for smoke ordinances to limit the production of smoke to six minutes of No. 3 smoke in any one hour.

It may be noted that the use of the side-bank method of firing in a conventional furnace produced smoke of relatively low density that would be within the limitations imposed by most smoke ordinances. The side-bank method of firing has not been universally employed in the field, in spite of the extensive campaigns that have been periodically conducted to train householders in the required technique. To some extent the adoption of the method has been retarded because of the limited space within the firepot of a conventional furnace, which has made it difficult for the operator to separate the coke charge properly from the fresh charge of coal. Furthermore, during periods of greatest heat demand, the charging of fresh coal tends to cool the fire and appreciably reduces burning rate during the first few minutes after firing.

Hence, although the widespread employment of the side-bank method would considerably reduce the amount of smoke produced, large numbers of householders continue to employ the spreading method of firing. The middle set of curves in Fig. 8 shows the smoke density records obtained with this method of firing. For a period of about one hour after a fresh charge was spread over the top of a hot fuel bed, the smoke densities greatly exceeded the maximum tolerated by most smoke ordinances.

Comparable smoke densities, obtained in the Laboratory with the Illinois Smokeless Furnace, are shown in the lower part of Fig. 8. The densest smoke occurring at any time during these tests was considerably less than a No. 1 density as measured by the Ringelmann Index.

A careful scrutiny of 220 smoke record charts made at the Research Residence and covering 5280 hours of operation showed that during this period of operation the density of the smoke from the Illinois Smokeless Furnace (quoted in terms of the Ringelmann Index) was less than one-half of a No. 1 during 97.5 per cent of the total time, less than a No. 1 for 99.3 per cent of the time, and less than a No. 1½ for 99.6 per cent of the time.

Visual observations of the top of the chimney together with a perusal of all recorded test notes and a study of the smoke record charts indicate that even under the worst conditions the smoke emitted at the top of the chimney rarely exceeded a light gray haze and that most of the time not even a light haze was visible.

Whenever the dampers closed at the end of a considerable period of sustained heat demand, and before volatilization of the last charge of coal was complete, a momentary discharge of smoke sometimes occurred. This smoke, which was similar to that which often may be observed immediately following the stopping of a stoker, seldom exceeded a No. 2 Ringelmann density and lasted for only a brief period varying from a few seconds to a few minutes. The smoke densities observed during these short periods were almost always well within the limitations imposed by most smoke ordinances.

If the firing was delayed until the coke in the coke-burning chamber was practically consumed, it was difficult to avoid the production of a light gray smoke immediately after a fresh charge had been placed in the coking chamber. This condition of the fuel bed would be encountered infrequently, and proper methods of firing to prevent its occurrence are discussed in Appendix D, Section 5.

In extremely cold weather, a white fog was observed at the top of the chimney. This discharge consisted of small droplets of water, condensed from the water vapor in the products of combustion. This water vapor is formed by the burning of the hydrogen in the fuel and is unavoidable. A similar discharge can usually be observed in cold weather at the top of a chimney handling the products of combustion from a furnace in which natural gas or oil is burned.

14. *Studies of Five Methods of Controlling Dampers.* — During mild weather the amount of overheating in a house heated by a hand-fired furnace is largely determined by the amount of burning which takes place after the room thermostat has acted to operate the check dampers. The burning rate should therefore be sufficiently reduced so that overheating in the rooms is negligible. On the other hand, it should not be reduced to the extent that the fire is extinguished or that the chimney gases are excessively cooled. In the latter case a reversal of the draft may occur, and smoke may back out through the firing door.

Accordingly, a study was made of the comparative effectiveness of five different methods of controlling the dampers; the results are shown in Fig. 9. For convenience in referring to the four dampers that controlled the rates of air input through the orifices, the dampers have been designated as A, B, C, and D, as indicated on the inset in the diagram. It should be noted that damper D consisted of the combined check damper and draft regulator described in Fig. 4. In this study the furnace was operated with a normal fuel bed in which the coke-burning chamber was filled with live coals and the coking chamber was filled with fresh fuel. Since changes in combustion rate are immediately reflected as changes in the temperature of the flue gases, the temperature of the gases at the smoke collar was adopted as a convenient index of the rate of burning. At the start of the tests, therefore, a draft of 0.06 in. was maintained at the smoke collar until the flue gases had attained a temperature of 710 deg. F., as measured by means of a thermocouple, T, inserted in the smokepipe about 3 in. ahead of the smoke collar. At this time dampers A, B, and C were open and the check damper was closed. The draft was controlled by means of the combined check damper and draft regulator. The draft was then quickly reduced to approximately 0.02 in. of water by opening the check damper D in the smokepipe, and the temperature of the gases was observed at 1-min. intervals for a total period of 10 min. At the end of that period the check damper was closed until the gases again attained a temperature of 710 deg. F. In the second test the coking-air damper B was closed simultaneously with the opening of the check damper. Three other tests were subsequently conducted, using different combinations of the dampers as indicated in Fig. 9. The following results were obtained with the different methods of operation.

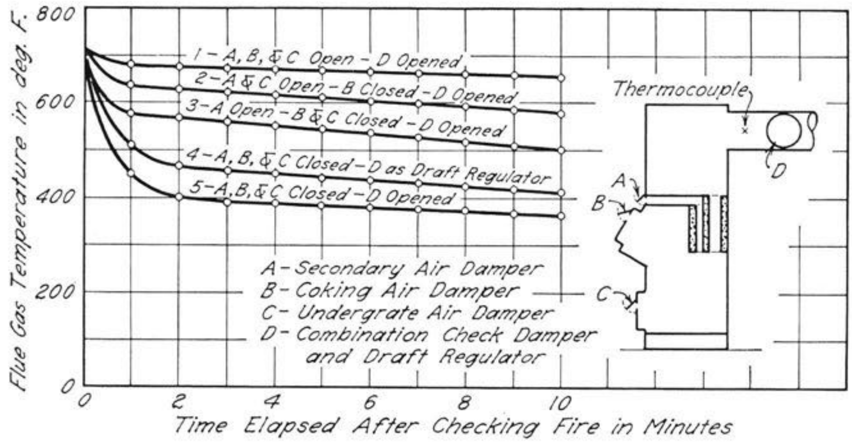

FIG. 9. REDUCTION IN FLUE GAS TEMPERATURE BY CONTROL OF DAMPERS

Method 1 consisted of controlling the burning rate by means of the check damper D alone. The use of this method resulted in a very low rate of decrease in the temperature of the flue gases. As shown by the top curve in Fig. 9, this temperature decreased from 710 deg. F. to 650 deg. F., representing a drop of only 60 deg. F. in 10 min. Control method 1 was used in all the preliminary tests in the Laboratory, and gave excellent results as far as the maintenance of high combustion efficiency was concerned. It also produced good results in the Residence in cold weather during which long on-periods were required to sustain high heat outputs. In mild weather, however, the heat outputs obtained during the relatively long off-periods resulted in considerable overheating of the house. It was also found that the furnace had a tendency to "puff-back," as discussed in Appendix D, Section 7.

Method 2 consisted of controlling the burning rate by the simultaneous operation of the coking-air damper B and the check damper D. The use of this method resulted in a slightly greater rate of decrease in the flue gas temperature than that obtained with method 1. The drop in temperature amounted to 140 deg. F. in 10 min. Furthermore, this method of control eliminated any tendency for smoke to puff back through the firing door. On the other hand, some amount of overheating was obtained in the rooms in the Research Residence and in other homes. In general, however, the results may be considered similar to those that would be obtained with a conventional furnace equipped with a check damper in the smokepipe and a damper over the opening in the ashpit door.

Method 3 consisted of controlling the burning rate by the simultaneous operation of both primary air-dampers B and C and the check damper D. The use of this method resulted in a considerable reduction in the rate of burning that occurred during the off-period after the furnace was checked. At the end of 10 min., a reduction of about 210 deg. F. in the temperature of the flue gases was obtained. As indicated in Section 18, method 3 was also used in the Research Residence throughout one heating season, and the results were entirely satisfactory. A slight amount of overheating of the house during mild weather was experienced, but the amount was not sufficient to cause any appreciable discomfort.

Method 4 consisted of controlling the burning rate by means of dampers A, B, and C with damper D serving as a draft regulator only. The secondary air-damper A was provided with "bleed holes," having approximately one-fifth the area of the secondary air orifices located underneath the damper. The operating lever of the combined check damper and draft regulator D was not connected to the motor, and for chimney drafts of less than 0.06 in. the balanced damper remained closed. For chimney drafts in excess of 0.06 in. the balanced damper opened sufficiently to maintain a maximum draft of 0.06 in. at the smoke outlet of the furnace. During the off-periods the burning rate was checked by closing both the primary air-dampers B and C and the secondary air-damper A. The use of this method resulted in a rapid decrease in the temperature of the flue gases, amounting to 300 deg. F. in 10 min. Method 4 has also been used in a number of homes with excellent results, in which case the "bleed holes" had approximately one-third the area of the secondary air opening. During the off-periods, the draft was usually less than 0.06 in. and damper D remained closed. As a result, very little heat was wasted by drawing basement air into the chimney and discharging it to the outdoors. Furthermore, since the damper D was always closed except when the draft exceeded 0.06 in., no manual operation of the damper motor was required in order to build up a maximum draft at the time of firing. That is, at any time that the firing door was opened, sufficient draft was available to draw the combustion gases immediately into the chimney. The application of this method of control seems particularly well adapted to those installations in which the chimney draft is none too strong, and any cooling brought about by air entering the chimney through the check damper may serve to reduce still further the draft available at the smoke collar. In this case the firing door and ashpit door should be well fitted, since considerable draft is always maintained at the smoke collar of the furnace, and any resulting air leakage into the furnace will maintain an excessive burning rate. For this reason it is probable that any adoption of method 4 is not suitable for conventional furnaces having loosely fitted doors.

Method 5 consisted of controlling the burning rate by simultaneously closing all the dampers, A, B, and C, over the orifices and opening the check damper D. This method proved the most effective in rapidly reducing the temperature of the flue gases, the reduction in this case amounting to 350 deg. F. in 10 min. Consequently, the reduction in the combustion rate is so large that the flue gases in the chimney may be cooled to a temperature lower than that of the outdoor air if the furnace is allowed to remain checked for several hours.

Hence, in residential installations, some difficulty may be experienced from reversal of the draft during warm weather operation.

From the evidence presented, it seems probable that a reduction in the temperature of the flue gases of from 710 deg. F. to about 400 deg. F. during the first 10 min. after the fire has been checked constitutes an index of the reasonable limit below which the burning rate should not be reduced if satisfactory operation is to be maintained. Furthermore, although the results of this study have indicated that several effective means are available for checking the fire by controlling the dampers in the Illinois Smokeless Furnace, it is probable that methods 3 and 4 may prove most practical for field installations and that the use of these methods will result in no appreciable overheating of the house in mild weather.

15. *Hold-Fire Operation.* — Incident to the operation of a hand-fired furnace during mild weather, extended periods of time, varying from two hours to as long as two days, may elapse before there is any occasion for a heat demand. After such a prolonged period of minimum burning, sufficient live coals should remain in the fuel bed to ignite the gases and produce a flame as soon as a heat demand occurs. Otherwise it would be necessary to rekindle the fire.

Observations of the fuel bed were made visually through a small opening extending through the side of the furnace wall and the firepot lining. This inspection hole was so located that the combustion occurring in the mixing zone immediately under the refractory baffle wall could be observed. Such observation, made while the draft was checked, indicated that during the latter part of a prolonged hold-fire period, the temperature maintained immediately below the refractory baffle wall was not sufficient to ignite the gases, and no flame was in evidence. On the other hand, it was also observed that, even if a fresh charge of coal were placed in the coking chamber just prior to a hold-fire period, no appreciable amount of volatile gases was released. Hence, although no high temperature surfaces were available for the purpose of ignition, no smoke was produced.

It became evident that the main problem incident to hold-fire operation was whether or not surface temperatures sufficiently high for ignition could be quickly established when a heat demand occurred. Accordingly, an investigation was made in which the laboratory furnace was used to determine the relation between the length of the hold-fire period and the time required for a flame to appear after the dampers were opened.

Two different methods were employed in starting the hold-fire periods. In some cases a fresh charge of coal was placed in the coking chamber just previous to the start of the hold-fire period. In other cases the furnace had been operated intermittently for as long as 24 hr. after placing a fresh charge, and the coal in the coking chamber was largely coked at the start of the hold-fire period. At the start of each hold-fire period, the fire was checked by completely closing the coking-air and undergrate-air dampers, and by adjusting the draft regulator to maintain a draft of 0.01 in. of water at the smoke collar. The secondary air-damper was then adjusted to reduce the effective area of the secondary air orifices to one-fifth of the normal operating area. It should be noted that this method of control was similar to that described as method 5 in Section 14, and that although the check damper was closed when the dampers over the air orifices were opened, as a matter of convenience this arrangement has been designated as the open-damper position. The hold-fire periods varied from a few minutes to 40 hr., and at the end of each period the dampers were opened and observations of the fuel bed were made to determine the time at which a flame first appeared.

The data obtained from a high-volatile Illinois coal are shown in Fig. 10, in which the time in minutes required for the flame to appear under the baffle wall has been plotted against the length of the hold-fire period in hours. Considerable variations were obtained in the time required for the flame to appear, particularly in the case of hold-fire periods longer than approximately 6 hr., and the curve is not well defined. However, it is evident that for hold-fire periods of less than 2 hr. the flame usually appeared under the baffle wall within one minute after the dampers were opened. The time required for flame to appear increased with the length of the hold-fire period amounting to about 6 min. for a 7-hr. hold-fire period. At the end of a hold-fire period of 40 hr., which seldom occurs during a heating season, it required only about 25 min. for flame to appear. The fact that the flame appeared at all was of greater importance than the time required, since it indicated that even after a hold-fire period as long as 40 hr. sufficient live coals remained in the fuel bed to permit picking up the heating load without the necessity of rekindling the fire.

The results of this investigation indicate that, in the course of normal operation with the furnace under thermostatic control, ignition of the volatile gases would usually occur under the baffle wall immediately after each demand for heat. During mild weather in the fall and spring it would be possible to encounter long periods in which

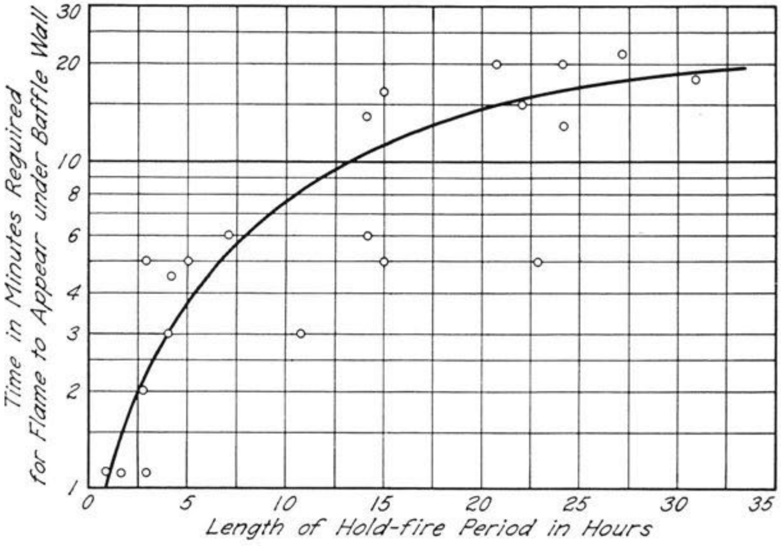

FIG. 10. TIME REQUIRED TO RE-ESTABLISH FLAME AFTER DAMPERS ARE OPENED

there was no demand for heat, and due to lack of high temperature surfaces below the baffle, some combustible gases might fail to be ignited and thus escape for a short time. Under these conditions, however, there is a lag between the time the dampers open and that at which the evolution of gases begins. This time lag tends to increase with the length of the hold-fire period. As a result, unburned combustibles would be lost only during the latter part of the period required to establish a flame and not during the entire period. Hence, even though surface temperatures sufficiently high for ignition were not maintained during the entire period over which the fire was becoming more active, the quantity of unburned gas and smoke released would be negligible.

When anthracite was burned in the furnace, during long hold-fire periods more than 24 hr. in length, it was found that the fuel in the coke-burning chamber would lose ignition, thus making rekindling of the fire necessary when heat was again required. To eliminate this difficulty, a bleed hole was provided in the undergrate air damper in order to maintain ignition in the lower part of the fuel bed. By providing such a bleed hole, ½ in. in diameter, it was found possible to maintain a fire on one charge of anthracite for as long as 100 hr.

Figure 11 shows the rate of increase of flue gas temperatures after the dampers were opened. Prior to the opening of the dampers the fuel

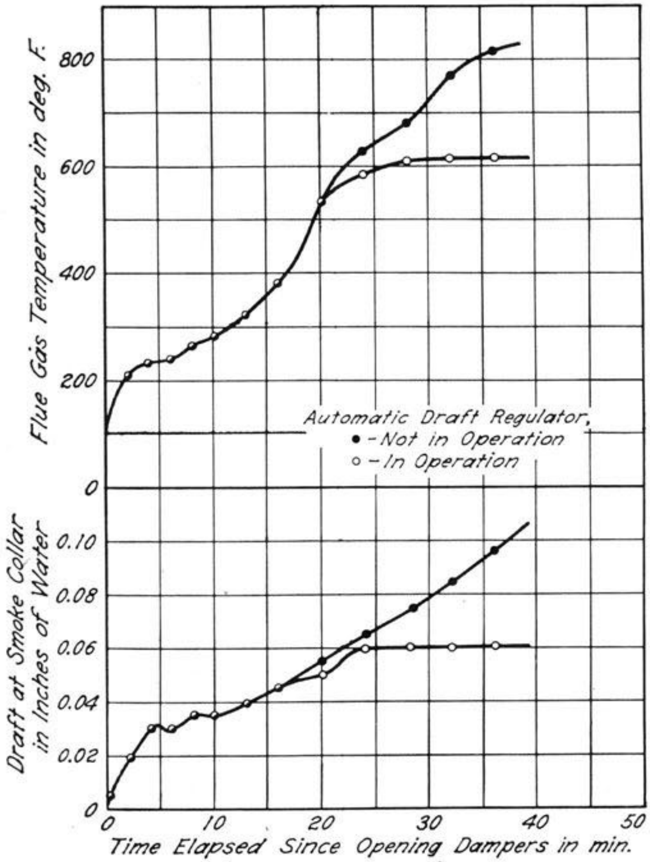

FIG. 11. EFFECTIVENESS OF AUTOMATIC DRAFT REGULATOR IN LIMITING DRAFT AND FLUE GAS TEMPERATURE

Bituminous coal was used in this test

bed was relatively inactive and the flue gas temperatures were about 100 deg. F. When the dampers were opened, a steady increase in flue gas temperatures and drafts was obtained. When an automatic draft regulator was not used the draft at the smoke collar continued to rise above 0.06 in. and flue gas temperatures increased beyond 800 deg. F. However, when the automatic draft regulator was in operation the draft was limited to 0.06 in., and flue gas temperatures stabilized at about 600 deg. F. As indicated in Sections 8 and 18, the use of the automatic draft regulator resulted in a slower pickup in room temperatures following a long hold-fire period, but this disadvantage was more than offset by the fact that the arrangement served as a safety limit control.

VI. RESULTS OF TESTS IN RESEARCH RESIDENCE

16. *Maximum Heat Output of 3-Section Furnace.* — Depending largely on the method of firing, several test codes either are in effect or have been proposed for the purpose of rating furnaces. In all these the maximum heat output allowable for rating is determined by placing limits on such factors as the draft at the smoke collar, the temperature of the flue gases, the temperature of the surface of the heat exchanger, the length of firing periods, and the bonnet efficiency. A discussion of these factors as related to the development of equations to be used in rating hand-fired furnaces has been presented in Engineering Experiment Station Circular No. 51. Small solid-fuel burning, forced-air furnaces having heat outputs not exceeding 80,000 B.t.u. per hr. are currently being tested and rated under the provisions of Commercial Standard CS 109-44.[6] The following limitations are established by the provisions of this code: draft not to exceed 0.06 in. of water at the smoke collar; flue gas temperature not to exceed 830 deg. F. above laboratory temperature; heat exchanger surface temperature not to exceed 930 deg. F. above inlet air temperature; bonnet pressure to be maintained at 0.20 in. of water; air temperature rise not to exceed 100 deg. F. or be less than 70 deg. F.; and bonnet efficiency to be not less than 55 per cent.

In conformity with Commercial Standard CS 109-44, a continuous test of seven hours' duration was conducted on the 3-section Illinois Smokeless Furnace. A normal fuel bed was first established by operating the furnace for several hours. Just before the start of the test the hot coke in the coking chamber was then pushed back into the coke-burning chamber, a 52-lb. charge of fresh fuel was fired, and the dampers on the furnace were so adjusted as to maintain a draft not in excess of 0.06 in. of water. Observations of air temperature, air volume, draft, flue gas temperature, and CO_2 content of the flue gases were made at frequent intervals during the test. The significant results are shown in Fig. 12.

During the first part of the test the draft at the smoke collar remained approximately constant at about 0.06 in. of water. As the fuel was consumed, however, the temperature of the flue gases decreased and as a consequence the draft also tended to decrease, attaining a value of approximately 0.05 in. of water during the latter part of the test. From the curves it is evident that the air orifices were properly proportioned, so that with a draft of 0.06 in. of water at the smoke

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[6] Promulgated by the Division of Trade Standards, National Bureau of Standards.

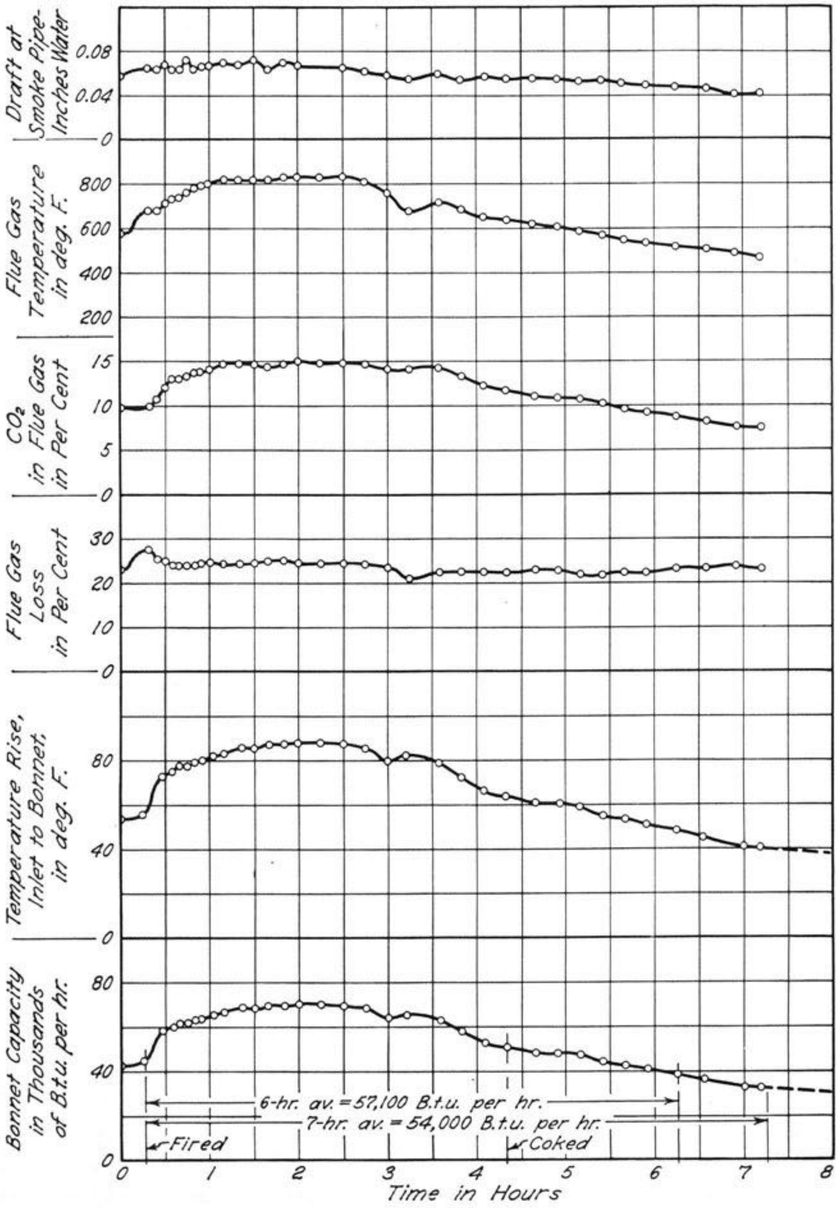

FIG. 12. PERFORMANCE OF 3-SECTION SMOKELESS FURNACE

collar the performance was within the limits specified under the provisions of Commercial Standard CS 109-44.

The fuel burned was a high-volatile bituminous coal from Vermilion County, Illinois, having a calorific value of 11,440 B.t.u. per lb. on the "as-received" basis. The proximate analysis of the coal is given in Table 1. Except for the last two hours of the test, the CO_2 content of the flue gas, which serves as an index of the completeness of the combustion, was between 10 and 15 per cent. The flue gas loss, however, determined from the CO_2 content and the flue gas temperature, remained practically constant at about 23 per cent.

The air volume circulated by the fan, amounting to 800 c.f.m., was sufficient to maintain a temperature rise not exceeding 90 deg. F. from inlet to bonnet. The bonnet capacity increased sharply at first and was then maintained at a value above 65,000 B.t.u. per hr. for a period of 2 hr., after which it decreased slowly until the end of the test. The average capacity based on an 8-hr. test period was 51,000 B.t.u. per hr. and the bonnet efficiency was about 65 per cent. This capacity would correspond to the maximum rating of the furnace as specified in CS 109-44. However, it seems evident that by using three firing periods during the day in connection with an 8-hr. period at night, this furnace could easily carry a heating load somewhat greater than 51,000 B.t.u. per hr. and still have sufficient reserve to raise the air temperature to 70 deg. F. soon after the first firing in the morning. This is particularly true because heat losses from the casing and smokepipe are regained as useful heat in the house.

It is often desirable to rate a furnace over a range of capacities by stating allowable minimum and maximum capacities. In Commercial Standard CS 109-44 the minimum allowable capacity is defined as the heat output obtained at a fuel-burning rate three times that observed during a separate banking test. This banking test is run under conditions similar to those prevailing during the hold-fire periods discussed in Section 15. Results of these hold-fire tests, made in the Laboratory plant, indicated that the capacity obtained during hold-fire periods was largely dependent upon whether the dampers over the orifices in the coking chamber and the ashpit were closed or open in connection with the open check damper. When the dampers over the air orifices were not closed and the reduction in draft was effected entirely by the open check damper in the smokepipe, the minimum capacity was about 25 per cent of the maximum obtained when the furnace was under full draft. In this case the minimum rating as defined by Commercial Standard CS 109-44 would be 75 per cent of the maximum rating; if the furnace were rated at 51,000 B.t.u. per hr. with maximum output, the minimum rating would be 38,000 B.t.u. per hr. When the dampers over the air orifices were closed simultaneously with the opening of the check damper, the hold-fire capacity was reduced to about 8 per cent of the maximum rating. In this case the minimum rating would be only about 25 per cent of maximum, and an output rating of 51,000 B.t.u. per hr. would be accompanied by a minimum rating of about 13,000 B.t.u. per hr. Under these conditions the same furnace would be considered as adequate to meet requirements for bonnet output ranging from 13,000 B.t.u. per hr. up to 51,000 B.t.u. per hr.

The results obtained with the 3-section furnace indicate the general characteristics with respect to smokelessness, combustion efficiency, and response to control. The heat output, however, as measured at the bonnet of a furnace is dependent upon the design and amount of the heating surfaces. Hence, the bonnet capacity obtained was characteristic only of the particular arrangement of heating surfaces in this particular furnace, and was not necessarily typical of other furnace designs incorporating the Illinois smokeless principle.

17. *Flue Gas Losses, Fuel Consumption, and Smoke Density.*— Continuous records were made each day of the CO_2 content and temperature of the flue gases at the smoke collar of the furnace. Arithmetical averages of both the CO_2 content and the flue gas temperature for each 24-hr. test period were obtained from the records and plotted against the difference in temperature between the indoor and the outdoor air, as shown in Figs. 13a and 13b. It may be observed that both the percentage of CO_2 and the temperature of the flue gases increased as the weather became colder. A comparison of Figs. 13a and 13b indicates that for a given indoor-outdoor temperature difference, the CO_2 content and flue gas temperature were both greater for the 3-section furnace than for the 4-section. For example, at an indoor-outdoor temperature difference of 38 deg. F., the CO_2 content and flue gas temperature were 7.6 per cent and 420 deg. F., respectively, for the 3-section furnace, and 6.3 per cent and 260 deg. F. for the 4-section unit. The latter was equipped with a greater amount of heating surface than the 3-section unit. Hence, for a given hourly fuel consumption a greater transfer of heat occurred from the flue gas to the circulating air, and as a result lower flue gas temperatures were obtained. The percentages of CO_2 shown in Figs. 13a and 13b are arithmetical averages including both on-period and off-period operation of the furnace. The slightly lower CO_2 values shown for the larger furnace probably resulted from the fact that a proportionally larger

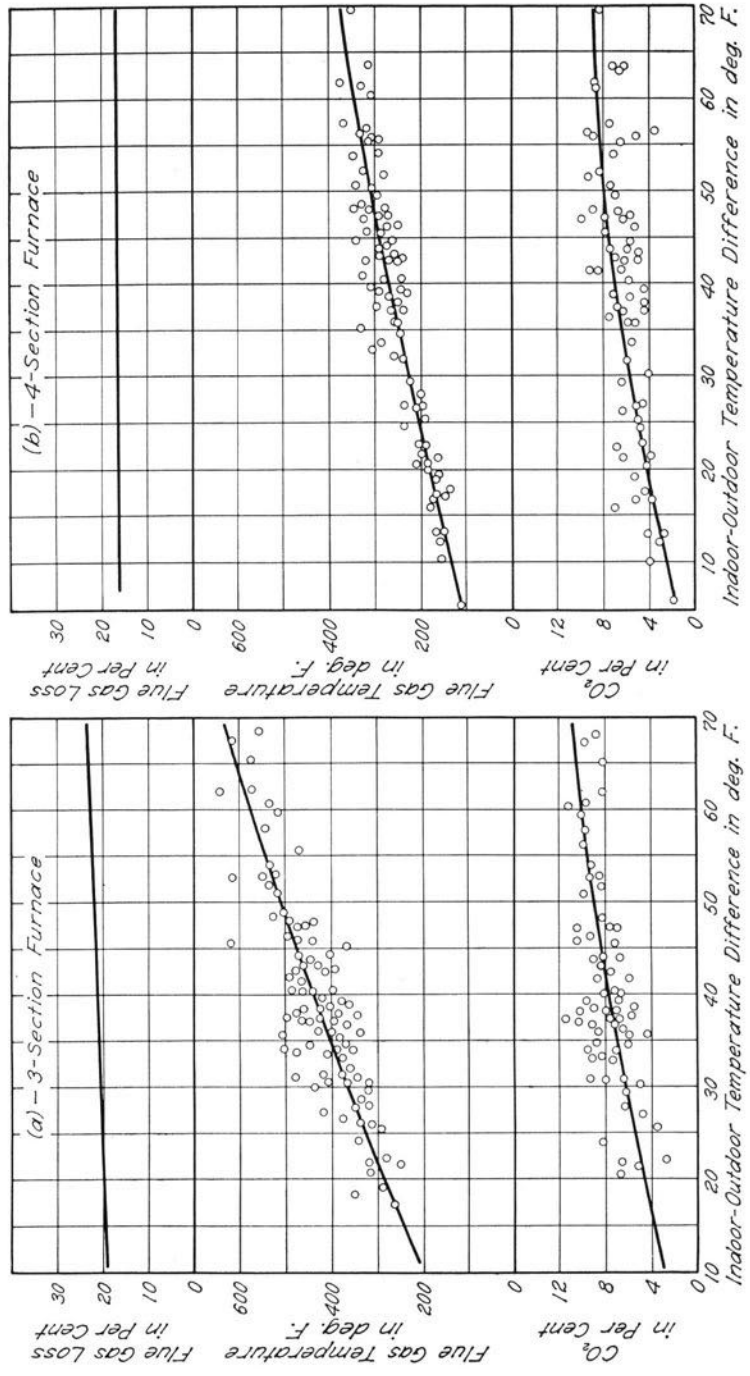

FIG. 13. FLUE GAS LOSSES FOR 3-SECTION AND 4-SECTION FURNACES

amount of secondary air was supplied during off-period operation. Also, the larger furnace operated with longer periods of closed dampers than did the smaller.

The losses due to sensible heat and water vapor in the flue gases at the smoke collar, represented by the top set of curves in Figs. 13a and 13b, were practically constant over a wide range of indoor-outdoor temperature differences, and amounted to approximately 21 per cent for the 3-section furnace and 16 per cent for the 4-section furnace. These losses, expressed as percentages of the heat liberated in the furnace, were estimated from generalized curves presented in Engineering Experiment Station Circular No. 44. They did not include losses resulting from unburned combustible in the ash and refuse. The latter amounted to about 5.5 per cent of the heat liberated for the 3-section furnace and about 4.6 per cent for the 4-section furnace. Hence the total losses, including those due to sensible heat and water vapor in the flue gases and to combustible in the ashpit, were about 26.5 per cent and 21 per cent, respectively, for the 3-section and 4-section units. The corresponding combustion efficiencies, defined as 100 minus the sum of the percentages of the flue gas and the combustible losses, were about 73.5 and 79 per cent, respectively.

The daily fuel consumptions for the two furnaces, plotted against indoor-outdoor temperature differences, are shown in the top and middle portions of Fig. 14. To avoid inconsistencies resulting from changes in the amount of fuel left in the furnace at the start of each test, fuel weights obtained over periods of 48 hr. or longer were used, and the average daily consumption was computed by dividing the total fuel consumed during these periods by the number of days involved. The average daily consumptions were then plotted against the averages of the indoor-outdoor temperature differences computed from the corresponding number of days used. The weights shown are expressed in terms of pounds of fuel fired, and thus include any combustible that was lost through the grates.

The curve for the 3-section furnace, shown in the upper part of Fig. 14, was based on coal having a calorific value of 11,440 B.t.u. per lb.; that for the 4-section furnace, shown as the middle curve, was based on coal having a calorific value of 13,030 B.t.u. per lb. In order to obtain comparable results for the two furnaces, the heat inputs equivalent to the fuel consumptions for both furnaces were expressed in terms of millions of B.t.u. per 24 hr. and plotted as shown in the lower part of Fig. 14. These heat inputs were obtained by multiplying the actual weights of fuel shown by the curves in the top and middle portions of Fig. 14 by the corresponding calorific values of the fuels.

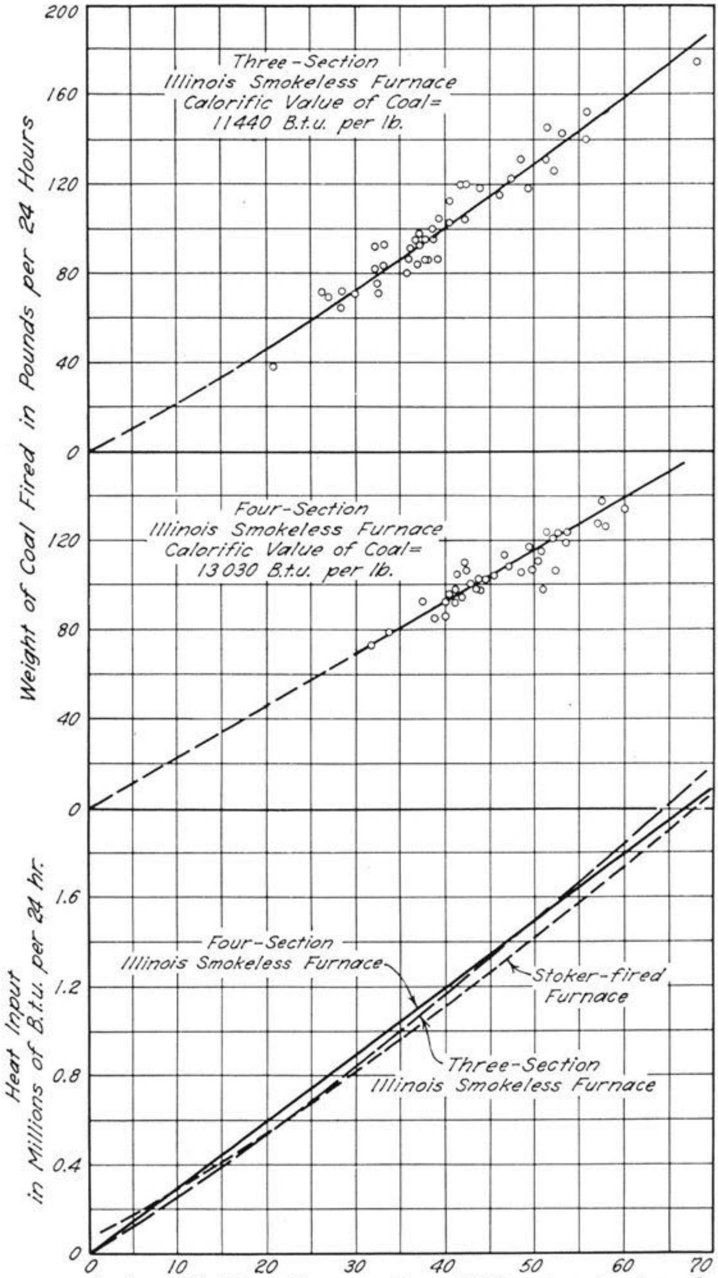

FIG. 14. HEAT INPUTS TO RESEARCH RESIDENCE

From Fig. 14 it is evident that the fuel consumption was almost proportional to the indoor-outdoor temperature differences. It is also evident that at given indoor-outdoor temperatures the equivalent fuel consumption, as represented by the heat inputs, was practically the same for the two furnaces, notwithstanding the differences in size and design of secondary heating surfaces.

The drop in the temperature of the flue gases that occurs between the smoke collar and the entrance to the chimney can be considered as representative of the heat regain into the basement. Therefore, combustion efficiencies as determined by flue gas temperatures measured at the inlet to the chimney would probably be more nearly representative of the heat input, or fuel required to offset heat losses from the house, than those obtained from the flue gas temperatures measured at the smoke collar. It is further probable that the temperature drop would be greater in the 6-in. smokepipe attached to the 3-section furnace than in the 9-in. smokepipe attached to the 4-section furnace, primarily because of high temperatures at the smoke collar. Hence, it seems evident that combustion efficiencies determined at the entrance to the chimney would be in closer agreement than those determined at the smoke collar. A close agreement between combustion efficiencies computed at the entrance to the chimney would serve as a reasonable explanation for the close agreement shown in Fig. 14 between the daily heat inputs for the two sizes of furnaces, in spite of the fact that considerable difference was exhibited in the efficiencies computed from the CO_2 contents and flue gas temperatures at the smoke collar.

The curve labelled "Stoker Fired Furnace" was transferred from a previous publication[7] in which the fuel consumption for a stoker-fired furnace was shown. Comparison of the curves for the stoker-fired furnace and the Illinois Smokeless Furnace indicates that fuel consumption for the stoker-fired furnace was about the same as for the hand-fired smokeless furnace in mild weather, and slightly less in cold weather. The differences shown, however, were small, and the slightly greater consumption for the hand-fired furnaces could be attributed to combustible loss occurring through the grates into the ashpit. It therefore seems safe to conclude that the fuel consumption for the Illinois Smokeless Furnace would in practice be comparable to that obtained with an underfeed stoker.

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[7] A. P. Kratz and S. Konzo, "Performance of a Stoker-fired Warm-air Furnace as Affected by Burning Rate and Feed Rate," ASHVE Transactions, Vol. 46, pp. 125-38. 1940.

The density of the smoke produced by the furnaces was measured by means of a beam of light passed through the smokepipe and received on a thermopile. The conclusions drawn concerning the occurrence and density of the smoke are discussed in Section 13. In general, the smoke densities observed were comparable to those obtained in connection with a stoker-fired furnace and were well within the limitations imposed by most smoke ordinances.

18. *Firing Periods and Temperature Control.* — The length of firing periods, or the number of hours between firings, required in the operation of a hand-fired furnace is determined by the amount of fuel charged, the burning rate maintained, and the amount of live coals necessary to remain as a reserve to ignite the succeeding charge. From the standpoint of maintaining uniform house temperatures, frequent firings of relatively small fuel charges were found to be more desirable than less frequent firings of larger charges. In the Residence tests, however, the furnace was not fired at regular stated times, but only when the house temperatures were sensibly below normal. Furthermore, charges varying from 10 lb. to 80 lb. were fired, depending upon the condition of the fuel bed, the anticipated load, and the judgment of the attendant. Daily records were made of the number of firings and the weight of coal fired, and the results were tabulated.

Some degree of correlation between the average outdoor temperature and the required number of firings was found, but it was observed that the data were subject to wide variations, especially in mild weather. Sometimes if no necessity existed for firing the furnace during a given 24-hr. period, the fuel bed would be burned so low that two firings would be required on the following day. In this case, though the outdoor temperatures might be the same on the two successive days, the records would contain one day with no firing and a second day with two firings. A number of such factors introduced discrepancies in the daily records; but, as shown in Table 3, by giving them due consideration, it was possible to separate the data into ranges of outdoor temperatures over which one, two, three, or four firings per day were required.

The firing period for the small 3-section furnace, based upon a fuel charge of 50 lb. of coal and a maximum burning rate of 7.5 lb. of coal per hr., was about 7 hr. Accordingly, under conditions of maximum demand, the furnace should require approximately four firings per day. However, during the heating season of 1943-1944 (which as

TABLE 3
NUMBER OF FIRINGS PER DAY REQUIRED FOR TWO SIZES OF FURNACES

Number of Firings per Day	Range of Average Daily Outdoor Temperatures Covered			
	3-Section Furnace	Average Number of Days*	4-Section Furnace	Average Number of Days*
1	65 deg. to 45 deg. F.	85	65 deg. to 40 deg. F.	109
2	45 deg. to 32 deg. F.	70	40 deg. to 15 deg. F.	110
3	32 deg. to 20 deg. F.	56	15 deg. to −10 deg. F.	8
4	20 deg. to −10 deg. F.	16	....	...

* Average number of days per year during which average daily outdoor temperatures were included in range of values indicated in columns 2 and 4. Based on records of U.S. Weather Bureau Station at University of Illinois, Urbana, Illinois. Includes all days from September 1 to May 31 for which average outdoor temperature was less than 65 deg. F. Data for period of September, 1936, to May, 1941.

shown by Table 3 was somewhat milder than a typical season) the weather was sufficiently cold to require four firings per day on only seven days out of the entire season, even though the furnace was small. With outdoor temperatures averaging between 20 deg. F. and 32 deg. F., three firings per day were required; with outdoor temperatures averaging between 32 deg. F. and 45 deg. F., two were sufficient; and with outdoor temperatures higher than about 45 deg. F., only one firing per day was necessary.

In the case of the 4-section furnace a normally full charge of about 75 lb. would represent firing periods of the order of 8 hr. In extremely cold weather, therefore, three firings per day would nominally be required. Actually, however, three firings were required on not more than four days out of the entire heating season, and over a large portion of the season, one or two per day were adequate.

As shown in Section 17, no difference in fuel consumption for the two furnaces was obtained, and with the same coal there would be no difference in the weights of ash to be handled. Hence the main advantage of the larger 4-section furnace was that it could be operated with less attention for firing than the 3-section furnace would require.

By means of a temperature-recording element located 5 ft. above the floor and near the room thermostat, continuous records were made of the temperature of the air in the dining room. Simultaneous observations of room air temperatures at the 5-ft. level in the 12 rooms in the Residence proved that the average of the room temperatures corresponded closely with those indicated by the recorder. Hence the latter temperatures were accepted as representative of the average

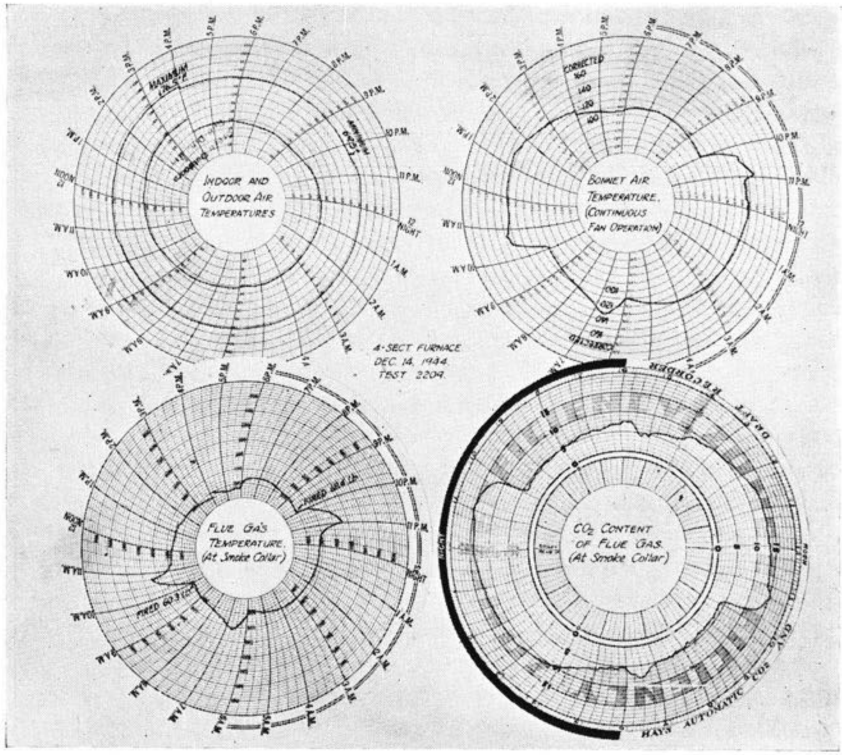


FIG. 15. TEMPERATURE RECORDS FOR OPERATION WITH ILLINOIS SMOKELESS FURNACE

for the entire house. The room thermostat, which operated the furnace dampers, was set to maintain an average temperature of about 71 deg. F. A fan switch placed in the bonnet controlled the fan circulating the air, and was so set that it started the fan when the bonnet air attained a temperature of about 125 deg. F., and stopped the fan when the temperature decreased to about 100 deg. F. Thus the fan continued to operate and to appreciably cool the heating surfaces of the furnace, even after the room thermostat had closed the dampers. A sample chart showing the variation in room temperature over a 24-hr. period is presented in the upper left-hand portion of Fig. 15. Since the furnace was fired only when the house had cooled appreciably, the minimum room temperatures, varying from 70 deg. F. to about 66 deg. F., always occurred just previous to a firing time. In the majority of cases the minimum room temperature was about 69 deg. F.

Preliminary tests in the Residence indicated that the use of control method 1, discussed in Section 14, was not satisfactory in that it resulted in some overheating. For this reason the methods designated as Nos. 2 and 3 were used. The amount of overheating which occurred in the rooms was largely dependent on the rate of burning that took place in the furnace after the draft was reduced and the dampers over the air orifices were closed, and the maximum room temperature was usually experienced within a few hours after a fresh charge of fuel was fired. In general, using control methods 2 and 3, the over-runs in room temperature usually ranged from 0.5 to 5.0 deg. F. in excess of 71 deg. F. In the majority of cases the over-run was about 2.5 deg. F., corresponding to a room temperature of about 73.5 deg. F. The experience in the Residence indicated that the occupants were entirely comfortable when room temperatures were anywhere between 71 deg. and 75 deg. F. That is, the 4-deg. range between these air temperatures did not result in any appreciable discomfort. Temperatures greater than about 76 deg. F., however, were sensibly warm and were not considered desirable. During one season of operation with the 4-section furnace, over-runs in room temperatures of between 5 and 7 deg. were obtained on only 13 days. These over-runs usually lasted but a few hours, and usually occurred only in mild weather when the average outdoor temperature was between 50 and 65 deg. F.

It was also observed that the over-runs could be considerably reduced during average and cold weather if the house temperature was not allowed to drop substantially below 70 deg. F. and the furnace was fired more frequently. In this case the pickup period was shortened, the fuel bed temperatures were more nearly normal, and a more rapid decrease in heat output was obtained after the dampers were closed.

The over-runs in room temperatures obtained with the Illinois Smokeless Furnace were from 1 to 2 deg. F. greater than those for a stoker-fired furnace, and were slightly less than similar over-runs with a conventional furnace given proper attention and fired four times a day. In general, the control of room temperature obtained on the tests with the Illinois Smokeless Furnace can be considered as satisfactory, particularly when dampers are used over the air orifices in the coking chamber and ashpit doors. Subsequent experience both in the Research Residence and in the field proved that when a more sensitive room thermostat was used, the Illinois Smokeless Furnace could be operated with over-runs not to exceed about 2 deg. F.

Observations were also made of the pickup rate, or rate of increase in room temperatures during the morning hours after the house temperatures had been allowed to drop from 1 to 5 deg. F. below the normal corresponding to the setting of the room thermostat. The 3-section furnace was somewhat undersize for the house, and the rate of temperature rise during cold weather was only from 1 to 1½ deg. F. per hr., whereas that for the 4-section furnace was somewhat greater. As a result, the duration of the pickup period was usually from 2 to 3 hr. In the case of the Illinois Smokeless Furnace, the maximum draft was limited to about 0.06 in. of water. If a maximum draft as great as 0.10 in. had been permitted, the rate of burning would have been increased and the pickup period would have been shortened. Since the furnace was limited in its fuel-holding capacity, however, any increase in burning rate would have been reflected in a decrease in the length of the firing period. Furthermore, such an increase in the burning rate would have been accompanied by possible overheating of the metal surfaces and by excessively high flue gas temperatures, neither of which is desirable from the standpoint of the life of the equipment and safety from fire hazard. In general, however, although the rate of pickup was smaller than that commonly encountered in connection with a conventional furnace having no limit placed on the flue gas temperatures, it is comparable to pickup rates usually obtained with fuels such as gas and oil, which are burned at a fixed rate of input. Inasmuch as the room temperature did not rise rapidly during a pickup period and did not fall quickly after the dampers were closed, the furnace and the fuel bed exhibited a pronounced "flywheel" effect, and reasonably uniform temperatures were maintained without marked difficulty.

It may be observed that the Research Residence in which these tests were conducted was somewhat unusual in that the calculated heat loss of 51,000 B.t.u. per hr. was very low for a house containing twelve heated rooms in addition to the large basement, which was also heated by the vagrant heat from the front of the furnace, the smokepipe, the warm air ducts, and other parts of the system.

Because of the three floors and the many interior partitions the house possessed considerable thermal capacity. This provided a large "thermal inertia" or "flywheel effect" which was imposed upon the "flywheel effect" of the furnace and fuel bed. When the thermostat was satisfied and the dampers were closed, the large thermal capacity of the house would tend to absorb the momentarily continuing high output of the furnace and thus reduce the degree of over-run in room temperature. However, during a warming-up period after the attendants had allowed the house temperature to drop a few degrees before refiring the furnace, the high thermal capacity of the house would tend to absorb the increased output of the furnace and delay its reflection in a rise in the room temperature.

The results that were obtained in the Research Residence are representative of those which may be expected in any home that is well insulated and completely equipped with storm sash and storm doors. It is expected that over-runs may be somewhat greater and the time required for "temperature pickup" somewhat less when the same type of furnace and the same system of control are used in a home in which the heat losses are greater in proportion to the mass of the interior floors and partitions.

APPENDIX A

Experiments with a Simplified Design

Since the manuscript for this bulletin was prepared a simplified version of the Illinois Smokeless Furnace has been developed by one of the manufacturers licensed by the University of Illinois Foundation. This work has been carried on in the manufacturer's development laboratory with the collaboration of the senior author.

In the simplified version, the inclined pinhole grate and the horizontal secondary air passage shown in Fig. 2 have been eliminated, and the baffle between the coking chamber and the combustion flue has been simplified. The new design is incorporated in a round furnace body using conventional shaking grates. A perforated channel through which the secondary air passes into the mixing region below the flue replaces a section of the lining of the coke-burning chamber. This air together with the undergrate air is brought into the channel through a tube at the rear side of the furnace. A slot in that portion of the circular grate ring which is directly below the channel permits the undergrate air to pass into the ashpit while the secondary air passes through the perforations into the mixing chamber.

Preliminary laboratory tests with the new design, together with limited experience with a few installations in private homes, indicate that the simplified version of the Illinois Smokeless Furnace has operating characteristics which are practically identical with those of the design that is described in detail in this bulletin. The advantages in the revised construction consist of decreased manufacturing cost and simplified firing technique.

Information about the simplified design will be presented in later publications.

APPENDIX B

DETAILS OF CONSTRUCTION

1. *General Specifications.* — As shown in Fig. 2, the Illinois Smokeless Furnace is an integrated assembly of a number of essential parts, including a coking chamber, a coke-burning chamber, a baffle wall, three separate air orifices, and two forms of grates. A brief discussion of the factors affecting the design of these parts is presented in the following sections. The fact that certain designs were tried and found successful does not preclude the possibility that other modifications might prove equally satisfactory or even better. In general, however, the present design is well adapted to normal production practices involving the fabrication of sheet steel. A study has not yet been made of the modifications necessary to adapt the smokeless principle to cast-iron furnaces.

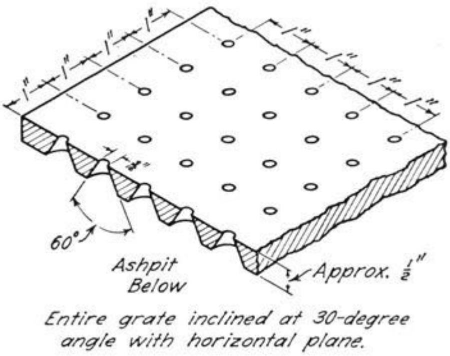
2. *Shaking Grate.* — The shaking grate, located below the coke-burning chamber, supports the bed of burning coke. The grate bars are agitated by a shaker mechanism in order to sift the ashes down into the ashpit. Two arrangements, one consisting of a single wide grate bar, and the other of two narrow grate bars, have proved satisfactory. It has been found that if the depth of the grate from front to back is less than about 8 in., a deep bed of ash will arch over the shaking grate, especially toward the rear of the furnace.

No clinkers have been obtained from any of a wide variety of coals burned over a wide range of combustion rates. However, if any clinkers did form and tend to clog the passages in the grate bars they could be readily removed before a fresh charge of coal was fired.

3. *Inclined Pinhole Grate.* — The pinhole grate, located immediately in front of the shaking grate, is designed to admit undergrate air to that portion of the coke bed which spreads forward from the lower front edge of the baffle, thus promoting uniform burning of the coke. The absence of any concentrated combustion zones has served to prevent the formation of clinkers.

In case it is desired to maintain only a small amount of coke in the coke-burning chamber during mild weather, the ash can be allowed to accumulate over the shaking grate in order to back up the small coke bed. Regardless of the amount of ash that is present over the shaking grate, the pinhole grate then provides for the admission of air into the part of the coke bed lying between the pinhole grate and the under side of the baffle, thus serving to maintain ignition temperatures under the baffle.

FIG. 16. SECTION THROUGH STATIONARY PINHOLE GRATE



Entire grate inclined at 30-degree angle with horizontal plane.

A satisfactory design of the pinhole grate is shown in Fig. 16. Holes larger than shown ($^3/_{16}$ in.) permit a considerable loss of unburned fuel into the ashpit. On the other hand, smaller holes, or holes having a smaller taper, may become clogged with ashes. No warping of the one-piece pinhole grate has been observed. However, the use of a reinforcing rib on the under side of the grate is recommended, and for a 5-section furnace it is probable that a two-piece grate would be required in order to avoid warpage of the plates.

4. *Special Fire Brick Used in Baffle Wall.* — The baffle wall, the vertical secondary air passages, and the combustion flues are formed by the special firebricks shown in Fig. 17. Each baffle wall section is

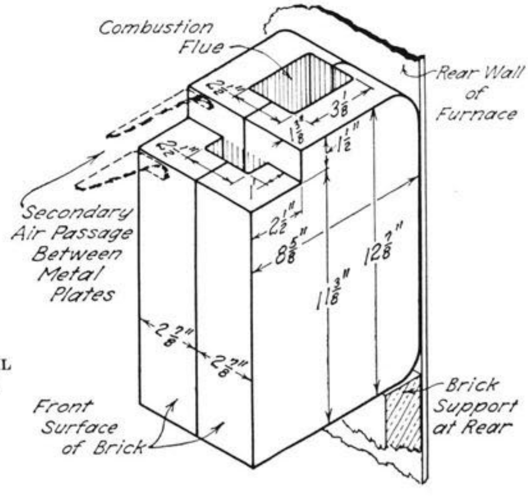


FIG. 17. DETAIL OF REFRACTORY UNIT

composed of two matching E-shaped bricks which are supported at the bottom by the firepot lining and at the top by the two horizontal metal plates which form the secondary air passage. The inside width of the furnace is then determined by the number of baffle wall sections required.

The refractory bricks used in lining the firepot are cemented into place, and the baffle sections are then inserted through the firing door. The back of each baffle brick is beveled in order to provide clearance, and when it is in place neither bolts, clamps, nor cement are required to hold it. A sufficiently tight fit between the matching surfaces is obtained by rubbing the bricks together and removing the burrs. These special bricks can be readily removed and replaced in a few minutes through the firing door, even if there is a low fire in the coke-burning chamber. Hence, replacement of these bricks entails no great expense or inconvenience.

The baffle brick sections that proved most satisfactory in a number of experimental furnaces were 6 in. wide, 9 in. deep, and 13 in. high. Each section contained a secondary air passage and a combustion flue. The secondary air passage was 1 in. deep and 2½ in. wide and was spaced 1½ in. from the front face. The combustion flue was 3½ in. deep and 2½ in. wide and was spaced 1½ in. from the back face. The bricks in the 3-section furnace in the Research Residence were found to be in excellent condition after six months of operation, and bricks of the same size used in the original laboratory furnace showed no appreciable signs of deterioration even at the end of more than two years of continuous service.

The larger baffle brick sections used in the 4-section furnace in the Residence were 6 in. wide, 13 in. deep, and 13½ in. high. The secondary air passage in each section was 1 in. deep and 2½ in. wide and was spaced 2 in. from the front face. The combustion flue was 4½ in. deep and 2½ in. wide and was spaced 1½ in. from the back face. Within a few days after these heavier bricks were placed in service, fine hairline cracks were observed on the front face of some of the bricks. Toward the end of one season of operation, small pieces dropped off from the lower front corners of two of the bricks. However, the absence of the small segments from the lower edge of the secondary air passages from two of the six bricks did not affect the performance of the furnace. In general, the thinner bricks were considered more satisfactory than those having the heavier walls.

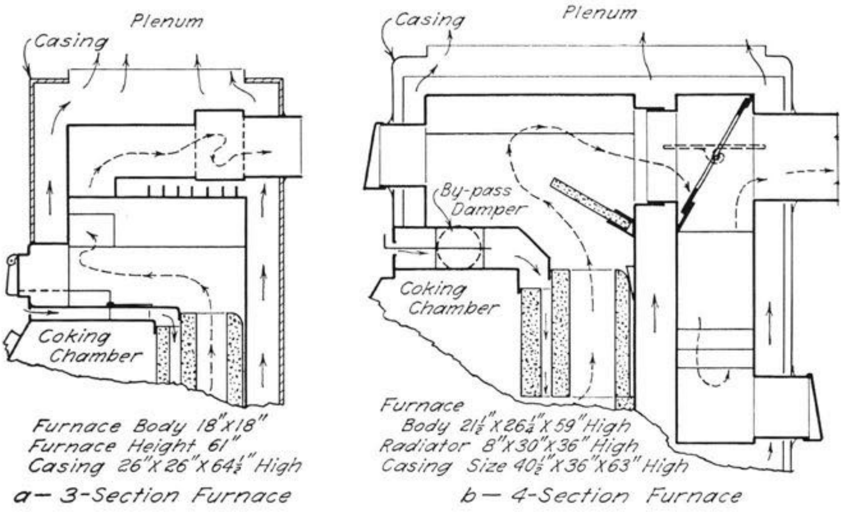
Most of the refractories used in the furnaces tested were made by a hand-mold process, and are not considered to be as resistant to thermal shock as are those made by the dry-press method, which is normally used for quantity production. Using the latter process, one refractories manufacturer has developed a 3-piece sectional construction which has proved even more satisfactory than the 2-piece construction described in this section.

5. *Horizontal Passage for Secondary Air.* — The secondary air entering the front of the furnace passes between two parallel steel plates which are welded to the side sheets of the furnace. A 1½-in. air space between the parallel plates was found to be adequate. The rear edge of each plate was bent at an angle of 90 deg. in order to form a flange to come in contact with the upper faces of the baffle bricks and thus hold them in place. No evidence of overheating of either of these parallel plates has been observed in any of the furnaces that have been tested.

A by-pass flue, which should be at least 7 in. in diameter, serves for the purpose of venting the coking chamber whenever the firing door is opened. This by-pass flue, extending through the horizontal air passage, is located at the top of the coking chamber and is closed by means of a damper. When the damper is opened, the gases can pass directly from the coking chamber to the secondary heating surfaces without entering the combustion flues at the rear of the furnace. During normal operation of the furnace the damper is closed.

Observations of the fire proved that the flames issuing from the center combustion flues were longer than those issuing from the flues at either side. This indicated that as a result of the obstruction caused by the by-pass flue the quantity of secondary air admitted to the center flues was less than that received by the flues at either side. The use of splitter vanes, or deflectors, in order to deliver the proper proportion of secondary air to all the flues is therefore recommended.

6. *Auxiliary Combustion Chamber.* — Space must be provided above the top of the combustion flues to complete the burning of the gases and to prevent impingement of the flames on the crown sheet above the combustion flues. In the arrangement shown in Fig. 18a, some impingement of the flames on the roof of the auxiliary combustion chamber occurred. However, it was found that if the minimum distance from the top of the flues to the top of the auxiliary combustion chamber was not less than 7 in. and the draft was limited to a maximum of 0.07 in. of water, the maximum temperature of the metal directly over the combustion flues did not exceed 1000 deg. F. In the



a— 3-Section Furnace

b— 4-Section Furnace

FIG. 18. ARRANGEMENTS OF HEATING SURFACES IN TWO FURNACES

arrangement shown in Fig. 18b, in which an inclined refractory baffle was placed above the top of the combustion flues, no flame impingement occurred and the top of the furnace was more uniformly heated.

7. *Inlet-Air Orifices.* — Proper proportions of the orifices controlling the admission of secondary air, coking air, and undergrate air are highly important. The proportions that were found to be most satisfactory with various types of fuels, as determined from tests made with the experimental furnace, are shown in Table 4a. For the purpose of these tests the furnace was charged, the doors were sealed, and the air entered only through three sets of orifices. The proportions given in Table 4a should be modified somewhat for normal construction, in which the doors may be well fitted but are not sealed. The necessary modifications are shown in Table 4b. In this case the proportion of secondary air is greater than that required for a furnace having sealed doors, since any leakage around the door is equivalent to a supply of primary air.

Suggested combinations of orifices for a 3-section furnace equipped with baffle wall sections 6 in. wide are given in Table 4c. The total area of all three sets of orifices is extremely small as compared to that provided in the damper opening for the admission of primary air alone in a conventional furnace. It should be observed that the sizes listed in Table 4c are based on the use of tightly fitting doors.

TABLE 4

ORIFICE PROPORTIONS

A. Best Air Proportions for Fuels of Different Types Determined from Tests with a Laboratory Model in Which the Doors *Were Sealed*

Type of Fuel to Be Burned	Approximate Percentages		
	Secondary Air	Coking Air	Undergrate Air
High-Volatile Bituminous Coal....................	60	20	20
Low-Volatile Bituminous Coal....................	45	20	35
Anthracite Coal or Coke.........................	15	20	65
North Dakota or Texas Lignite..................	15	65	20

B. Proportions of Actual Orifice Areas That Gave Good Results in a Commercial 3-section Unit Equipped with Well-fitted Doors *That Were Not Sealed*

Type of Fuel to Be Burned	Approximate Percentages		
	Secondary Air	Coking Air	Undergrate Air
High-Volatile Bituminous Coal....................	66	17	17
Low-Volatile Bituminous Coal....................	50	17	33
Anthracite Coal or Coke.........................	20	20	60
North Dakota or Texas Lignite..................	20	60	20

C. Suggested Orifice Combinations for 3-section Illinois Smokeless Furnace (Assuming That Both Doors Will Be Well-fitted but Not Sealed)

Type of Fuel to Be Burned	Number and Diameter of Orifices		
	Secondary Air	Coking Air	Undergrate Air
High-Volatile Bituminous Coal....................	4-1″	1-1″	1-1″
Low-Volatile Bituminous Coal....................	3-1″	1-1″	2-1″ (or 1-1 7/16″)
Anthracite Coal or Coke.........................	1-1″	1-1″	3-1″ (or 1-1¾″)
North Dakota or Texas Lignite..................	1-1″	3-1″ (or 1-1¾″)	1-1″

For 4-section unit increase orifice diameters to 1 3/16 in. and for 5-section unit to 1⅜ in.

8. *Secondary Heating Surfaces.* — Neither the arrangement nor the extent of the secondary heating surfaces of the furnace has any effect on the degree of smokelessness that can be attained, provided that the auxiliary combustion chamber has sufficient volume to permit complete burning of the gases. However, the arrangement of secondary heating surfaces has a direct bearing on the effectiveness of the transfer of

heat from the hot gases to the circulating air. The presence of more effective heating surfaces results in lower temperatures of the flue gases and hence in greater efficiency of the furnace. In recent rating codes for furnaces, the specified capacity ratings are those limited by a maximum flue gas temperature of approximately 900 deg. F. Hence, all other factors remaining the same, a furnace having more effective heating surface, and consequently a lower flue gas temperature, may be entitled to a higher rated capacity than would one with less effective heating surface. In general, for a given capacity output, approximately the same amount of heating surface is required in the Illinois Smokeless Furnace as for a conventional furnace.

The two arrangements of secondary heating surface used in connection with the Illinois Smokeless Furnace are shown in Figs. 18a and 18b. In each case the gases leaving the combustion flues were brought toward the front of the furnace and then passed over the secondary heating surfaces. As shown in Fig. 18a, the secondary surfaces in the 3-section furnace were located at the top. In the 4-section furnace the secondary surfaces, shown in Fig. 18b, were provided by a conventional-type radiator attached to the rear of the furnace. Obviously other arrangements of heating surface are feasible.

Due to the relatively high velocities of the gases in the combustion flues, an amount of fly ash comparable to that obtained from a stoker-fired furnace was carried over, and settled in the radiator and smoke-pipe. For this reason an access door should be provided in the radiator, so that any accumulation of fly ash on horizontal heating surfaces can be readily removed.

9. *Temperatures of Metal Surfaces.* — All metal in the primary heating surfaces of the furnace is protected from direct contact with the fuel bed by the refractory linings of the coking and coke-burning chambers. The temperature of the metal at the back of the furnace, adjacent to the entrance of the flames into the combustion flues, did not exceed 800 deg. F. when the combustion rate was limited to that obtainable with a draft of 0.07 in. of water. This temperature was below the limiting temperature of 900 deg. F. regarded as the maximum permissible in a hand-fired furnace.

With the arrangement of heating surfaces shown in Fig. 18a, some impingement of the flame occurred on the roof of the auxiliary combustion chamber. The highest temperatures were obtained in that portion of the surface directly over the opening of the combustion flues. However, it was observed that if the distance from the top of the combustion flues to the top of the auxiliary combustion chamber was not less than 7 in. and if the draft was limited to a maximum of 0.07 in. of water, the temperature at this location did not exceed 900 deg. F.

Although the roof of the coking chamber is exposed to radiation from the newly formed coke, which may become incandescent toward the end of the coking process, no evidence of overheating of the metal plate was observed. This plate is continuously cooled by the secondary air and is also protected to some extent by any soot deposit occurring on the under surface. The plate forming the upper boundary of the secondary air passage is subjected to flame in the auxiliary combustion chamber, but this plate is also cooled by secondary air and is further protected by the layer of fly ash that collects on the top. No sign of scaling or warping of either of the two metal plates forming the secondary air passage has been observed in any of the three furnaces that have been tested.

10. *Smokepipe.* — A smokepipe 6 in. in diameter was used on one of the 3-section furnaces. This size was ample for carrying away the products of combustion during normal operation of the furnace, but proved inadequate to take care of conditions at the time of firing the furnace.

When the firing door is opened and a charge is added, the fresh coal comes in contact with live coals, and some amount of smoke is released. If the draft at the furnace collar is sufficient, any smoke produced can be vented through the by-pass tube located at the top of the coking chamber. However, if either the smokepipe or the by-pass tube is undersize, the draft available at the firing door is insufficient and smoke may escape into the basement while the furnace is being fired. Furthermore, since there is always a possibility that fly ash may accumulate and reduce the effective area of the smokepipe, it is recommended that the latter be made not less than 8 in. in diameter for a 3-section furnace and not less than 9 in. in diameter for one having 4 or 5 sections.

11. *Firing Door and Ashpit Door.* — Since any leakage of air into either the coking chamber or the ashpit supplements the air entering through the orifices and therefore tends to increase the combustion rate, it is essential for controlled combustion that any such leakage

around poorly fitted doors and through holes made for the insertion of the shaker handle be reduced to a minimum. The firing and ashpit doors should be well fitted and should preferably be equipped with locking handles. The use of a durable gasket around the door frames is also recommended.

As shown in Figs. 3 and 5, the firing doors are inclined at an angle of about 30 deg. from the vertical. The projecting lip of the feed pouch serves to keep the coal from spilling out of the firing door while the furnace is being fired.

If the ashpit door were accidentally left open for several hours, it is probable that the coke in the coke-burning chamber would be completely consumed before the fresh charge in the coking chamber was converted to coke. Furthermore, under some conditions of operation, an open ashpit door might result in smoke escaping from the furnace. For these reasons it is essential that the ashpit door be closed except when ashes are being removed. Any possibility that the ashpit door may accidentally be left open might be minimized by so constructing the door that it inclines at an angle of about 30 deg. from the vertical.

12. *Deflector Plate Behind Firing Door.* — The deflector plate attached to the back of the firing door, shown in Fig. 2, effectively prevented the distilled vapor arising from the fresh coal in the coking chamber from condensing on the back side of the door and dripping on the floor. This deflector also reduced any tendency toward obtaining a "puff-back," as explained in Appendix D, Section 7. Furthermore, the air entering the coking-air inlet was deflected toward the bottom of the coal charge and thus effectively burned the lower front edge of the fresh charge where the coke bed was thick and difficult to break. The presence of the relatively porous coke thus formed at the bottom facilitated the later handling of the coked charge. The deflector plate also effectively shielded the firing door from the incandescent mass of coke which filled the coking chamber during the latter stages of the coking cycle, and thereby prevented the door from warping.

The deflector plate was found to be most satisfactory when the top edge and the sides were sealed as shown in Fig. 2. The coking air then entered the coking-air orifice and passed downward to the bottom opening. A distance of 1 in. from the bottom of the deflector plate to the bottom of the firing door was found to be ample.

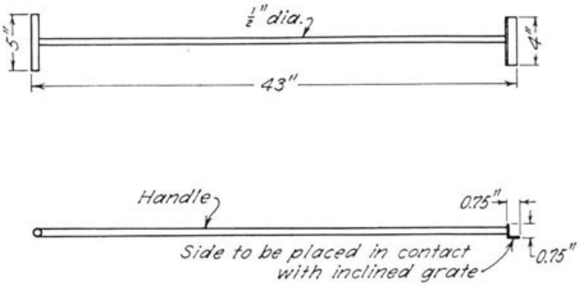


FIG. 19. DIMENSIONS OF PUSH POKER

13. *Push Poker.* — The conventional poker or clinker hook furnished with most furnaces can be used for pushing the coke back into the coke-burning chamber. However, the push poker illustrated in Fig. **19** is a more efficient tool for this purpose. This poker is so designed that the fine ash is scraped from a section of the inclined grate with each forward stroke. In this way the resistance of that portion of the fuel bed is reduced to a minimum, thus insuring that a portion of the air supplied to the ashpit is effectively utilized for burning the fuel on the inclined grate.

APPENDIX C

Instructions for Operation of Illinois Smokeless Furnace

1. *Starting the Fire.* — Before starting a fire, the inclined grate should be cleared of ashes by scraping it with the push poker, but a small amount of ash should be left over the shaking grate. The fire may then be readily started by employing the following procedure:

(a) Open the dampers and close the check damper. This may be done by setting the room thermostat about 5 deg. above the room temperature or by closing the shorting switch on the damper motor.

(b) Move the by-pass handle, located above the feed door, to the open position.

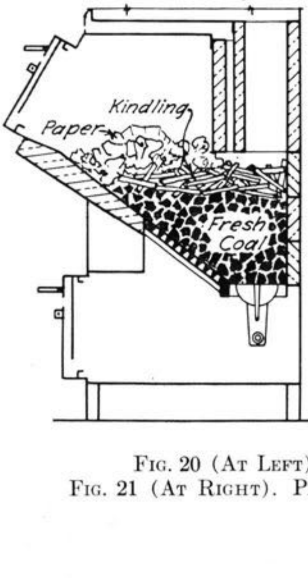
(c) Place a small charge of coal in the coke-burning chamber, allowing it to extend upward on the inclined grate and to within approximately 3 in. of the under side of the baffle wall. (See Fig. 20.)

(d) Pack the remaining space under the baffle wall with short sticks of kindling laid parallel to the sides of the furnace.

(e) Place crumpled paper in front of the kindling and ignite the paper. When the kindling is thoroughly ignited, add a little more coal to seal the space at the forward edge of the baffle wall.

(f) Partly close the firing door, leaving it open about 1 in. at the left edge to provide the large quantity of air needed for the rapid formation of hot coals under the baffle. Close the by-pass damper to intensify the draft under the baffle.

(g) After approximately 30 min., add a normal charge of coal and close the firing door.



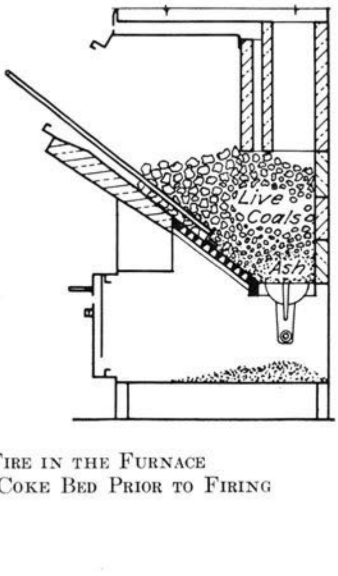


Fig. 20 (At Left). Starting a Fire in the Furnace
Fig. 21 (At Right). Preparation of Coke Bed Prior to Firing

(h) Adjust the setting of the room thermostat or the damper motor to the normal operating position.

2. *Charging the Furnace.* — A fresh charge of coal can be added to the fuel bed as follows:

(a) Set the room thermostat about 5 deg. above the room temperature, or close the shorting switch on the damper motor.

(b) Move the by-pass handle, located above the feed door, to open position.

(c) If a large bed of hot coke remains, shake the grates to clear the coke-burning chamber of the accumulated ash. If only a small amount of coke is left, shake the grates very little or not at all. In this case, ash is needed at the back of the firepot to support the coke so that a large void is not formed under the baffle. If too much ash remains in the coke-burning chamber, grates may be shaken after the coke has been partly pushed back.

(d) Push the coke back as far as possible, so that the space under the baffle is completely filled, as shown in Fig. 21. Surplus coke, if any, may be left in front of the baffle wall. If the coke forms a solid mass, it may have to be loosened with the "pick" that is provided. The push poker should slide along the inclined grate during each forward stroke, so that the pinhole grate is cleared of ash. At the end of each forward stroke of the poker, pry down on the handle before withdrawing the poker.

(e) Place a charge of coal in the coke-burning chamber. It is advisable to use somewhat smaller charges in extremely mild weather.

(f) Close the firing door, move the by-pass damper to the closed position, and adjust the setting of the damper motor or room thermostat to normal operating position.

3. *Precautions.* — A fresh charge of coal should be placed in the coking chamber only when a sufficient amount of hot coke is available to fill the coke-burning chamber to the bottom of the baffle wall. Smokeless operation is not obtainable unless there is a bed of coke under the flues.

If, at the time of firing, it is found that practically all the hot coke has been consumed, the few remaining pieces should be pushed back and upward, a small charge of fresh coal should be placed in front to seal the front edge of the baffle, and the firing door should be opened about 1 in. and should remain so for about 30 min. This procedure will insure the production of a sufficient amount of hot coke before a normal charge of coal is placed in the furnace.

APPENDIX D

INCIDENTAL STUDIES

1. *Coal Fired Without Pushing Coke into Coke-Burning Chamber.* — If a charge of fresh coal is merely placed on top of the previous charge, without pushing the coke back into the coke-burning chamber, two possibilities arise.

(a) If the fresh coal is added shortly after a previous small charge has been placed in the furnace, the result will be about the same as if the original charge had been large, and no difficulty will be encountered.

(b) If the coke in the coke-burning chamber is almost completely burned, the addition of fresh fuel will result in a fire that responds slowly to the action of the draft. Furthermore, some smoke may be obtained as a result of the low temperature in the fuel bed immediately below the end of the baffle wall.

As a rule, in order to maintain a responsive fire with the least amount of handling, it is recommended that prior to a fresh charge of coal the coke be pushed back into the coke-burning chamber.

2. *Premature Disturbance of Fuel Bed.* — In general, an attempt to push back the coke into the coke-burning chamber before the previous charge is completely coked will not prove satisfactory. If part of the previous charge is coked and the remainder is in a partly plastic state, any disturbance of the fuel bed will result in a momentarily large liberation of smoke and gases, which may escape out of the firing door. Best results have been attained by firing the charge of fresh fuel and then allowing the fuel bed to remain undisturbed until time for the next firing.

3. *Excessively Heavy Coal Charge.* — The normal capacity of the 3-section furnace is about 50 lb. of fresh coal. In a few instances excessively heavy charges amounting to about 80 lb. were added at a single firing. No marked differences in performance were obtained with the heavy charges. The firing of a large charge of coal in the coking chamber does not result in a correspondingly high rate of burning, since the latter is dependent entirely upon the amount of air entering through the orifices, which in turn depends on the available draft. On the other hand, there are possible objections to the use of excessively heavy fuel charges:

(a) In later servicing, a heavy charge of coke may be difficult to push back.

(b) The coke in the coke-burning chamber may burn out, and the fire may cease to respond to an increase in draft, before the fresh charge is coked. Under these conditions, some difficulty may be experienced in servicing the furnace because of the necessity for prematurely disturbing the fuel bed.

The furnace volume is properly proportioned for a reasonably large charge, and the practice of firing excessively large charges is, therefore, not recommended.

4. *Firing Door Left Open.* — When kindling a new fire or when the fuel bed has burned low, the firing door may be left ajar for a short time only. (See Appendix C for instructions on firing.) At all other times, the doors should be tightly closed between firing periods. The air orifices of the furnace are correctly proportioned for maintaining proper combustion. Hence, if the firing door is opened an excessive amount of air passes through the fresh charge and an increase in the combustion rate takes place. Since the secondary air passages have a fixed area, and with a given draft no more air can pass through them, an appreciable increase in the evolution of gas can result only in an insufficient supply of secondary air. Under these conditions, the CO content of the flue gases will be excessive, and smoke may be obtained.

5. *Extremely Low Fuel Bed.* — Entirely satisfactory performance of the furnace will be obtained if a bed of hot coals is maintained under the baffle wall at all times. However, it is probable that at times the fire may be allowed to burn very low before refueling. A study was therefore made in the laboratory to determine the recommended procedure when only a small quantity of coke is left in the firepot. It was found that a coke bed could be quickly re-established and that very little smoke was produced in the process if the procedure outlined in Appendix C was followed.

The possibility of maintaining too low a fuel bed is not as great in cold weather as in mild, when examination of the fire may be neglected for as long as several days. It is recommended, therefore, that even in mild weather the furnace should be inspected morning and evening as a matter of routine, and that fresh fuel be added when required. In mild weather, one firing a day will usually be sufficient.

6. *Burning Fine Coal.* — Tests were made with two coal preparations intended for use with underfeed stokers, namely ¾ in. x 48 mesh, and ¾ in. x 1½ in. In addition, some tests were made with fines resulting from breakage, commonly referred to as yard screenings. Excellent results were obtained with the ¾ in. x 1½ in. stoker coal. The finer stoker coal and the yard screenings were unsatisfactory because the portion of the charge adjacent to the floor of the coking chamber did not coke. It was found, however, that 10 to 15 lb. of very fine coal could be placed on top of a charge of nut-size coal without interfering with the maintenance of satisfactory burning characteristics.

7. *Puff-Back.* — Puff-backs consist of periodic puffs resulting from the ignition of gas accumulated in the coking chamber, and have been troublesome to overcome in many designs of stoves and furnaces. A thorough investigation was made in the laboratory of some of the factors promoting puff-backs. These factors included coal sizing, smokepipe draft, size of coking-air orifice, and design of the coking-air deflector passage. The following conclusions were drawn from the results of the study:

(a) Puff-back occurs only when a critical amount of coking air enters the coking chamber coincident with the presence of flames over the surface of the charge of fresh coal. An increase or a decrease in the amount of coking air will prevent the puffs.

(b) Puff-backs can be eliminated by the use of proper control of the coking air. The use of a damper which completely closes the coking-air inlet during the off-periods of operation is believed to be essential. The firing door should be well fitted, since excessive leakage around a poorly fitted door may cause the furnace to puff even when the coking-air damper is closed.

(c) Smokepipe draft has no effect on puff-back except as it may affect the amount of air that enters the coking chamber.

(d) All other conditions being equal, the manner in which the coking air was delivered into the coking chamber was found to be important. A properly designed deflector plate, as described in Appendix B, Section 12, was helpful in reducing the possibility of puff-backs.

APPENDIX E

DOWN-DRAFT CONVERSION BURNER

1. *Description.* — The conversion burner shown in Fig. 22 incorporates the down-draft coking principle and is designed for installation in a conventional warm-air furnace. The burner consists of a box-shaped container having a double-walled roof, sides, and an end through which secondary air is drawn into the furnace. The burner may be installed in any conventional furnace by placing the open side down and shoving it in the firing door, as shown in Fig. 23, until it extends well into the combustion chamber. No alterations to the furnace are necessary. The space between the burner and the firing neck of the furnace may be sealed with mineral wool or other suitable

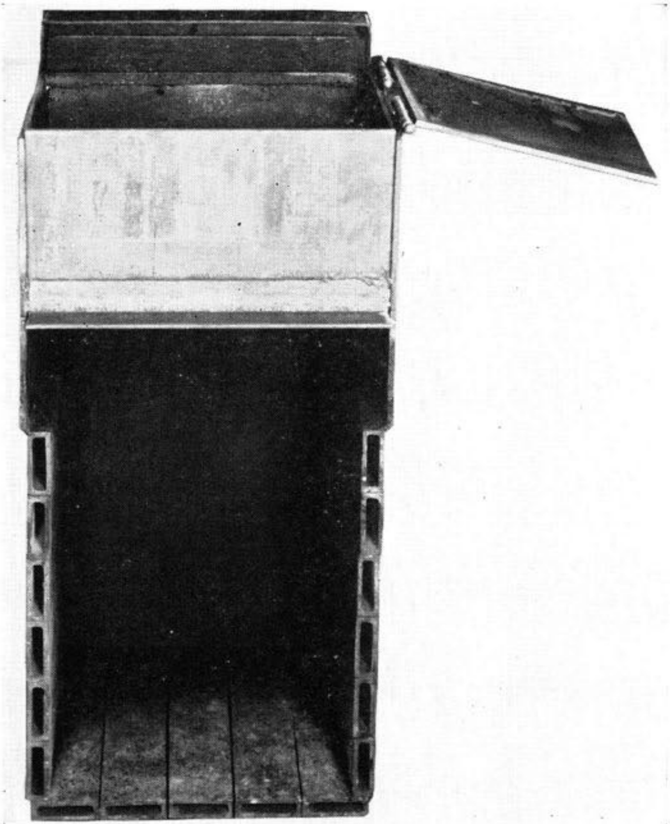


FIG. 22. DOWN-DRAFT BURNER — BOTTOM VIEW

FIG. 23. DOWN-DRAFT BURNER BEING INSTALLED IN FURNACE

material. The burner is filled with coal through the firing door on the outer end. Air entering between the plates of the double roof leaves the burner along the bottom edges of the side walls. The top and the upper portions of the side walls are made of firebox steel. The lower portion of the latter is made of a heat-resisting alloy.

Figure 24 shows a vertical cross-section of the test furnace with the burner in place, and also the relative positions of the fresh coal and coke immediately after firing. Air entering at A promotes combustion in the coke on the furnace grate, while air entering at B passes down through the fresh coal and promotes slow combustion at the ignition plane. The rate of travel of the ignition plane up through the fresh coal and the consequent rate of coking are proportional to the rate at which air enters at B. The rate of coking is therefore determined by the area of the air inlet orifice at B. Secondary air entering at C flows through the passage in the roof of the burner, which connects with vertical passages in the walls. This air emerges from the walls at D, where it mixes with the volatile gases as they are drawn under the burner walls by the natural draft of the chimney. The

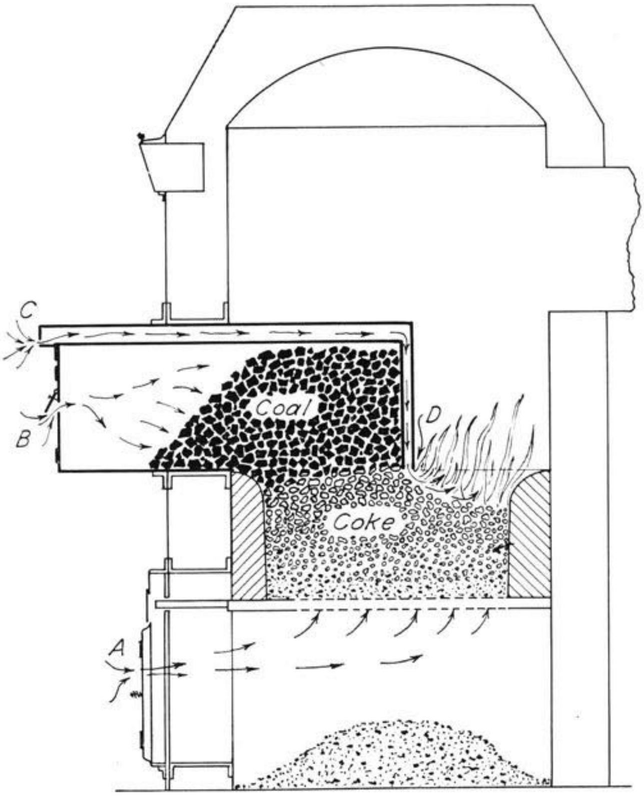


FIG. 24. VERTICAL CROSS-SECTION OF TEST FURNACE WITH DOWN-DRAFT BURNER IN PLACE

burner side walls, which extend into the furnace, are provided with air passages similar to those in the rear wall, as shown by Fig. 22.

The horizontal air passage in the roof and the vertical passages in the wall are designed to distribute the secondary air in essentially a uniform sheet around the sides and end of the burner. The coke which is burned in the lower part of the furnace firepot provides the incandescent surface necessary for igniting the mixture of air and volatile gases.

A series of tests was conducted in the laboratory for the purpose of studying the performance of a hand-fired furnace both with and without a down-draft burner. For these tests a conventional refractory-lined steel furnace having a 21-in. grate was used. The smokepipe was connected to a steel stack 12 in. in diameter and approximately 30 ft. in height. The instruments used in obtaining the data were in general the same as those previously described in Section 7.

2. *Test Procedure.* — A variety of fuel types and preparations, as listed in Table 5, were fired in the test furnace, both with and without the use of a down-draft burner. Before starting a test a normal fuel bed was established with the type of fuel to be tested. The coke remaining in the burner from the previous charge was then pushed into the firepot of the furnace, and a charge of fresh coal was fired. Except for refiring, the fire was not disturbed after starting any test. When the burner was not in use, any residual coke left at the time of firing was pushed to one side of the firepot, and the fresh fuel placed on the other side. In the cases in which coke or anthracite was fired, however, the fresh fuel was spread directly over the remaining coals. In all tests the grates were shaken at the time of firing only as much as was necessary to obtain the desired combustion rate. Each fuel preparation was

TABLE 5

RESULTS OF TESTS WITH AND WITHOUT CONVERSION BURNER

Test No.	Fuel Burned	Max. CO_2 per cent	Av. CO_2 per cent	Max. Flue Gas Temp. deg. F.	Av. Flue Gas Temp. deg. F.	Max. Smoke Dens. per cent	Av. Smoke Dens. per cent	Max. Ringel. No.	No. Min. at Max. Ringel. No.
	HOLD-FIRE OPERATION — 24 Lb. of Coal Fired Every 24 Hr.								
	Tests with Burner								
30	Ill. ¾ x ⅒	9.0	2.61	230	131	18.3	0.7	0.5	1
27	Ill. ¾ x 1½	9.7	2.95	315	145	12.1	0.1	0.5	1
28	Ill. 2 x 3	5.0	2.66	197	126	22.8	0.9	1.0	1
5	Ill. Fur. Lump	6.0	2.40	221	...	6.4	1.0	0.0	..
29	Ill. 3 x ⅒	6.9	2.19	225	127	22.7	0.8	1.0	1
51	West Va. 1 x 2	8.2	2.36	287	156	4.3	0.4	0.0	..
	Tests Without Burner								
59	West Va. 1 x 2	3.4	1.79	225	150	25.5	1.3	1.0	23
	MILD WEATHER OPERATION — 25 Lb. of Coal Fired at 8 a.m. and 8 p.m.								
	Tests With Burner								
12	Ill. ¾ x ⅒	8.7	3.78	409	157	5.1	0.6	0.0	..
10	Ill. ¾ x 1½	8.0	3.76	220	141	6.7	0.7	0.0	..
11	Ill. 2 x 3	10.4	4.27	292	159	14.3	0.7	0.5	1
14	Ill. Fur. Lump	9.0	4.07	305	164	37.7	0.5	1.5	1
52	Ill. 3 x ⅒	9.2	3.29	314	164	9.2	0.4	0.0	..
42	West Va. 1 x 2	10.0	5.05	342	183	4.3	0.1	0.0	..
	Tests Without Burner								
26	Ill. 2 x 3	6.3	3.51	265	160	53.1	5.4	2.5	15
25	Ill. Fur. Lump	5.5	4.38	195	177	23.5	3.2	1.0	11
23	West Va. 1 x 2	3.8	2.83	184	149	11.0	1.1	0.5	9
22	Coke	8.0	4.30	362	199	17.1	0.6	0.5	1
24	Ark. Anth.	3.4	2.56	148	143	6.3	0.6	0.0	..

TABLE 5 (Concluded)
RESULTS OF TESTS WITH AND WITHOUT CONVERSION BURNER

Test No.	Fuel Burned	Max. CO_2 per cent	Av. CO_2 per cent	Max. Flue Gas Temp. deg. F.	Av. Flue Gas Temp. deg. F.	Max. Smoke Dens. per cent	Av. Smoke Dens. per cent	Max. Ringel. No.	No. Min. at Max. Ringel. No.
AVERAGE WINTER OPERATION — 35 Lb. of Coal Fired at 7 a.m., 12 m., 5 p.m., and 10 p.m.									
Tests With Burner									
48	Ill. ¾ x ⅒	12.6	7.65	380	252	28.0	0.9	1.0	1
45	Ill. ¾ x 1½	14.1	7.30	446	255	20.0	0.6	1.0	1
47	Ill. 2 x 3	14.9	7.97	400	254	26.0	1.2	1.0	1
53	Ill. Fur. Lump	10.2	8.51	310	249	9.7	0.6	0.5	1
40	Ill. 3 x ⅒	15.3	8.22	400	240	6.8	1.1	0.0	..
49	West Va. 1 x 2	13.0	8.68	438	266	15.6	0.1	0.5	1
Tests Without Burner									
56	Ill. 2 x 3	12.7	6.91	440	253	40.0	5.6	2.0	30
55	Ill. Fur. Lump	9.0	4.89	350	230	21.0	3.2	1.0	22
54	West Va. 1 x 2	15.2	5.59	350	257	28.0	1.7	1.0	10
43	Coke	7.8	6.01	334	214	4.1	0.6	0.0	..
44	Ark. Anth.	6.0	4.03	403	218	2.1	0.3	0.0	..
COLD WEATHER OPERATION — 50 Lb. of Coal Fired at 7 a.m., 12 m., 5 p.m., and 10 p.m.									
Tests With Burner									
2	Ill. ¾ x ⅒	14.0	10.83	364	253	9.0	0.7	0.0	..
1	Ill. ¾ x 1½	15.6	11.98	350	291	17.5	0.8	0.5	1
3	Ill. 2 x 3	14.8	10.11	357	298	16.0	1.1	0.5	1
4	Ill. Fur. Lump	15.1	10.67	385	306	23.0	1.5	1.0	5
39	Ill. 3 x ⅒	15.0	11.49	450	264	20.0	1.1	1.0	8
41	West Va. 1 x 2	13.0	10.42	376	259	6.1	0.3	0.0	..
Tests Without Burner									
8	Ill. 2 x 3	15.1	9.94	527	296	82.0	9.4	4.0	65
9	Ill. Fur. Lump	15.4	9.44	450	311	65.0	6.6	3.0	11
6	West Va. 1 x 2	11.4	7.48	291	259	27.2	1.5	1.0	5
7	Coke	17.0	9.76	476	335	8.1	0.5	0.0	..
35	Ark. Anth.	11.0	8.41	495	276	2.8	1.0	0.0	..
EXTREME COLD WEATHER OPERATION — 45 Lb. of Coal Fired Every 3 Hr.									
Tests With Burner									
18	Ill. ¾ x ⅒	15.3	12.68	560	386	3.8	1.1	0.0	..
17	Ill. ¾ x 1½	16.6	13.18	423	380	14.0	2.1	0.5	1
16	Ill. 2 x 3	15.3	12.73	370	340	28.0	3.7	1.0	5
15	Ill. Fur. Lump	14.9	12.09	490	410	5.0	1.1	0.0	..
38	Ill. 3 x ⅒	16.0	14.45	436	394	15.0	2.8	0.5	6
50	West Va. 1 x 2	13.4	12.92	351	344	2.4	0.3	0.0	..
Tests Without Burner									
36	Ill. 2 x 3	13.8	5.89	680	448	61.0	11.1	3.0	21
37	Ill. Fur. Lump	9.6	4.52	540	395	35.0	7.2	1.5	6
20	West Va. 1 x 2	13.2	7.12	551	429	16.0	2.0	0.5	15
19	Coke	13.3	9.59	619	448	0.9	0.02	0.0	..
21	Ark. Anth.	13.8	9.89	683	489	2.5	0.2	0.0	..

burned under conditions simulating those encountered during a complete heating season — namely, hold-fire, mild weather, average winter weather, cold weather, and extremely cold weather, corresponding to burning rates of approximately 1, 2, 6, 8, and 15 lb. per hr., respectively. With the exception of those in which the fuel was burned at the maximum rate, each test was 24 hr. long.

Fuel was fired every 3 hr. in the tests simulating extreme cold weather, four times per day in those simulating cold and average winter weather, two times per day in those simulating mild weather, and once a day in the hold-fire tests. Since the fire would not last more than 12 hr. except in the case of West Virginia coal, hold-fire tests were not conducted when the furnace was used without the burner.

The combustion rate was controlled in the burner-equipped furnace by a conventional check damper in the smokepipe and a damper regulating the amount of coking air entering the front of the burner. For tests without the burner the conventional combination of a check damper in the smokepipe and an ashpit air damper was used. Since sufficient air leaked into the ashpit to burn completely all the coke in the firepot, the ashpit door and the ashpit air damper were kept closed throughout all tests with the burner. No adjustments were made in the secondary air during any test.

The smoke density meter was calibrated in terms of Ringelmann

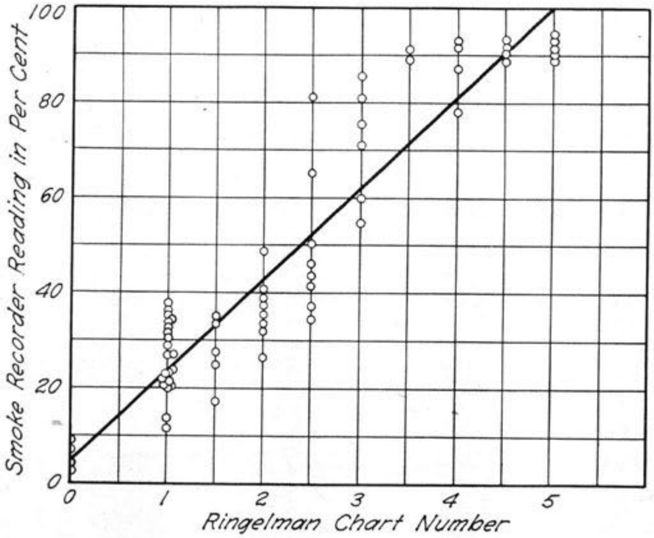


FIG. 25. SMOKE DENSITY CALIBRATION CURVE

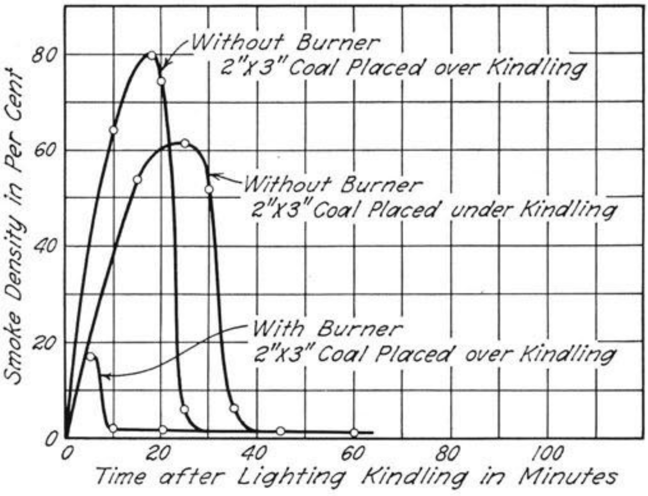


FIG. 26. SMOKE DENSITY PRODUCED IN STARTING FIRE

numbers, as shown in Fig. 25, by observing the smoke at the top of the stack. The wide spread of the points illustrates the limitations of the human eye in judging the exact density of smoke.

Table 5 presents a summary of all data collected. The maximum CO_2, maximum flue gas temperature, and maximum smoke density were read directly from charts; the average values for the other data were determined from hourly readings for each test. The Ringelmann numbers tabulated were obtained from Fig. 25. The length of the period over which smoke is emitted is just as important as the maximum smoke density attained. Accordingly, the number of minutes during which the given smoke density persisted is shown in the right-hand column of the table.

3. *Starting Fires.* — Figure 26 shows the amount of smoke produced in starting a fire. Two tests were made in the conventional furnace without the burner, one in which the coal was placed on top of the kindling, and one in which the coal was first placed in the furnace and a kindling fire was then built on top of the coal. It may be noted that the smoke having a density of 80 per cent, corresponding to a Ringelmann number of 4, was produced when the coal was placed on top of the kindling. Building the kindling fire on top of the coal resulted in a considerable decrease in maximum smoke density, and an increase in the length of time that the smoke persisted.

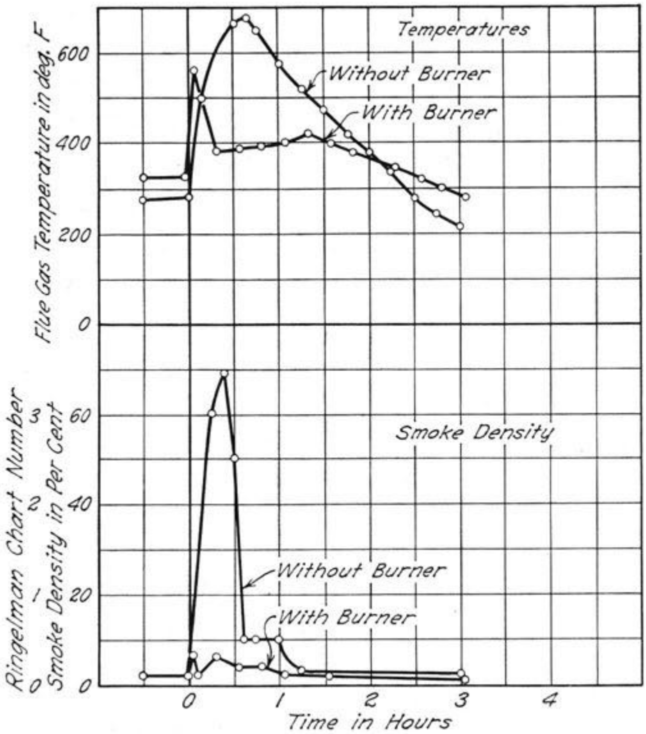


FIG. 27. SMOKE DENSITIES AND FLUE GAS TEMPERATURES WITH AND WITHOUT DOWN-DRAFT BURNER

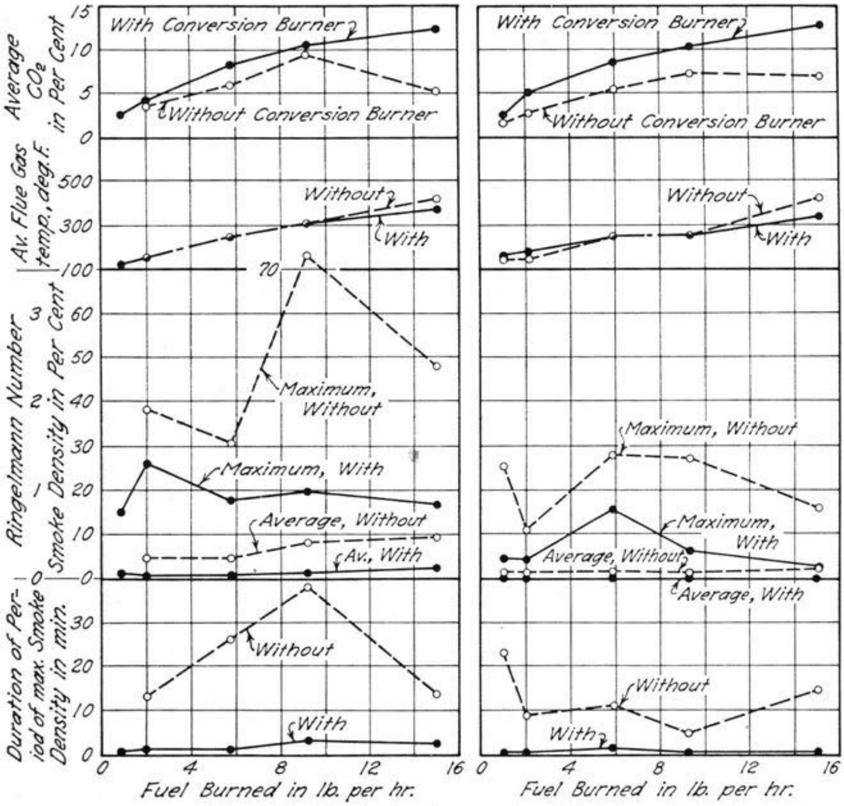
The smoke produced in starting a fire in a burner-equipped furnace was negligible as compared with that produced by either of the two methods used in connection with the conventional furnace. The volatile gases evolved from the coal were forced to pass directly over the burning kindling, which was placed just below the burner and provided the temperature necessary for the ignition of the air-gas mixture.

4. *Heat Release.* — The performance curves for a conventional furnace operated both with and without the burner under conditions accompanying cold weather are shown in Fig. 27. It may be observed that the smoke density was negligible when the burner was used. The fact that the flue gas temperature reached a maximum while the coal was being fired indicates that the fire responded almost instantly to the action of the draft. The low maximum values shown by the curve representing flue gas temperatures prove that the burner definitely

limited the combustion rate and thus minimized any danger of overheating the furnace. The maximum rate of heat delivery was slightly less when the furnace was equipped with a burner than when no burner was used, but observations of actual installations over a period of nine years indicate that burner-equipped furnaces installed in conformity with good practice will amply meet peak demands occasioned by extreme cold weather. The burner may be filled with coal at night and the dampers set to produce steady burning. As a result the house temperature does not drop as much as in the case of a furnace used without a burner, and it is not necessary to force the fire in order to warm the house in the morning.

5. *Smoke Density, CO_2 Content, and Temperature of Flue Gases.* — The results obtained with preparations of high-volatile Illinois coals of two sizes, namely lump and 2 in. x 3 in. nut, were averaged from data given in Table 5 and plotted as shown in Fig. 28. Similar results obtained with a low-volatile coal are shown in the same figure. Both the maximum and the average smoke densities were plotted against the combustion rate, as was also the duration of the period over which smoke of maximum densities was produced. It may be noted that the smoke resulting from the burning of Illinois coal in the conversion burner was practically negligible under all conditions of operation. A smoke density as high as the equivalent of number 1 on the Ringelmann chart was obtained on only a few tests with the burner, and in these cases the time during which the smoke persisted was practically negligible. The greatest tendency to smoke occurred incident to tests simulating cold weather operation. In these tests 50 lb. of coal were fired every 5 hr. except at night, when the fire was checked the greater part of the time. On some occasions the fuel in the burner was not completely coked when it was pushed into the furnace firepot, and as a result there was a tendency for the furnace to smoke. However, there was never sufficient smoke produced to constitute a violation of any smoke ordinance.

As shown in Fig. 28, no great amount of smoke was produced by low-volatile coal regardless of how it was burned, but the best results were obtained when the coal was fired in a burner-equipped furnace. It was found that, without the burner, even the low-volatile coal caused a smoldering fire if the fuel bed temperature was low at the time of firing. One point on the curve representing smoke density for tests on the furnace without a burner is considerably higher than the curve as a result of a smoldering fire which persisted for nearly one-half hour after firing.



a — With High-Volatile Coal b — With Low-Volatile Coal

FIG. 28. FLUE GAS CHARACTERISTICS FOR HIGH-VOLATILE AND LOW-VOLATILE COALS WITH AND WITHOUT CONVERSION BURNER

With both high-volatile and low-volatile coals, the CO_2 obtained with the burner-equipped furnace was appreciably higher than it was for the furnace without the burner, especially at higher burning rates. In the latter case the curve representing average CO_2 declines sharply at the higher rates as a result of holes that formed in the fuel bed toward the end of the cycle. Higher CO_2 content could have been maintained by more frequent firing. One purpose of the tests, however, was to compare various fuels and methods of burning under similar conditions, and since a 3-hr. cycle had been used for tests on the burner-equipped furnace, this method was also employed for the tests on the furnace without the burner.

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