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DEVELOPMENT OF A MODEL VIBRATING-GRATE STOKER FOR STRONGLY CAKING COALS

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FUELS AND MINING PRACTICE DIVISION

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Development of a Model Vibrating-grate Stoker for Strongly Caking Coals

By F. D. FRIEDRICH, B.Sc.*

Research was undertaken to develop a stoker capable of satisfactory performance with strongly caking, low-ash-fusion coals, and adaptable to packaged boiler systems, for a capacity range of 50 to 1 000 lb of coal/h. To obtain a simple, compact design, a combination of an air-cooled vibrating grate, with a plate feeder extending the full width of the grate, was chosen. The feasibility of the design was demonstrated by experiments on a model stoker having a grate 1 ft wide and 2 ft long, housed in a refractory furnace. Grate surface temperatures of up to 1 200° F were recorded, and ash fused to the grate at average grate heat-release rates of about 225 000 Btu/ft² h. However, experiments on a full-size air-cooled vibrating-grate stoker installation showed that, with a water-cooled furnace and about 160 per cent total air, grate surface temperatures can be maintained below 500° F. Hence it should be possible to avoid the complication of water cooling the grate. A combination of experiments on the model stoker and full-sized vibrating-grate installations showed that a vibrating frequency of 1 200 c.p.m. is substantially more effective than frequencies of 400 to 800 c.p.m. in breaking up coke formations from strongly caking coal. It was established that the optimum fuel-bed thickness for good performance with strongly caking coal is 3 to 4 in, and that a positive means of providing a uniform fuel bed must be provided. Zone control of primary combustion air is also necessary. Data are given from tests on the model stoker with lignite, a non-caking coal, and a strongly caking coal. Extrapolation of the results to the design of full-scale stokers is attempted.

1. INTRODUCTION

THE combustion of high-volatile bituminous coal on mechanical stokers has not compared favourably with its combustion in pulverized form, nor with the combustion performance of oil and natural gas. Stokers often lead to inefficient combustion, resulting in excessive smoke and high fuel consumption; they are large, expensive to maintain and often do not operate without manual attention. In view of the resulting trend to oil, natural gas and pulverized-coal firing, and because a varied array of stoker-fired equipment already exists, the need for research to develop a new type of stoker may well be questioned.

However, coal remains Canada's basic source of fuel. Although oil and natural gas have captured much of the market, their reserves appear to be limited, and their properties suit them for applications where more expensive fuels are justified. Therefore, an eventual return of the commercial and industrial markets to coal is anticipated, but considerable hardship will be experienced unless adequate combustion equipment is developed beforehand.

For this reason alone research to improve mechanical stoking is justified at the present time, but some peculiarities of certain Canadian coals and of the Canadian market situation make it even more urgent.

First, although pulverized-coal-fired installations are steadily increasing in number and size, most of the important Canadian coal producers must still depend on substantial sales in the large-volume commercial market to maintain mine production at an economical level. Commercial stokers are defined as those having a capacity ranging from 50 to 500 lb of coal/h. This market is fiercely competitive, and many users are willing to pay a premium for convenience and automatic operation, such as are so readily provided by oil- and gas-fired packaged boilers. At present no commercial stoker can provide these features to the same degree.

Secondly, Canada's main resources of bituminous coal, those of Eastern Canada, combine very strongly caking properties with low-ash-softening temperatures. This is in sharp contrast to the situation in Britain and the United States, where similar coals are little used because of competition from large deposits of free-burning, medium- to high-ash-fusion coals. However, most of the stoker designs used in Canada are of American or British origin and, while they provide relatively good performance with either the free-burning of the high-ash-fusion coals for which they were intended, their performance with Canadian coals of the type just described leaves much to be desired.

In the past three or four decades single-retort underfeed stokers enjoyed a widespread popularity in the commercial market in Canada, as elsewhere. This was because they were simple and inexpensive, and because little else but hand firing was available in the stoking capacity range of 50 to 500 lb of coal/h. Unfortunately, underfeed stokers with their thick fire-beds are probably the worst possible equipment for firing strongly caking, low-ash-fusion coals. This is because the so-called " distillation zone " provides ideal conditions for the development of massive formations of dense coke, which make the fuel bed impenetrable by air. This results in poor burn-out and chemically reducing conditions in localized areas, which in turn aggravates slagging. As a result, the many underfeed stoker installations burning Eastern Canadian bituminous coal compete at a disadvantage.

In these circumstances, to improve the competitive position of sized industrial coal in the commercial market, research was undertaken to develop a stoker that could :

(*a*) Be suited to the peculiar properties of Canadian coals ;

(*b*) Be able to operate automatically to a large degree ;

(*c*) Be adaptable to the package boiler concept, and

(*d*) Burn higher-quality coals with equal facility.

This paper describes the progress on this work.

2. EQUIPMENT DEVELOPMENT

2.1. General Considerations

The vibrating-grate stoker development project de-

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scribed in this paper evolved from the background of a broad research programme in which the author's group studied the application of Eastern Canadian bituminous coal to the entire array of mechanical stokers used in Canada. The results of this study have been fully reported elsewhere ;[1] it is sufficient to reiterate here that for optimum performance with high-volatile, strongly caking, low-ash-fusion coals the following conditions must be met :

(*a*) The coal must be burnt in relatively thin fire-beds about 4 in thick.
(*b*) Continuous ash discharge must be provided.
(*c*) Caking must be reduced to a minimum.

The foregoing criteria and the reasons that follow left no alternative to selecting a vibrating-grate type of stoker for laboratory investigation. The requirement of a thin fire-bed immediately ruled out any form of underfeed or retort firing, while spreader firing was ruled out by the fact that it is not readily adaptable to equipment burning less than 500 lb of coal/h, and by the fact that it requires dust collectors, a complication it was desired to avoid. Continuous ash discharge can be provided by chain grates, travelling grates or vibrating grates. Of these, the last are the simplest and most compact in construction, and, while the means required to lay down a thin bed of coal are more elaborate than on chain-grate or travelling-grate stokers, the vibrating action is valuable in breaking up coke formations and compacting the fire-bed.

2.2. The Laboratory Stoker

The author's group has had previous experience with three commercial types of vibrating grates. One is air-cooled, spreader-fired and vibrates at a frequency of about 1 200 c.p.m. ; the second is water-cooled, induces feed by means of the vibrating action and vibrates at about 600 c.p.m. ; and the third is water-cooled, has a positive worm feed and vibrates at a frequency of about 400 c.p.m. After comparing their performance when burning strongly caking coal, the following features were decided upon for the laboratory stoker :

(1) A frequency of 1 200 c.p.m. This was decided upon because in experiments with full-scale stokers it was demonstrated that frequencies of 400 and 600 c.p.m., while providing good fuel-bed travel with weakly caking and free-burning coals, were ineffective in breaking up and compacting coke formations from a strongly caking coal. However, a full-scale stoker vibrating at 1 200 c.p.m. broke up such coke formations very well. In addition, rig-scale tests in the laboratory at 800 and 1 200 c.p.m. showed the latter to be more effective in handling strongly caking coals.

(2) An air-cooled grate. This was decided upon because the complications involved in water-cooling the grate are not amenable to the packaged-boiler concept, and because the greater weight of a water-cooled grate makes it necessary to provide stiffer flexure plates to achieve the desired frequency of 1 200 c.p.m. Stiffer flexure plates in turn make it difficult to achieve the desired amplitude of $\frac{1}{8}$ to $\frac{3}{16}$ in. That an air-cooled grate could be maintained at safe temperatures by limiting grate heat-release rate to 350 000 $\text{Btu/ft}^2\,\text{h}$ had been demonstrated in experiments on a full-size industrial vibrating stoker.[2]

(3) Positive feed. This was felt necessary because experiments with an industrial stoker had shown feed induced by the vibration of the grate inadequate to handle coal containing 6 to 8 per cent moisture and a fines content of up to 60 per cent through a $\frac{1}{4}$-in mesh screen. To provide positive, uniform feed over the entire grate a simple mechanism, comprising a mechanically driven plate feeder extending across the full width of the grate, was chosen.

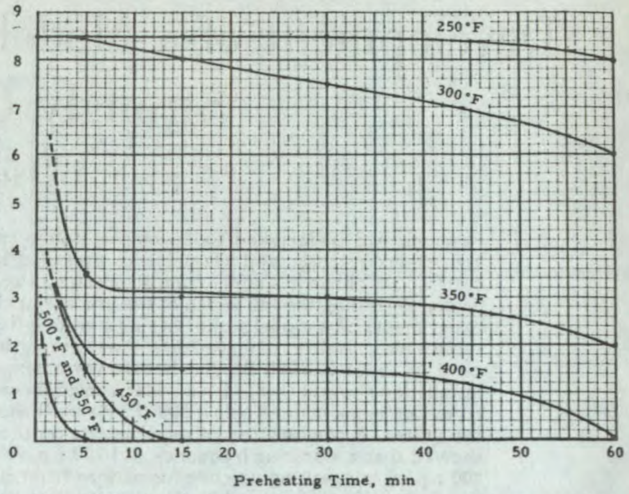

FIG. 1.—*Effect of preheating at a range of temperatures on the free-swelling index of* – 200 *mesh strongly caking Eastern Canadian coal.*

It has been established that the free-swelling index or swelling number of Eastern Canadian coal can be reduced by preheating the coal before combustion. The results of some preliminary experiments on this phenomenon are summarized in Fig. 1. The author postulates that a similar mechanism of preheating contributes to the superior performance of spreader stokers compared with chain grate or underfeed stokers when burning strongly caking coal.

Preheating may also be achieved by providing a suction zone under the grate immediately following the feeder discharge, so that hot furnace gases may be drawn downward through the bed of green coal. The resulting mixture of furnace gases and distilled volatile matter may then be reinjected into the furnace to provide turbulence to ensure complete combustion. Such a system has been patented by members of the author's group, and the stoker described in this paper can be readily adapted to employ it. For the sake of simplicity, however, the present development incorporates only the conventional pressure air zones under the grate, and the only means for minimizing caking is to establish brisk combustion in the bed of incoming coal, so that fissures are burnt through it before it has an opportunity to cake into a solid mass.

Once the means were established by which the aforementioned requirements would be met, a working model of a vibrating-grate stoker was built. Grate dimensions were fixed at a width of 1 ft and a length of 2 ft, and a downward slope of 12° toward the rear or ash discharge end was selected. A locomotive-type boiler was used as a heat sink but, to provide high furnace temperatures, the stoker was enclosed in a " dutch oven " made of castable refractory poured into steel frames which were then bolted together. These, together with the coal hopper and feeder assembly, are shown in Fig. 2. The dutch

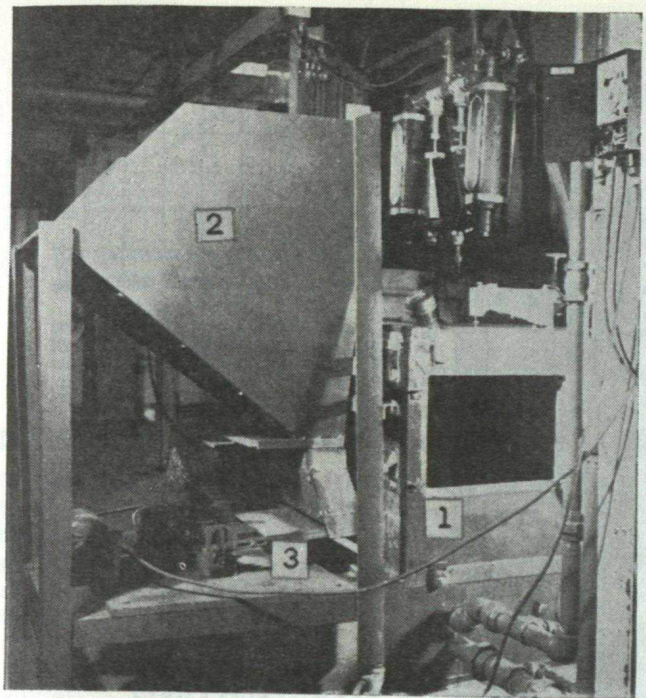

FIG. 2.—*Assembly of coal hopper and refractory "dutch oven" for first model of vibrating-grate stoker.*

1. *Refractory " dutch oven."* 2. *Coal hopper.* 3. *Coal feeder.*

oven had no water cooling, and the grate was made of a $\frac{1}{4}$-in steel plate ; this combination resulted in overheating of the stoker, clinkering on the grate and eventual damage. However, the feasibility of the firing system was sufficiently demonstrated to warrant the development of an apparatus more closely resembling a prototype stoker.

2.3. Redesigned Mark 2 Stoker

The redesigned stoker, which was designated the Mark 2 model, incorporates alloy cast-iron grates and water cooling in the furnace. The grate and windbox assembly is shown in Fig. 3. As before, the grate is 1 ft wide by 2 ft long, but the slope has been reduced to $\frac{1}{2}$ in/ft, because comparison of the performance of the previous model with that of a full-sized industrial vibrating grate sloped at $\frac{1}{2}$ in/ft showed that the increased slope offered no practical advantages. The burning surface is made up of heavy bars having air-cooled fins. These bars are cast in grey iron alloyed with 1 per cent chromium and 1 per cent nickel, a composition which has been found capable of withstanding 1 200° F without oxidation growth, compared with 800° F for ordinary grey iron. There are four air zones under the grate, each equipped with a sliding damper to regulate air flow from the main windbox. Total grate air opening equals 2·6 per cent of the effective grate area.

The grate and windbox assembly is mounted on flexure plates, which are inclined away from the discharge and at 15° from the vertical. Thus, when vibrating the grate moves up and down as well as backward and forward. The design of the flexure plates is explained in Appendix 1 to this paper. The assembly is surrounded by a welded steel water jacket $3\frac{1}{2}$ in high, as shown in Figs. 4 and 5. This serves as a clinker chill. To provide clearance between it and the vibrating grate, yet prevent coal from falling off the sides of the grate, the windbox side plates were first extended 2 in above the grate surface, as shown in Fig. 3. These extensions were cooled to some extent by the water-walls, which were parallel to them. However, with this arrangement it was impossible to obtain a reliable sample of flue gas because of dilution by air passing upward between the windbox side plates and the water-walls. The side plates were, therefore, cut off flush with the grate surface, and sealing is now accomplished by means of a $\frac{3}{8}$ by 1-in steel strip welded to each water-wall, overlapping the grate by about $\frac{3}{4}$ in, with about $\frac{1}{8}$ in vertical clearance to the grate. With the present arrangement any leaking air coming up the

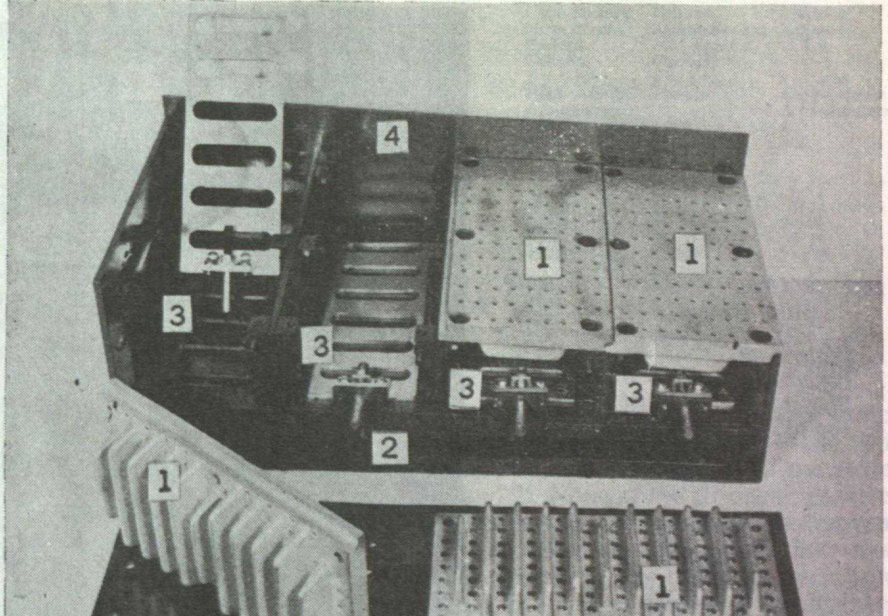

FIG. 3 (*Right*).—*View of Mark 2 vibrating grate during assembly.*

1. *Finned grate bars.*
2. *Main windbox.*
3. *Damper-controlled air zones.*
4. *Windbox side plates.*

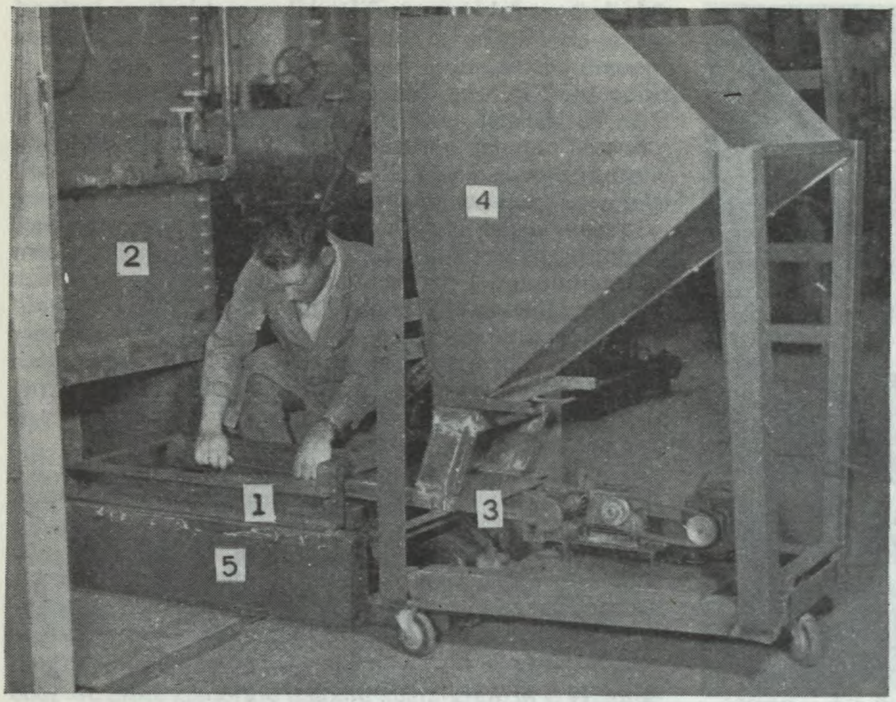

FIG. 4 (*Left*).—*Assembly of grate, coal feeder and water-wall.*

1. *Water-wall.*
2. *Locomotive boiler used as heat sink.*
3. *Plate feeder.*
4. *Coal hopper.*
5. *Cover plate.*

outside of the windbox must pass through the fire-bed, while the fire is contained laterally by the water-walls and the refractory furnace walls.

A single-plane vibrator is mounted on the front of the windbox and is driven by an electric motor controlled through a timer having both ON and OFF periods adjustable. Combustion air is supplied by a small high-speed blower through a flexible connector, as shown in Fig. 5.

The coal-feeding system is a separate moveable unit consisting of a mechanically driven, variable-stroke plate feeder 1 in high by 11 in wide. It reciprocates in a coal spout fastened to the bottom of the coal hopper, as shown in Fig. 4. A portion of the furnace water-wall passes over the feeder spout to prevent coal from coking in the spout and jamming the feeder. The front of the stoker under the feeder spout is also water-cooled to prevent the oil-bath vibrator overheating.

The dutch oven is mounted on the water-wall. Rather than attempting to seal between the stoker and the furnace walls, the entire furnace cavity is sealed with gaskets and cover plates like the one shown in Fig. 4.

The Mark 2 stoker is fairly completely instrumented for research purposes. Indicators to measure furnace

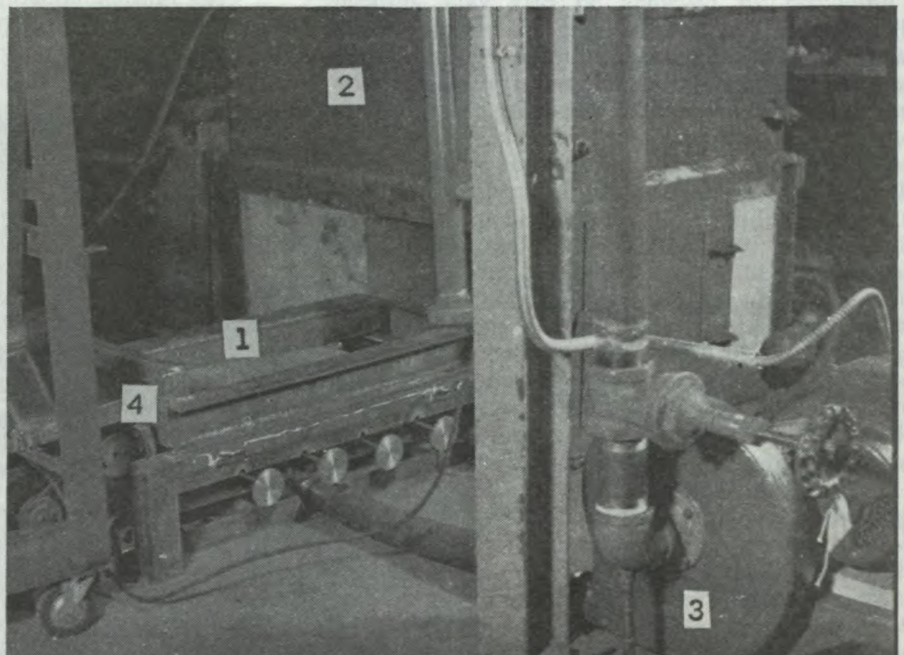

FIG. 5 (*Right*).—*View of grate, water-wall and blower.*

1. *Water-wall.*
2. *Locomotive boiler used as heat sink.*
3. *Blower supplying combustion air.*
4. *Top of one flexure plate.*

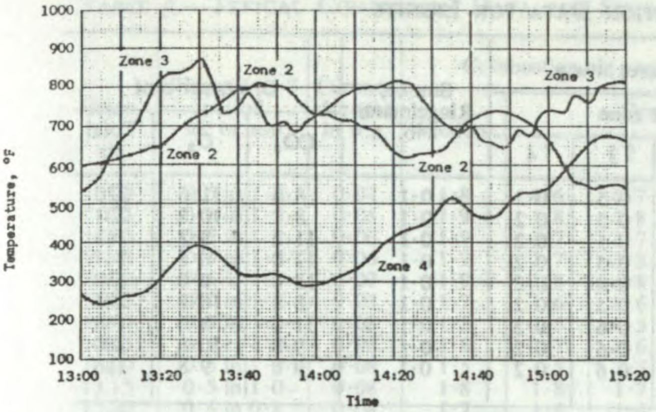

FIG. 6.—*Grate surface temperatures when burning lignite.*

draught and windbox and grate zone air pressures have been provided, while a number of thermocouples measuring temperatures of the grates and other critical parts of the stokers are connected to an automatic recorder. Smoke emission is measured by a smoke density indicator in the stack.

3. COMBUSTION TESTS WITH MARK 2 VIBRATING-GRATE STOKER

3.1. General Description

Since the model stoker just described is intended as an apparatus for burning strongly caking, low-ash-fusion coal, such a fuel has been used for most of the combustion testing. However, for purposes of comparison, some tests were conducted burning lignite, and one was conducted burning a premium quality, weakly agglomerating, medium-ash-fusion American coal that appears to resemble the Nottinghamshire coals, except that it has an ASTM free-swelling index of 7. Table 1 gives the classifications and analyses of the three coals used for combustion testing. The performance of each coal will be discussed separately.

The object of the combustion tests is to determine the optimum firing conditions that can be maintained automatically. The procedure consists of establishing a well-ignited fire-bed on the grate, adjusting air and vibrator settings to maintain combustion conditions and increasing coal feed to what appears, from experience, to be the maximum safe rate. Furnace draught, windbox and air zone pressures, smoke density and flue-gas analyses are recorded at 15-min intervals, while grate temperatures are measured continuously by an automatic recorder. Grate temperature patterns have been a very helpful indicator of combustion conditions, therefore they accompany each set of data. No attempt was made to obtain quantitative data on riddlings or grit carry-over, although it may be said that riddlings were minimized by the small grate air openings and correspondingly high windbox pressure, and although there was a substantial amount of grit carry-over from the grate, typical of stoker operation, it consisted of large particles which for the most part settled out at the point where the gas stream changed direction entering the boiler.

3.2. Combustion Tests with Lignite

Lignite was slow to ignite because of its high moisture content and good performance was achieved only after the refractory furnace walls had heated sufficiently to radiate heat on to the incoming coal bed. At this point the furnace temperature was estimated at about 1 500° F. The fire then became very stable, and the stoker operated automatically for several hours with no change in the fire-bed. Under typical conditions there were 3 to $3\frac{1}{2}$ in of unignited coal on Zone 1, about 2 in of rapidly burning coal on Zone 2, a thin layer of glowing coal on Zone 3 and well burnt-out ash on Zone 4. Grate temperatures remained low, hence any clinker that formed did not stick to the grate, Combustion was very clean ; smoke density never reached No. 1 Ringelmann. Typical combustion data are given in Table 2, while corresponding grate surface temperature patterns are given in Fig. 6.

3.3. Combustion Tests with Weakly Agglomerating Bituminous Coal

The coal used for this test is sold as a premium fuel for domestic and commercial use under the trade name " Cavalier Queen." In addition to the attractive properties listed in Table 1, it is oil-treated and the fines have been removed. Its performance on the vibrating stoker was exemplary ; it fed easily, formed a porous uniform fire-bed, and burnt furiously and completely. Although its ASTM free-swelling index would suggest considerable coke formation in the fire none was actually observed ; presumably the vibration of the grate immediately broke up weak coke masses. Normally there were 3 in of well-ignited fire-bed on Zone 1, tapering to 2 in of glowing coals on Zone 3, with unignited refuse on Zone 4. Once good combustion was established and the furnace was hot, no smoke was produced even when the grate was vibrating. Small streamers of smoke emanated from the raw coal but were quickly consumed in the furnace.

TABLE 1.—CLASSIFICATION AND ANALYSES OF COALS USED FOR COMBUSTION TESTS WITH THE MARK 2 VIBRATING STOKER

Location of coal mine	Cape Breton, Nova Scotia, Eastern Canada.	Estevan, Saskatchewan, Mid-western Canada.	Elkhorn, Kentucky, U.S.A.
Coal size	$\frac{3}{4} \times 0$ in	$\frac{3}{4} \times \frac{1}{4}$ in	$\frac{3}{4} \times \frac{1}{4}$ in
ASTM classification	High-volatile A bituminous	Lignite	High-volatile A bituminous
ISO classification	635	1 200	632
British classification	402	—	702
Percentage proximate analysis, ASTM :			
Moisture	3·98	35·46	1·71
Ash	8·25	10·44	3·04
Volatile matter	36·94	27·53	39·06
Fixed carbon (by diff.)	50·83	26·57	56·19
Calorific value, Btu/lb gross	13 270	6 720	14 420
Ash fusibility :			
Initial deformation, ° F	1 925	2 020	2 080
Softening, hemispherical, ° F	2 050	2 110	2 300
Fluid, ° F	2 280	2 320	2 550
Free-swelling index, ASTM (crucible swelling test)	8·5	N/A	7
Gray–King coke type	G-9		E-G

Because of the very low ash content of the coal, grate temperatures were high. As a result, after a $5\frac{1}{2}$-h test run about $\frac{1}{8}$ in of clinker was stuck to portions of the grate surface on Zones 1 and 2. None of the air openings were blocked, and there was no interference with combustion or the movement of coal down the grate, but this probably would occur after a longer period of operation as the clinker built up to a greater extent. It would then be necessary to slice the fire to loosen the clinker. However, clinkering could probably be avoided completely by means described later.

TABLE 2.—TYPICAL COMBUSTION DATA FOR LIGNITE

Time	Timer " on " period sec in min	Furnace draught in w.g.	Combustion air pressure, in w.g.					Smoke, Ringelmann No.	Orsat, per cent		
			Windbox	Grate zone					CO_2	O_2	Total air
				1	2	3	4				
13.15	0·5 in 1·0	0·05	1·5	0·2	0·8	0·5	0·2	0·1	8·0	11·6	220
13.30	0·5 in 1·0	0·05	1·0	0·2	0·7	0·5	0·2	0·1	8·8	10·8	203
13.45	0·5 in 1·0	0·06	1·0	0·2	0·7	0·5	0·2	0·1	11·2	8·2	163
14.00	0·5 in 1·0	0·03	1·0	0·2	0·6	0·5	0·2	0·1	13·0	6·8	147
14.15	0·5 in 1·0	0·03	1·0	0·2	0·7	0·4	0·2	0·1	13·6	6·0	139
14.30	0·5 in 1·0	0·03	1·0	0·2	0·6	0·5	0·2	0·1	8·8	10·8	203
14.45	0·5 in 1·0	0·01	1·0	0·2	0·8	0·6	0·2	0·1	11·6	8·0	160
15.00	0·5 in 1·0	0·03	1·0	0·2	0·7	0·6	0·2	0·1	9·0	10·6	200
15.15	0·5 in 1·0	0·03	1·0	0·2	0·7	0·6	0·2	0·1	9·8	9·8	186

Average grate heat-release rate, Btu/ft² h = 154 900. Combustible in ash, per cent = 3·8.

TABLE 3.—TYPICAL COMBUSTION DATA FOR WEAKLY AGGLOMERATING BITUMINOUS COAL

Time	Timer " on " period sec in min	Furnace draught in w.g.	Combustion air pressure, in w.g.					Smoke, Ringelmann No.	Orsat, per cent		
			Windbox	Grate zone					CO_2	O_2	Total air
				1	2	3	4				
13.30	0·5 in 1·0	0·02	2·2	2·2	2·2	1·0	0·5	0·2	14·4	4·0	123
13.45	0·6 in 1·0	0·02	2·2	2·2	2·2	1·0	0·5	0·3	13·0	5·2	132
14.00	0·6 in 1·0	0·01	2·0	2·0	2·0	1·1	0·5	0·2	13·6	5·2	132
14.15	0·6 in 1·0	0·02	2·0	2·0	2·0	1·0	0·5	0·2	15·0	2·4	112
14.30	0·6 in 1·0	0·02	2·0	2·0	2·0	1·0	0·5	0·2	12·0	6·4	142
14.45	0·6 in 1·0	0·02	1·8	1·8	1·8	1·0	0·5	0·2	11·8	6·6	144
15.00	0·6 in 1·0	0·02	1·8	1·8	1·8	1·0	0·4	0·2	12·0	6·4	142
15.15	0·6 in 1·0	0·03	1·8	1·8	1·8	0·8	0·5	0·2	16·2	2·4	113
15.30	0·6 in 1·0	0·02	1·8	1·8	1·8	0·8	0·5	0·2	13·6	5·1	131

Average grate heat-release rate, Btu/ft² h = 245 100. Combustible in ash, per cent = 8·6.

Typical combustion data are given in Table 3 while corresponding grate temperature patterns are given in Fig. 7.

3.4. Combustion Tests with Strongly Caking Low-ash-fusion Bituminous Coal

The most interesting test with the strongly caking coal was one in which the stoker was overfed somewhat beyond the capacity of the forced draught fan in an attempt to achieve a burning rate near that recommended for commercial equipment. This resulted in low values of excess air and rather high grate temperature.

Beginning with a clean grate, intense combustion was established on the first two zones. The fire-bed was about 4 in thick, remained porous and burn-out was completed on the third zone. With each vibration cycle of the grate there was a 2 or 3 sec puff of smoke, which often exceeded No. 1 Ringelmann in density. Temperatures at the surface of the first two grate zones were about 1 100° F. After about 45 min these temperatures began to drop, which was an indication that clinker was forming on the grate surface and beginning to obstruct air flow. Then the previously porous fire-bed on the first zone began to agglomerate into a solid mass 5 to 6 in thick, which was advanced down the grate more through the action of the feeder than through the action of the vibrator. This coke mass broke up on the second grate zone and burnt out on the third grate zone, but was continually regenerated by the incoming coal on the first zone.

Gradually, as the clinker continued to build up on the grate and began to obstruct air flow to the second grate zone, the coke mass thickened to 7 or 8 in and lengthened so that it covered the first and second zones ; it then broke up and burnt out on the third and fourth zones. Combustion conditions were still good and burn-out

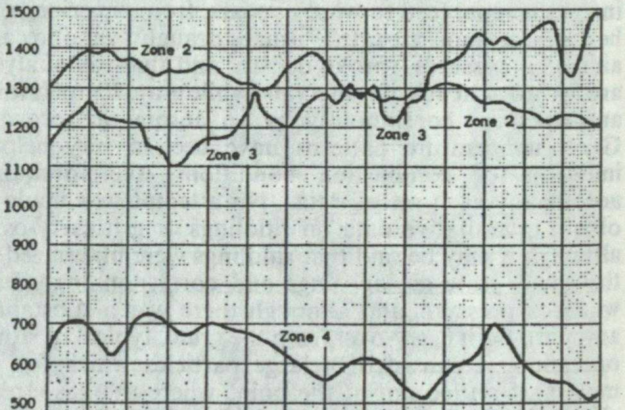

FIG. 7.—*Grate surface temperatures when burning non-caking bituminous coal.*

TABLE 4.—TYPICAL COMBUSTION DATA FOR STRONGLY CAKING, LOW-ASH-FUSION BITUMINOUS COAL

Time	Timer " on " period sec in min	Furnace draught in w.g.	Combustion air pressure, in w.g.					Smoke, Ringelmann No.	Orsat, per cent		
			Windbox	Grate zone							
				1	2	3	4		CO_2	O_2	Total air
11.00	0·5 in 1·5	0·04	1·8	1·6	1·7	0·6	0·3	0·1	13·3	5·3	133
11.15	0·5 in 1·5	0·05	1·9	1·8	1·8	0·3	0·3	0·1	15·4	2·6	114
11.30	0·5 in 1·5	0·06	1·9	1·7	1·7	0·5	0·3	0·2	15·6	2·4	112
11.45	0·5 in 1·5	0·06	1·9	1·7	1·8	0·5	0·3	0·1	15·2	2·8	115
12.00	0·5 in 1·5	0·07	1·9	1·8	1·8	0·5	0·3	0·3	13·6	3·6	120
12.15	0·5 in 1·0	0·08	1·7	1·6	1·6	0·7	0·2	0·2	12·0	6·4	142
12.30	0·5 in 1·0	0·08	1·5	1·5	1·5	1·0	0·3	0·2	17·0	1·0	105
12.45	0·5 in 1·0	0·08	1·8	1·7	1·6	0·7	0·4	0·2	11·2	7·0	148
13.00	0·5 in 1·0	0·08	1·5	1·5	1·5	0·7	0·6	0·3	14·8	3·6	120
13.15	0·5 in 1·0	0·08	1·8	1·8	1·7	0·7	0·4	0·2	14·2	3·8	121
13.30	0·5 in 0·8	0·08	1·7	1·7	1·6	1·0	0·4	0·3	16·2	1·6	108
13.45	0·5 in 0·8	0·08	1·7	1·6	1·5	1·0	0·3	0·1	14·0	4·6	127
14.00	0·5 in 0·8	0·08	1·5	1·5	1·5	0·9	0·7	0·2	16·4	2·4	114

Average grate heat-release rate, Btu/ft² h = 226 900. Combustible in ash, per cent = 12·4.

was still complete, but continued operation would have caused unburnt coke to go over the ash retarder, so the coal feed was stopped.

When the fire had burnt down, it was found that a dense glassy clinker about ¾ in thick was fused to most of the first and second zones. The clinker was easily loosened by means of a slice bar, and it was possible to resume normal operation, whereupon the whole cycle began to repeat itself. About 3½ hours had elapsed from the time that good combustion was established on the clean grate until it was necessary to stop the coal feed. During operation it was observed that the puffs of smoke caused by grate vibration terminated as soon as the coal began to agglomerate into a mass of coke. As mentioned previously, it is felt that the problem of clinkering on the grate can be avoided.

Operating data recorded during the foregoing test are given in Table 4, and grate temperature patterns are given in Fig. 8. The pattern for the second zone shows dramatically the effect of clinkering on grate temperature.

4. EXTRAPOLATION TO FULL-SCALE STOKERS

Predicting the performance of large-scale combustion equipment from data obtained from a small-scale apparatus such as that just described incurs a danger of disastrous errors in judgment. However, such pilot plants appear to offer the only compromise between the even more nebulous results of crucible-scale testing and the money and time required by full-scale experimentation. Furthermore, if assessment of the pilot-plant data is tempered by considerable experience with large-scale equipment somewhat similar in type, fairly reliable predictions can be made. In this light, an extrapolation of the data given in this report will be attempted.

The pilot-scale combination of a plate feeder and a vibrating grate was able to burn strongly caking, high-volatile coal without smoke and at remarkably low rates of excess air. On the other hand, common industrial practice has shown that for such coals, heat-release rates of 350 000 Btu/ft² of effective grate area/h are feasible with quiescent-bed, continuous-ash discharge stokers, while spreader-fired continuous-ash discharge stokers may safely be operated at apparent burning rates of 400 000 Btu/ft² h. The heat-release rate on the model stoker was only one-half to two-thirds of that, and even then the grate overheated to the extent that clinker fused to the surface. However, for the reasons about to be given, it is felt that vast improvement can be achieved through suitable furnace design.

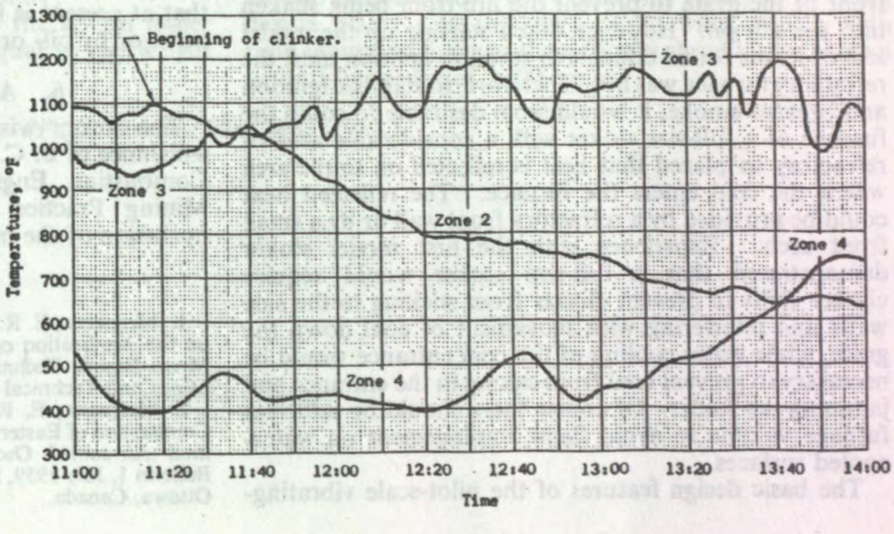

FIG. 8 *(Right).—Grate surface temperatures when burning strongly caking low-ash-fusion coal.*

The performance of any stoker is profoundly influenced by the design of the furnace which houses it, and certainly the refractory furnace must be considered when evaluating the pilot-scale vibrating grate. The only water cooling in the furnace was a narrow clinker chill along each side and a loop around the feeder spout; the rest of the furnace was maintained at near incandescent temperatures during operation. The resulting high furnace temperature was doubtless largely responsible for the smoke-free combustion of high-volatile coal. However, it doubtless also contributed to the high grate temperature and resultant clinkering.

Another factor contributing to clinkering on the grate was the low excess air value of 20 to 30 per cent. In Canadian industry it is normal practice to operate with 50 per cent excess air when burning strongly caking, low-ash-fusion coals. This minimizes clinkering in two ways: first, by lowering grate temperature through the increased mass of cooling fluid, and second, by providing more uniformly oxidizing conditions in the fire-bed, with corresponding rise in ash softening temperature.

The conclusion that a water-cooled furnace and increase excess air will reduce grate temperature is supported by results of experiments with strongly caking coal on a full-size vibrating stoker in a water-cooled furnace.[2] In these experiments, with other factors such as fire-bed thickness, resembling those applying to the model stoker, it was found that grate temperatures could be maintained at less than 500° F at heat release rates of 350 000 Btu/ft^{2}h, at about 160 per cent total air.

Of course high grate temperatures and clinkering could be prevented by water cooling the grate, but, as previously mentioned, this results in a complicated construction which is unattractive for application to a packaged boiler, and to vibrate the greater weight at the desired frequency of 1 200 c.p.m. requires stiffer flexure plates, which in turn makes it difficult to achieve the desired amplitude.

It would appear, then, that a suitable furnace for a full-size plate feeder air-cooled vibrating grate burning strongly caking, low-ash-fusion coal would be one having water-cooled walls to prevent the excessive fire-bed temperatures conducive to clinkering. On the other hand, the vibrating action of the grate advances green coal much more rapidly than coal which has begun to agglomerate, hence ignition must be stabilized at the front of the grate to prevent the fire from being shaken into the ash pit. However, when starting up the model stoker it was found difficult to stabilize ignition until the refractory furnace was hot. Therefore, to stabilize ignition and prevent smoke, it would seem desirable to equip the furnace of a full-size stoker with a considerable area of refractory so placed that heat is reflected on to the area where the coal enters the furnace. The reflected heat could be provided by a refractory front wall or by a small front arch. Experience with the first model stoker demonstrated that a full-size stoker would require clinker chills to prevent clinker from sticking to the side walls and interfering with movement of coal down the grate, while water cooling of the coal entrance would be necessary to prevent coal from caking in the entrance and jamming the feeder. Of course there should be sufficient furnace volume to avoid flame impingement on water-cooled surfaces.

The basic design features of the pilot-scale vibrating-grate stoker appear to be sound, and the feasibility of extrapolating them directly to a full-scale grate has been demonstrated by the previously mentioned experiments on a full-size industrial spreader-fired vibrating grate having many of the same features. That is to say, a full-scale grate should be sized for a grate heat-release rate of 350 000 Btu/ft^{2}h, with air openings totalling 2·5 to 3 per cent of grate area. It should vibrate at a frequency of about 1 200 c.p.m., with an amplitude of $\frac{1}{8}$ to $\frac{3}{16}$ in. The forced-draught fan should be sized to provide 50 per cent excess air at maximum firing rate, at a static pressure of about 3 in water gauge, and the windbox should be zoned to permit control of primary air to obtain maximum grate cooling with a minimum of excess air. The stoker feeder plate should be about $1\frac{1}{2}$ in high to permit fire-beds 2 to 4 in thick. It was observed during the tests that when a heavy bed of coke built up, with perhaps some clinker resisting movement down the grate, vibration was not very effective in advancing the fire-bed, and operation continued only because the feeder was capable of moving the whole coke mass. In anticipation of this a powerful feeder mechanism should be provided.

To minimize caking the thickness of the incoming fuel bed should be no more than 4 in. This means that burn-out will normally be accomplished within 4 ft of grate travel, hence there is little point in building a grate longer than 6 or 7 ft. Accordingly, large stokers should be made wider than long to meet the grate area requirements.

5. CONCLUSION

The combination of a plate feeder with a vibrating grate appears to have considerable potential as a rugged, flexible stoker capable of burning a wide variety of coals automatically. The basic simplicity of the apparatus should permit manufacture and control costs to be competitive with those for conventional stokers. An important advantage of this stoker is that, by virtue of being adaptable to the packaged boiler concept and having continuous ash discharge, it is capable of providing automatic operation from a capacity of about 50 lb of coal/h, where at present no equivalent equipment exists except for stokers requiring premium coals, to a capacity of about 2 000 lb of coal/h, where spreader-fired continuous ash discharge stokers become economically feasible. It thus spans a gap in a very popular size range that at present is filled only by inadequate stoker equipment or by oil- or gas-fired equipment.

6. ACKNOWLEDGMENTS

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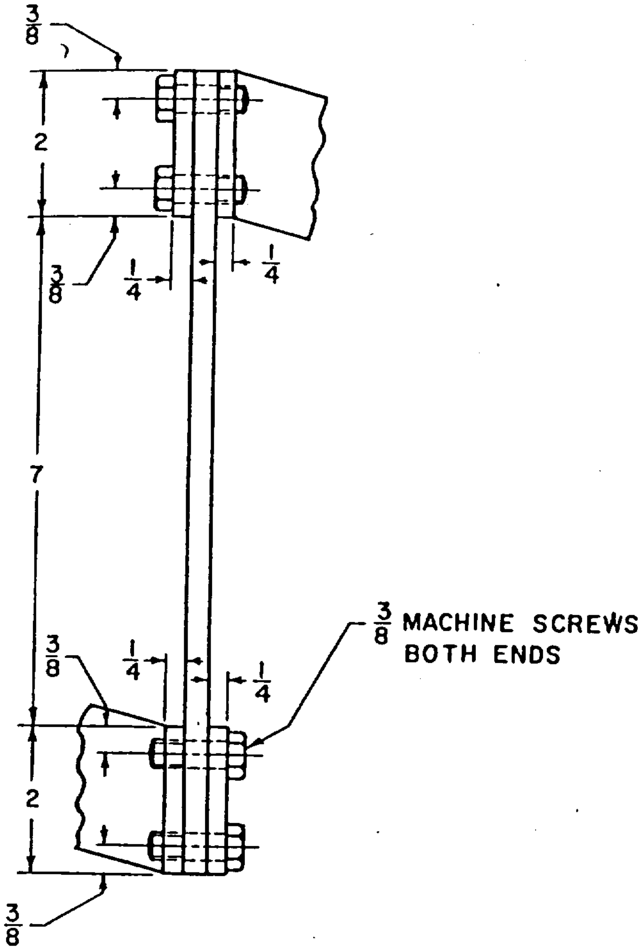

FIG. 9.—*Flexure plate mounting.*

APPENDIX 1

Design of Flexure Plates for Pilot-scale Vibrating Grate

The formulae used in designing the flexure plates were:

$$T = 2\pi\sqrt{\frac{d_{st}}{32{\cdot}2}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Where T = period of vibration in seconds;
d_{st} = static deflection in feet of the system under a perpendicular load equal to the weight of the system;

$$\text{and } d_{st} = \frac{QL^3}{48EI} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The latter formula is derived, for a system having four flexure plates, from the formula:

$d_{st} = \dfrac{QL^3}{24EI}$, derived for a system having two flexure plates, given on page 100 of "Vibration Problems in Engineering," by Timoshenko.

In this formula:

Q = weight of the system, lb
L = length of the flexure plates, in
E = modulus of elasticity, for steel = 30×10^6
I = moment of inertia of a flexure plate, in^4

On the basis of space considerations in the stoker design it was decided to use flexure plates with a free or flexing length of 7 in, and to support them as shown in Fig. 9. The grate and windbox assembly had already been built, hence its weight was readily established at 200 lb. For reasons previously given, a natural frequency of 1 200 c.p.m. was desired, thus T was established at 0·05 sec. Substituting this value for T in equation (1) gave a value for d_{st} of 0·00204 ft or 0·0245 in. It was then possible to solve equation (2) for I, and a value of 29×10^{-4} was obtained.

It had been decided to make the flexure plates from cold-rolled mild steel, and to facilitate manufacture it was desirable to choose dimensions that would require little modification to stock sizes. Therefore, in the formula $I = \dfrac{bh^3}{12}$, which applies for a rectangular cross-section, figures representing stock thickness were substituted for h, and the formula was solved for width b, until a value was obtained that met the space requirements of the grate design. For example, if h was assumed to be $\frac{1}{4}$ in, b had to be 2·23 in, which was too wide for the space available. When h was assumed to be $\frac{5}{16}$ in, b had to be 1·14 in, which was acceptable.

The above calculations are based upon the ideal assumption that the ends of the flexure plates have absolutely no angular motion. In practice, this is difficult to achieve. Fastened as shown in Fig. 9, flexure plates $\frac{5}{16}$ in thick by 1·14 in wide, which should have given the system a natural frequency of 1 200 c.p.m., actually gave it a natural frequency of about 720 c.p.m. The desired natural frequency of 1 200 c.p.m. was obtained by using flexure plates $\frac{3}{8}$ in thick by 1·50 in wide, which, with rigid mounting fixtures, theoretically should have given a natural frequency of 2 200 c.p.m.

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