

FOREWORD

It is realized that oil and natural gas resources cannot long continue to meet the heavy supply demands placed on them. Therefore, coal's return to industry is foreseen as inevitable.

There could be disruptions when this happens because several generations of expertise in coal selection and combustion have been allowed to pass into oblivion. Although this Guide was conceived, in the beginning, to fill the gap of lost expertise for the benefit of administrators, planners and purchasing agents, it is hoped that it will be useful to engineers as a companion to the "Combustion Handbook for Canadian Fuels, Volume 3, Coal", Mines Branch Monograph 882, 1974.

November 1974

D. F. Coates  
Director  
Mines Branch

## AVANT-PROPOS

Il est évident que les ressources en pétrole et en gaz naturel ne pourront plus répondre bien longtemps à la grande demande. Donc, il semble inévitable que l'industrie charbonnière renaisse.

Nous pourrions, à ce moment-là, faire face à des bouleversements parce que nous aurons laissé tomber dans l'oubli plusieurs générations d'expertises sur la combustion et la sélection du charbon. Même si, au début, ce Guide a été conçu pour pallier à la perte d'expertises pour le bénéfice des administrateurs, des planificateurs et des acheteurs, il est à espérer qu'il sera utile aussi aux ingénieurs comme compagnon du "Combustion Handbook for Canadian Fuels, Volume 3, Coal", Monographie 882, 1974, de la Direction des Mines.

Novembre 1974

D.F. Coates  
Directeur  
Direction des Mines

MINES BRANCH INFORMATION CIRCULAR IC 316

A GUIDE FOR EVALUATING  
COAL PROPERTIES WHICH AFFECT COMBUSTION

by

E. R. Mitchell\*, F. D. Friedrich\*\* and G. K. Lee\*\*

ABSTRACT

This Guide explains the effects which coal properties have on combustion systems, beginning with mechanical stokers. A critical evaluation of the sensitivity of stokers to most coal properties makes them unacceptable for the majority of future coal-burning applications and they are, therefore, considered to be obsolescent.

More emphasis is placed on pulverized-coal firing in both dry-bottom and slag-tap furnaces and on cyclone firing in large steam generators because these systems will continue to be used universally for many decades.

Coal-in-oil fuel is described as a useful strategy in simplifying the transition from oil and natural gas to coal use in many existing boilers and heat processes.

Ultimately, it is anticipated that the bulk of coal will be burned in fluidized-beds for most applications whether large or small. The insensitivity of this new combustion technology to <sup>the</sup> coal <sup>or</sup> properties is described.

---

\* Head and \*\*Research Scientist, Canadian Combustion Research Laboratory, Energy Research Laboratories, Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada.

Circulaire d'information IC 316

Un guide pour l'évaluation des propriétés du charbon qui influent  
sur la combustion

par

E. R. Mitchell\*, F. D. Friedrich\*\* and G. K. Lee\*\*

RESUME

Ce guide explique les effets des propriétés du charbon sur des systèmes de combustion, en commençant par les chargeurs automatiques. Une évaluation critique de la sensibilité des chargeurs à la plupart des propriétés du charbon les rend inacceptables à la majorité des applications futures de combustion de charbon, et sont, par conséquent, désuets.

On accorde une importance plus considérable à la combustion du charbon pulvérisé dans des fourneaux à fond sec et à déversement de scories et sur la combustion à cyclone dans des générateurs à vapeur, car ces systèmes seront encore utilisés universellement pendant plusieurs décennies.

Le combustible de charbon en suspension dans huile est présenté comme une stratégie apte à simplifier la transition de l'usage de l'huile et du gaz naturel à celui du charbon dans plusieurs chaudières et procédés de chaleur déjà existants.

Finalement, on anticipe de brûler l'amas de charbon dans des lits fluidisés pour la plupart des applications, larges ou petites. L'insensibilité de cette nouvelle technique de combustion aux propriétés du charbon y est décrite.

---

\*Chef et \*\*chercheur scientifique, Laboratoire canadien de recherche sur la combustion, Laboratoires de recherche sur l'énergie, Direction des mines, Ministère de l'énergie, des mines et des ressources, Ottawa, Canada.

CONTENTS

Page

Foreword .....	i
Avant-Propos .....	ii
Abstract .....	iii
Résumé .....	iv
Contents .....	v
List of Figures .....	vii
1. Introduction .....	1
2. Stokers .....	2
2.1 Coal Properties Affecting Stoker Firing .....	2
2.2 Stoker Classification .....	2
2.3 Underfeed Stokers .....	3
2.4 Gate-Feed Stokers .....	3
2.5 Spreader Stokers .....	4
2.6 Effects of Ash Content .....	4
2.7 Summary of Stoker Technology .....	5
3. Pulverized-Fired Systems .....	6
3.1 Scope of P-F Technology .....	6
3.2 Coal Properties Affecting Pulverized Firing .....	6
3.3 Dry-Bottom Systems .....	7
3.3.1 System Description .....	7
3.3.2 Effects of Moisture Content .....	9
3.3.3 Effects of Size Consist.....	10
3.3.4 Effects of Grindability.....	10
3.3.5 Effects of Volatile Matter Content.....	11
3.3.6 Effects of Petrographic Constituents .....	13
3.3.7 Effects of Ash Content .....	14
3.3.8 Effects of Sulphur .....	15
3.3.9 Effects of Chlorine .....	16
3.3.10 Effects of Organic Nitrogen .....	16
3.3.11 Effects of Ash Fusion Temperature .....	18
3.3.12 Effects of Ash Composition .....	20
3.3.13 Effects of Physical Characteristics of Ash .....	24
3.3.14 Effects of Electrical Resistivity of Ash .....	25

	<u>Page</u>
3.4 Slag-Tap Combustion Systems .....	26
3.4.1 System Description .....	26
3.4.2 Effects of Moisture Content .....	28
3.4.3 Effects of Size Consist and Grindability .....	29
3.4.4 Effects of Volatile Matter Content .....	29
3.4.5 Effects of Petrographic Constituents .....	29
3.4.6 Effects of Ash Content .....	30
3.4.7 Effects of Sulphur and Chlorine .....	30
3.4.8 Effects of Organic Nitrogen Content .....	31
3.4.9 Effects of Ash Fusion Temperature .....	31
3.4.10 Effects of Ash Composition .....	32
3.4.11 Effects of Physical Characteristics of Ash .....	33
3.4.12 Effects of Electrical Resistivity of Ash .....	34
3.5 Cyclone-Fired Systems .....	34
3.5.1 System Description .....	34
3.5.2 Effects of Moisture Content .....	37
3.5.3 Effects of Size Consist .....	37
3.5.4 Effects of Grindability .....	38
3.5.5 Effects of Volatile Matter Content .....	38
3.5.6 Effects of Petrographic Constituents and Ash Content .....	38
3.5.7 Effects of Sulphur Content .....	38
3.5.8 Effects of Chlorine Content and Organic Nitrogen Content .....	38
3.5.9 Effects of Ash Fusion Temperature and Ash Composition .....	39
3.5.10 Effects of Physical Characteristics of Ash .....	39
3.5.11 Effects of Electrical Resistivity of Ash .....	39
3.6 Summary of Coal Properties Affecting Pulverized Firing .....	39
4. Coal Properties in Relation to Coal-in-Oil Fuels .....	40
4.1 Nature and Advantages of Coal-in-Oil Fuels .....	40
4.2 Slurry Behaviour .....	41
4.2.1 Density and Swelling .....	41
4.2.2 Coal Particle Size .....	42
4.2.3 Particle Porosity .....	42
4.2.4 Particle Wettability .....	43
4.2.5 Moisture .....	43
4.3 Slurry Combustion .....	44
4.4 Pollutant Emissions from Slurry .....	44

	<u>Page</u>
5. Fluidized-Bed Combustion Systems .....	44
5.1 System Description .....	44
5.2 Coal Properties Affecting Fluidized-Bed Combustion Systems .....	49
5.2.1 Effects of Coal Moisture .....	49
5.2.2 Effects of Size Consist and Grindability .....	50
5.2.3 Effects of Volatile Matter Content, Petrographic Constituents and Ash Content .....	50
5.2.4 Effects of Sulphur Content .....	50
5.2.5 Effects of Chlorine Content .....	51
5.2.6 Effects of Organic Nitrogen Content .....	51
5.2.7 Effects of Ash Fusion Temperature .....	51
5.2.8 Effects of Ash Composition .....	52
5.2.9 Effects of Physical Characteristics of Ash .....	52
5.2.10 Effects of Electrical Resistivity of Ash .....	52
5.2.11 Effects of Coal Caking Properties .....	52
5.3 Summary of Fluidized-Bed Combustion Systems .....	53
6. Bibliography .....	54
6.1 Textbooks and Handbooks .....	54
6.2 Conference and Symposium Proceedings .....	55
6.3 Papers and Journal Articles .....	56
6.3.1 Stokers and P-F Systems .....	56
6.3.2 Fluidized-Bed Combustion Systems .....	60

FIGURES

1. Pulverized-fired, dry bottom boiler with positive circulation and twin-furnace .....	8
2. Pulverized-fired boiler with slag-tap furnace and opposed directional burners .....	27
3. Crushed coal, cyclone furnace boiler .....	36
4. Crushed coal cyclone combustor .....	36
5. Schematic of a fluidized-bed combustion system .....	46
6. Size comparison of low- and high-pressure fluidized-bed boilers with a conventional boiler. After Hoy and Roberts .....	48

1. INTRODUCTION

'Coal properties which affect combustion' is a short title but a long subject if it is to deal with the wide range of coals used in Canada, and the equally wide variety of equipment available for burning it. A comprehensive treatment would amount to a history of the development of combustion technology for coal over the past century, and would fill several volumes. That will not be attempted here, for much of the technology in common use only twenty years ago has been phased out due to changing needs, and is now only of historical interest.

This review will be concerned only with combustion technology which is now in use or on the immediate horizon. Reducing the scope to this extent still does not permit a short paper, for Canadian coal, ranging from lignite to anthracite, exhibits a bewildering array and range of properties which strongly influence the performance of the best technology developed to date. In the past it was sufficient that designers and, to some extent, operators of equipment understood the complexities of coal properties affecting combustion. Now, however, as we enter a period in which coal becomes an increasingly important source of energy, supplies become less reliable, and individual plants may have to utilize coal of varying quality from several sources. Consequently, it is important that administrators, system planners, purchasing agents and operators have a better understanding of the practical limitations in the use of coal, and it is hoped that this Guide will help to meet the need. It is not intended to be a handbook for designers, for they already possess the most accurate and detailed information available, but it does provide a general guide to others who require some understanding of coal combustion technology.

In preparing this Guide it was necessary to draw information from a vast number of sources and from experience. To identify each reference in the text would have been unduly cumbersome, but for the convenience of those who may wish more detailed information a fairly extensive bibliography has been included. It should be made clear, however, that it represents only a small fraction of the technical literature on the subject of coal combustion.



## 2. STOKERS

### 2.1 Coal Properties Affecting Stoker Firing

A discussion of coal properties affecting combustion on stoker grates is more of a lesson in the history of combustion than a dissertation on modern combustion technology, since stokers have for the most part passed from the scene, and are not likely to make a significant comeback. However, history holds useful lessons; a summary of the factors which contributed to the decline of stoker technology may be enlightening.

Stoker-fired combustion systems are sensitive to the following coal properties and combinations of them:

1. Moisture Content
2. Size Consist
3. Volatile Matter Content
4. Caking Properties (Free Swelling Index)
5. Ash Content
6. Ash Fusion Temperature

### 2.2 Stoker Classifications

The variety of stoker designs developed in the first half of this century is so great that listing, let alone describing them, becomes impractical within the scope of this paper. However, they may be conveniently classified according to methods for feeding the coal and removing the ash; the feeding methods being underfeed, gate feed and spreader firing; the ash removal methods being intermittent manual, intermittent mechanical, and continuous mechanical. Various combinations of feed and ash removal methods have been employed in attempts to cope with one troublesome coal property or another.

### 2.3 Underfeed Stokers

In general, the stokers least sensitive to moisture and volatile matter content are the underfeed type, but they require a double-screened coal for uniform combustion. They are quite sensitive to the caking properties;

as an example, if the Free Swelling Index of the coal exceeds 5, massive cakes of devolatilized coal form in the firebed, resulting in uneven combustion, burnt grates, and high carbon content in the ash.

With respect to the ash fusion temperature of the coal, underfeed stokers present a somewhat split personality. To facilitate ash removal, particularly with intermittent manual ash removal systems, a certain amount of clinkering is desirable. Indeed, it is often encouraged by the application of a fluxing agent. Usually, the ash fusion temperature of coal is lower under chemical reducing conditions than under oxidizing conditions, and the former usually prevail in the deep firebed typical of underfeed stoking. Thus, low ash fusion coals may produce massive clinker formations which plug the grate air openings, resulting in poor performance. Some eastern Canadian coals have both low ash fusion temperatures (ca. 2000°F) and strong caking properties (FSI of 8 or 9). This combination accentuates the undesirable effects of each, and such coals are generally unsuitable for underfeed stoking.

#### 2.4 Gate-Feed Stokers

Gate feed stoking is generally employed in conjunction with continuous ash discharge. These systems are better able to cope with strong caking properties and low ash fusion temperatures than underfeed stokers because the firebed is only 2 to 6 in. thick, and oxidizing conditions are likely to prevail, but caking and clinkering may still occur if the coal contains excessive fines. Excessive surface moisture and excessive fines may interfere with uniform feed. If moisture content is high, or volatile matter is low, there may be problems in maintaining ignition. This can be overcome by designing the furnace with refractory arches to reflect heat onto the fresh coal bed, albeit at high cost. In general, gate-feed stokers perform best with a double-screened coal having a least 25% volatile matter, a Free Swelling Index of 5 or less, and an ash softening temperature of 2250°F or more.

## 2.5 Spreader Stokers

The spreader stoker was developed to cope with coals containing a high proportion of fines, and has been applied with a variety of ash discharge systems. With a nut-slack coal such as 1-1/4 in. x 0 or 3/4 in. x 0 containing up to 50% minus 1/4 in., it can cope very well with strong caking properties. When spreader firing is combined with a continuous mechanical ash discharge system operated to maintain a thin firebed, oxidizing conditions prevail and coals with an ash softening temperature of 2000°F can be burned without difficulty. However, fine coals with high surface moisture are likely to clog in the hoppers, thus interfering with uniform feed. Like gate-feed stokers, spreader stokers have difficulty with coals which, because of high moisture content or low volatile matter content, are hard to ignite, unless ignition arches are incorporated into the furnace.

## 2.6 Effects of Ash Content

Up to this point nothing has been said about the effects of ash content because they relate more to the method of ash removal than to the method of coal feed. There is, of course, the physical problem of removing and disposing of the ash, which increases in proportion to the ash content. Furthermore, ash tends to trap unburned carbon, so the combustible-in-refuse loss tends to increase with increasing ash content. On the other hand, alkaline components in the ash tend to react with sulphur, and may substantially reduce the emission of sulphur oxides.

More important than any of these effects is the fact that ash serves to insulate the grate from the intense heat of the fire. Thus, grates on which very low-ash coals are burnt suffer catastrophic oxidation, and require frequent replacement. Unfortunately, this does not necessarily mean that grate maintenance is low when a high ash coal is burnt. For example, with intermittent ash removal systems-power dump grates- there is a period immediately after cleaning when the grate is bare of ash and unprotected from the furnace temperature. Grate metal temperatures may quickly rise to

the order of 1800°F, then decline over a period of an hour or two as an insulating layer of ash builds up again. With systems of this nature, the higher the ash content, the more frequently the grate must be cleaned, and the more rapid the cycles of extreme temperature. The result is warpage of the grate components, catastrophic oxidation, and high maintenance costs.

## 2.7 Summary of Stoker Technology

The foregoing comments, while providing only an outline of the complex art of stoker firing, demonstrate a most significant fact: stokers are sensitive to a number of coal properties, and no single design can successfully cope with all the combinations of properties likely to be encountered. Each type is designed for a rather narrow range of coal properties, therefore if an unwise selection is made, or if a suitable coal becomes unavailable, the resulting incompatibility may lead to severe operating difficulties, high maintenance and excessive pollution. It's inflexibility with respect to fuel properties, as much as its high capital cost and the strong competition from oil and natural gas, led to the decline of the stoker in the 1950's and 60's.

It should also be noted that the applicability of stokers is generally limited to relatively small boilers, such as those generating 100,000 lb/hr of steam or less, although a few boilers of up to 300,000 lb/hr capacity have been successfully stoker-fired.

### 3. PULVERIZED-FIRED SYSTEMS

#### 3.1 Scope of P-F Technology

Pulverized-fired systems presently comprise the overwhelming bulk of coal-burning technology in industry and electricity generation, particularly if the definition is stretched slightly to include cyclone burners. The latter are not true P-F systems in that they burn crushed rather than pulverized coal, but their performance in terms of coal properties is sufficiently similar to conventional pulverized firing that a separate discussion would be repetitive.

P-F systems are not amenable to small-scale operation. While it is technically feasible to operate a P-F burner with a throughput of a few pounds of coal per hour, economic considerations usually place the lower threshold of application at systems having several burners with a total throughput of about 10,000 lb of coal per hour. Systems burning 100,000 lb of coal per hour are common, and systems burning up to 500,000 lb of coal per hour in a single boiler have been built.

P-F systems can be divided into three major types; dry-bottom, slag-tap and cyclone-fired. Dry-bottom systems are the most common in North America, therefore coal properties affecting their operation will be discussed most extensively in this Guide. Coal properties affecting slag-tap and cyclone-fired systems will be discussed insofar as they differ from their effects on dry-bottom systems. Furthermore, the discussion will relate mainly to furnaces for steam boilers, since raising steam for electricity generation or industrial processes is the main application of P-F systems. Admittedly, there are other applications, the cement industry being an important one, but these usually have special requirements which cannot be dealt with in a short manual.

#### 3.2 Coal Properties Affecting Pulverized Firing

A combustion system consists not only of burners and furnace, but the fuel preparation system, the gas side of the heat recovery system, the

gas handling and cleaning equipment, and the stack. Thus, a discussion of coal properties affecting combustion should begin at the point where the coal enters the plant, and end with the combustion gases leaving the chimney and the ash stream leaving the plant. Other properties may still play a role in coal selection for a particular plant, but, for example, tendency to spontaneous combustion is best left to the realm of coal handling, and the by-product value of fly ash is best left to the realm of ash utilization. The coal properties affecting the combustion system, then, may be listed as follows:

- |                              |                                     |
|------------------------------|-------------------------------------|
| 1. Moisture Content          | ✓ 8. Chlorine Content               |
| 2. Size Consist              | 9. Organic Nitrogen Content         |
| ✓ 3. Grindability            | ✓ 10. Ash Fusion Temperature        |
| ✓ 4. Volatile Matter Content | 11. Ash Composition                 |
| 5. Petrographic Constituents | 12. Physical Characteristics of Ash |
| 6. Ash Content               | 13. Ash Electrical Resistivity      |
| 7. Sulphur Content           |                                     |

3.3 Dry Bottom Systems

3.3.1 System Description

A typical dry-bottom P-F boiler is shown in Figure 1. The furnace is normally a large square or rectangular shaft lined with water-cooled tubes, and having a hopper-shaped bottom. In North America the burners are mounted in the lower part of the furnace, either in rows on the front wall, or stacked vertically at each of the four corners. In Europe many other furnace and burner configurations are used as well. Combustion is initiated and completed in the furnace, and the products of combustion travel up the furnace to enter the convective heat transfer zones. After passing through superheaters, reheaters, economizers and air heaters, the gases are cleaned, usually in electrostatic precipitators, and then exhausted to the stack. Most of the ash travels through the entire boiler to the gas cleaning equipment, although about 20% settles out in the furnace hopper and hoppers under the convection zones; from there it is removed either in the dry state or by a water sluice.

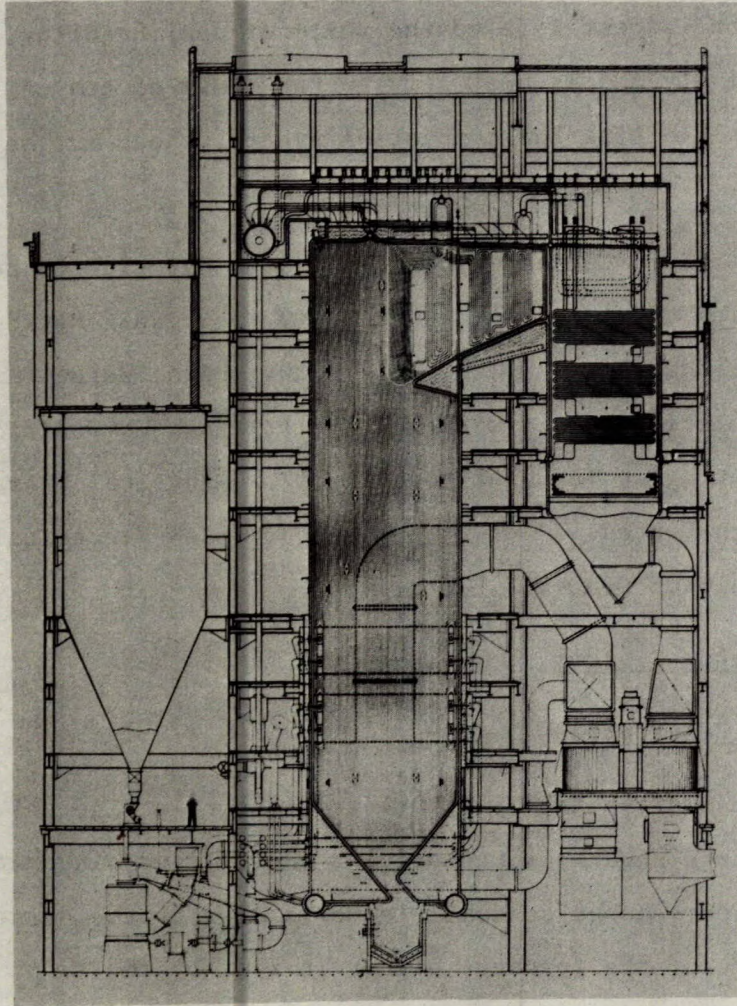


Figure 1. Pulverized-fired, dry-bottom boiler with positive circulation and twin-furnace.

### 3.3.2 Effects of Moisture Content

Coal analyses typically refer to two moisture contents. One is the "surface moisture", which is mechanically retained on the surfaces of the coal particles or between them, and can be removed by air drying without the application of heat. The other is "inherent moisture" which is bound up in the structure of the coal and can only be driven off by heating.

Surface (air dried) moisture, if it exceeds about 5% by weight of the coal, can cause handling difficulties such as bridging in conveyors and hoppers. These difficulties are accentuated at freezing temperatures. It also tends to reduce pulverizer capacity, retard ignition and increase flame length, but these effects are small unless the surface moisture content exceeds 10%. It has the further effect of reducing boiler efficiency by about 0.1% for each 1% of moisture content.

Inherent moisture does not influence the handling properties of a coal, but has all the other effects of surface moisture. These are significant for low-rank coals, which usually have a high inherent moisture content. Typical inherent moisture values for Alberta sub-bituminous coal and Saskatchewan lignite are 20% and 35% respectively. To cope with high moisture content, some or all of the following measures may be required.

1. Increase pulverizer capacity.
2. Increase air temperature to the pulverizer and the burners.
3. Provide refractory or flame turbulence to stabilize ignition.
4. Increase furnace volume to accommodate longer flames.
5. Increase induced draft fan capacity to handle the increased volume of flue gas.
6. Design for a higher stack temperature to avoid condensation in the economizer and air heater sections.
7. Make liberal use of ignition torches to stabilize the flame.



### 3.3.3 Effects of Size Consist

Size consist affects pulverizer capacity, and consequently may affect system capacity, to the extent that a particular coal, if coarse, will require more energy to pulverize than if it is fine. Usually the difference is not great and can be made up by installing a crusher upstream of the bunkers. It is not uncommon, though, for the fine fraction from a screening plant to be more difficult to grind than a coarser fraction, due to concentration of incombustible mineral matter in the fine fraction. Thus, a steam plant which has been successfully burning 3/4 in. x 1/4 in. coal may not have sufficient pulverizer capacity to maintain full load with -1/4 in. coal from the same mine.

### 3.3.4 Effects of Grindability

For pulverized firing, coal is usually ground fine enough that 80% of it will pass through a 200-mesh screen. The amount of energy required to accomplish this depends on a number of factors such as the percentage and hardness of the ash, the physical structure of the coal, the amount of moisture present, and the coefficient of friction of the coal particles. Furthermore, different pulverizer-mill designs vary in relative efficiency with different coals.

Because the factors involved are too complex for rational analysis, coal grindability is usually determined by empirical tests. There are several different test methods in use, but the most common is the Hardgrove method. In this method a 50 g sample of coal, sized to minus 16-mesh and plus 30-mesh, is placed in the Hardgrove grindability machine which is then turned through 60 revolutions. The weight of the sample then passing through a 200-mesh screen is substituted for W in the following formula:

$$\text{Hardgrove Grindability Index} = 13 + 6.93 W$$

Thus, the lower the index, the more energy will be required to grind a coal to the desired fineness. Typical Hardgrove grindability indices are as follows:

Dominion Mine Run (Nova Scotia bituminous)	67
Utility Mine Run (Saskatchewan lignite)	49
Century Slack (Alberta sub-bituminous)	34

Unfortunately, the grindability index does not provide a direct quantitative measure of mill capacity. It simply provides a relative guide which must be used in conjunction with substantial operating experience with a given mill design, preferably with a coal of similar rank.

It is not difficult to recognize that if an existing steam plant was designed for a coal having a high grindability, and subsequently had to utilize a coal having a low grindability, capacity might be limited by inability of the existing mills to grind the substitute coal fast enough. Even if both coals have the same grindability, a reduction in boiler capacity could occur if the substitute coal has a lower calorific value, and therefore a higher throughput is required. It is not uncommon for changes in grindability to result in a 30% de-rating of a boiler when one coal is substituted for another. Therefore, when designing a P-F system, unless the coal supply is very reliable, the pulverizers should be sized to provide ample reserve capacity, or provision should be made for installing additional pulverizers should the need arise.

### 3.3.5 Effects of Volatile Matter Content

Volatile matter is that part of a coal which burns in gas phase, as distinct from the fixed carbon, which burns in solid state. The volatile matter content is defined as the weight percentage of a coal sample, exclusive of moisture, which can be driven off by heating at 950°C for seven minutes.

Typical values are as follows:

High-volatile bituminous coal:	35%
Low-volatile bituminous coal:	20%
Sub-bituminous coal:	30%
Lignite:	27%
Anthracite:	5%

Ignition and flame length are both strongly influenced by volatile matter content. A high percentage of volatile matter is conducive to rapid, reliable ignition of the coal-air mixture, and short, intense flames. Coals with 20% or more volatile matter can generally be burned successfully in water-wall furnaces, whereas anthracite is notoriously difficult to burn in P-F systems, unless refractory surfaces or special burner designs are employed to stabilize ignition.

Maintaining stable ignition is the most crucial aspect of pulverized firing, since instability incurs the risk of a furnace explosion. Any change in coal supply must be carefully considered from the viewpoint of possible effects on ignition stability.

Flame length is also an important combustion parameter. Flame impingement on the furnace walls must be avoided, and combustion must be completed before the gases enter the convective heat transfer sections of the boiler. The boiler designer attempts to provide sufficient cross-section and height in the furnace to accommodate the combustion characteristics of the coal he is designing for, but to minimize capital cost, he tends to avoid over-generous dimensions. Consequently, if a furnace designed for a specific coal is subsequently fired with a coal which tends to produce longer flames, due to lower volatile matter content or higher moisture content, it may not be possible to achieve full capacity without flame impingement. Thus, Ontario Hydro boilers designed for high-volatile bituminous coal can produce less than half their design capacity when burning lignite.

Even if combustion of a substitute coal can be satisfactorily completed in the furnace, other problems, such as control of superheat and reheat temperature, may arise due to relatively minor changes in the pattern of heat release from the flame.

There is much to be said for designing new boilers to accommodate the lowest quality coal they are likely to burn in their lifetime. However, aside from the difficulties of predicting coal availability twenty or thirty years into the future, the increased furnace size and the complications of maintaining superheat and reheat control make for a high capital cost.

### 3.3.6 Effects of Petrographic Constituents

Petrographers describe coal as "a dark brown or black combustible sedimentary rock formed from accumulations of variously altered plant remains by their chemical alteration, compaction and induration as a result first of the partial decomposition of the plant remains without free access of air and under the influence of moisture, then by their burial under younger sediments and thus exposure to elevated pressures and temperatures". Chemical and physical properties vary widely due to differences in kinds of source plant material, the conditions and degrees of change which these have undergone in their geological history, and the amount, kind and distribution of mineral matter present.

Coal properties can, to some extent, be predicted from petrographic studies, and petrographers classify the microscopically discernible components of coal (macerals) into three main groups; vitrinite, exinite and inertinite.

Vitrinite forms the bulk of most coal seams, and includes the bands of vitrain visible in most bituminous coals. Vitrain is a shiny, black, brittle, vitreous material probably formed through the coalification of relatively large fragments of wood and bark. Vitrinite usually contains little mineral matter, and is mainly responsible for the coke-making or combustion property of coal.

Exinite is a group of macerals derived from plant remains such as spores, pollen, algal remains and cell secretions of plants. It is dull in appearance but usually has a high content of resin and volatile matter.

Inertinite comprises a very diverse group but two major components are fusinite and semi-fusinite. These macerals usually show prominent and well-defined cellular structure. It is believed that they are derived from relatively rapid charring of plant cell wall substances prior to, or soon after, incorporation into the enclosing sediment.

From the combustion viewpoint, inertinite is well-named, because it is difficult to burn. The carbon content is somewhat higher than in vitrinite,

and the x-ray structure resembles graphite. Residence times in P-F furnaces are usually too short for complete reaction. Unfortunately, the concentration of these constituents varies from coal to coal, and may even vary from top to bottom of the same seam. Washing a coal tends to concentrate the inertinite into the washery rejects, and may make the rejects unsuitable even as a low-grade fuel for combustion.

High organic inertinite contents are generally found only in bituminous coal and anthracite, but before attempting to burn a coal with which there is no previous combustion experience, it should be subjected to petrographic analysis, to provide an indication of its reactivity.

### 3.3.7 Effects of Ash Content

Ash content is often considered in terms of boiler fouling and corrosion. These problems are discussed later under more specific headings, and it is proposed to discuss here only those effects directly related to the percentage of ash in the coal.

First, since it dilutes the combustible components, increased ash content generally means reduced Btu value per pound of coal. The effect on the coal handling system may well be negligible, but the effect on the gas cleaning system and the ash handling system is likely to be large. For example, if a coal having 5% ash and 13,000 Btu/lb is replaced with a similar coal having 10% ash, the higher heating value is likely to be about 12,300 Btu/lb  $\left( \frac{0.90}{0.95} \times 13,000 \right)$  therefore to maintain the same heat input, the firing rate must be increased by about 5.4%  $\left( \frac{13,000 - 12,300}{13,000} \times 100 \right)$ . However, where in the first case 13,000 Btu is accompanied by 0.05 lb of ash, in the second case it is accompanied by 0.1054 lb of ash  $(0.10 \times 1.054)$ . Thus, the load on the dust collectors and ash handling system has been increased by 111%. The situation will be aggravated by incomplete burn-out; unburned combustible in the fly ash generally increases with the square of the ash content.

High ash content may also impair the ignition stability of a coal, but the effect is usually minor unless it exceeds 10%. Ash may also have a substantial influence on the heat transfer patterns in a boiler. It has a high emissivity, therefore it readily absorbs and transmits radiant heat. It may increase heat transfer to the furnace walls by absorbing heat by convection and transmitting it by radiation, or it may retard heat transfer by imposing a radiation-absorbing blanket between the flames and the walls of large furnaces. Thus, when substituting a coal having a substantially different ash content, predictions of changes in heat transfer distribution must depend more on experience than theory.

The same applies to operating techniques because cleaning furnace tubes by soot blowers while fuel is being fired represents a safety hazard if proper operating procedures are not strictly observed.

#### 3.3.8 Effects of Sulphur

Sulphur in coal varies from a fraction of 1% up to 10% by weight. During combustion most of it forms sulphur dioxide ( $\text{SO}_2$ ), although a small percentage (less than 2%) is converted to sulphur trioxide ( $\text{SO}_3$ ) and a substantial portion may be trapped as sulphates in the ash.

$\text{SO}_2$  is an air pollutant of concern in some quarters. Many coal-burning steam plants in the United States have been forced to switch to low-sulphur (less than 1.5% S) coals to meet air pollution regulations. While lignite and sub-bituminous coals are generally low in sulphur, most bituminous coals contain 2 to 5%, and it becomes increasingly difficult to avoid using them for large-scale power generation. In relatively isolated areas, high ground-level concentrations of  $\text{SO}_2$  may be avoided by using tall stacks to increase dispersion of the flue gas. Urban areas using medium or high sulphur coals may incur the capital, operating and energy penalties of flue gas washing plants.

The small percentage of the sulphur in a coal which is converted to  $\text{SO}_3$  during combustion readily combines with water vapour to form sulphuric

acid vapour ( $H_2SO_4$ ). This has two major effects. Firstly, it condenses on relatively cool surfaces (150 to 300°F, depending on acid concentration) such as air heaters and economizers, where it may cause serious corrosion and secondly, it affects the electrical resistivity of the fly ash, and therefore affects the performance of electrostatic precipitators. The absence of  $H_2SO_4$  or sulphates resulting from the chemical reaction of  $H_2SO_4$  with cation components of the fly ash, impairs precipitator efficiency because the ash particles do not readily take an electrical charge. On the other hand, excessive concentrations of acid cause shorting across precipitator elements, and corrosion. Generally, a precipitator designed for a coal with 2.5% sulphur will have its performance significantly impaired if the sulphur content is either halved or doubled.

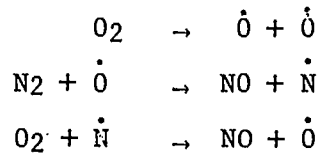
### 3.3.9 Effects of Chlorine

Significant quantities of chlorine are not normally found in North American coals, although it is common in British coals, where it causes problems of fouling and corrosion if its concentration exceeds 0.6 wt % of the coal. It is mentioned here only as something to be on guard against when opening new coal seams.

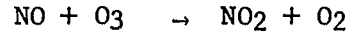
### 3.3.10 Effects of Organic Nitrogen

Air pollution by nitrogen oxides has been recognized as a problem in the last few years. Two mechanisms of formation have been established; in the first, nitrogen is provided by the combustion air, while in the second it is provided by nitrogen-containing organic compounds in the fuel.

The mechanism involving air-source nitrogen may be summarized as follows. At high temperatures, such as are produced in flames, some oxygen molecules dissociate to form highly reactive atoms of oxygen. These then react with molecules of nitrogen to form NO and free atoms of nitrogen, which in turn react with molecules of oxygen to form NO and free atoms of oxygen. The reactions can be expressed by chemical symbols as follows:



Following discharge to the atmosphere the NO oxidizes to NO<sub>2</sub>, probably through reaction with ozone in the atmosphere:-



It has been found that the rate of reaction increases sharply with temperature, and that oxygen concentration is also important. Therefore, NO formation can be minimized by reducing flame temperatures and excess air. One technique commonly employed is staged firing, in which a low-temperature flame is initiated with sub-stoichiometric air, and secondary air is injected slightly later to complete combustion. In this way the flame is diffused and peak temperatures are reduced. Another technique is flue gas recirculation, in which flame temperatures are kept low by diluting the combustion air with an oxygen-deficient stream of flue gas from cooler regions of the boiler. There is also evidence that the same effect can be achieved by using high-swirl burners to generate internal flue gas recirculation.

In the second mechanism (fuel-source nitrogen) organic nitrogen-bearing compounds in the fuel break down during combustion and may yield free atoms of nitrogen which react readily with oxygen to form nitric oxide (NO). No satisfactory method of inhibiting this reaction has been found, since it takes place even at the lower limits of flame temperatures. Thus, the organic nitrogen content of a coal is indicative of the minimum nitrogen oxides which will be emitted when burning it, and may be a factor in the application of certain coals in urban areas.

At present, standard coal analyses do not include a determination of organic nitrogen content, although techniques for analysis exist. There is a substantial need for research both on methods for determining organic nitrogen content, and on correlation of analytical results with measured levels of NO emission.



### 3.3.11 Effects of Ash Fusion Temperature

The ash fusion temperature of a coal is determined as follows: A sample of coal is ground and reduced to ash by holding it above the ignition temperature in a muffle oven. The resulting ash is pulverized, mixed with a binder, and moulded into sharp, three-sided cones about half an inch high. When dry the cones are placed in a laboratory furnace whose temperature is gradually increased and monitored by means of a shielded thermocouple in the furnace. As the temperature in the furnace rises, the cones are carefully observed through a quartz window, and the following temperatures are noted for each cone:-

1. Initial deformation temperature; defined as the furnace temperature at which the tip of the cone melts or rounds,
2. softening temperature (spherical); defined as the furnace temperature at which the cone melts sufficiently to form a sphere,
3. softening temperature (hemispherical); defined as the furnace temperature at which the cone melts to form a hemisphere,
4. fluid temperature; defined as the furnace temperature at which the cone is reduced to a flat pool of liquid.

Normally, each temperature is established by averaging determinations from several cones, and the resulting set of four temperatures comprise the ash fusibility data. It is typical of North American coals that the ash fusibility is somewhat lower under reducing conditions than under oxidizing conditions. Therefore, the determinations are carried out under the former to establish the lower limits, and are sometimes repeated under the latter to establish what is likely to happen under normal firing conditions, which usually involve an oxidizing atmosphere.

Ash fusibility data for a few well-known Canadian coals are summarized in the following table:-

<u>Coal Name and Rank</u>	<u>Temperature °F</u>			
	<u>Initial Deformation</u>	<u>Softening, Spherical</u>	<u>Softening, Hemispherical</u>	<u>Fluid</u>
Dominion No. 26 Mine (Nova Scotia) High Volatile A Bit	1960	2180	2240	2370
Utility Coals (Saskatchewan) Lignite A	2040	2130	2350	2500
Forestburg (Alberta) Semi-anthracite	1960	2110	2160	2280
Canmore (Alberta) Semi-anthracite	2640+	2700+	2700+	2700+

It is clear from the table that ash fusion temperatures are likely to be exceeded in the flame envelope. Obviously, molten ash must be prevented from impinging on furnace walls and convective heat transfer surfaces. Otherwise, it forms a dense slag which inhibits heat transfer and cannot be removed by soot blowing. Either the superheater or furnace exit is the most critical area. If the ash is still molten at these points, it will freeze onto the tubes, and in the course of a few hours sufficient slag may build up to block the gas passages, forcing shut-down of the boiler.

To prevent slag formation, the furnace dimensions and cooling capacity must be such that ash-laden combustion gases reach the furnace walls or furnace exit only after they have been cooled below the ash softening temperature. Any ash which then deposits on the heating surfaces will be in the form of a dry powder, and can be removed by soot blowers. Another technique is to recirculate relatively cool flue gas from the convection sections to the furnace exit, to reduce gas temperatures below the ash softening temperature.

The ash fusibility data is a guide to the designer in selecting furnace dimensions and in spacing tubes at the furnace exit. It is not a positive criterion; in practice, no simple correlation between it and slagging

problems has been found. Furthermore, ash fusibility characteristics may vary between shipments from the same mine, and, as mentioned earlier, are influenced by the furnace atmosphere. While ash fusibility data must only be applied in the light of substantial experience, there is at present no better single guide to coal's slagging characteristics. Some designers size completely water-cooled, dry-bottom furnaces according to the following guidelines:-

<u>Ash Softening Temp., °F</u>	<u>Furnace Heat Release Rate, Btu/cu ft. hr</u>
2200 and less	19,000
2200 - 2400	24,000
2400 - 2600	32,000
above 2600	36,000

These values may require substantial modification, depending on ash analysis.

### 3.3.12 Effects of Ash Composition

The standard ash analysis involves ten elements; silicon, aluminum, iron, titanium, phosphorus, calcium, magnesium, sulphur, sodium and potassium. Their concentrations are determined by wet chemistry techniques, and are reported as oxides. The actual chemical structure of the ash is, of course, much more complex, and can now be determined by analytical techniques such as x-ray diffraction and spectroscopy. Obtaining detailed knowledge of coal ash compositions, and correlating it to combustion performance, is an undertaking that will require many years of research to complete.

Ash fusibility is, of course, a function of ash composition. Silica and alumina tend to raise the ash softening temperature, while most of the other components, particularly iron and alkalis such as sodium and potassium, tend to act as fluxes. Several indices have been devised to correlate slagging properties to data from the standard ash analysis. The CCRL ash index, for example, is the ratio of silica and alumina to the sum of all the

ash components. It is shown that ash softening temperature is lowest when the index is about 0.5, and any change in ash composition, such as by blending coals or mixing in an additive, will tend to raise the softening temperature. If the ash index is 0.6 or more, adding silica or alumina will tend to raise the softening temperature, while adding iron oxide or sodium oxide will tend to lower it. The converse is true if the ash index is 0.4 or less. None of the correlating indices hold for all coals and all combustion conditions, although they often provide a useful supplement to the ash fusibility data.

It was mentioned in the previous section that coal ash generally exhibits a lower ash softening temperature under chemical reducing conditions than under oxidizing conditions. This is primarily due to the influence of iron compounds. Ferrous compounds generally have lower melting temperatures than ferric compounds. The former predominate in reducing conditions, the latter predominate in oxidizing conditions.

The ash composition has effects on combustion beyond its influence on ash fusibility. The most important of these concerns fouling of the heat transfer surfaces. Slagging and fouling are separate phenomena, although they are often confused because one may lead to the other.

Slagging denotes the deposition of molten ash on fireside surfaces of the boiler. If the surface is below the ash softening temperature, the slag freezes and remains as a hard, impervious layer. As further layers of slag are deposited, heat transfer is reduced and the fireside surface of the slag layer rises in temperature, approaching the ash softening temperature. The surface becomes sticky, then wet, and finally reaches an equilibrium at which fresh deposits of slag drip off, probably to congeal in another part of the boiler. The effect on heat transfer is likely to be catastrophic, and the boiler must be shut down and cleaned.

Fouling denotes the deposition of dry ash on the heating surfaces. There are several physical mechanisms by which this can occur. In general, fine particles adhere more readily than coarse particles, and deposition

increases with increasing temperature differential between the gas stream and the tubes. Dry deposits can usually be removed by soot blowing, but not all the heating surfaces are accessible to sootblowers, and chemical reactions may occur in the deposit which harden it and bond it to the tubes. As the deposits build up, heat transfer deteriorates, gas temperatures in the upper levels of the furnace increase, and the softening temperature of the ash may be reached. A layer of sintered ash may be super-imposed on the dry deposit, and as heat transfer deteriorates further, slagging may occur. Thus, fouling is frequently followed by slagging, or fouling on the furnace walls may cause slagging at the furnace exit. The results are just as catastrophic as straight-forward slagging. Operators of lignite-fired boilers are particularly well aware of how, in the course of a few hours, a combination of fouling and slagging can bridge over the furnace exit tube banks, blocking the gas passages and forcing shutdown of the boiler.

The measures taken to avoid slagging have already been discussed. Much the same approach is taken in order to control fouling. The furnace is given ample heat transfer surface to keep gas temperatures from rising sharply as heat transfer deteriorates; a multitude of sootblowers and furnace wall blowers are provided, tube banks at the furnace exit are spaced about two feet apart, the banks are kept relatively short, and the tubes are in line rather than staggered. Typical furnace heat release rates for coals having a high fouling tendency, such as Saskatchewan lignite, are 13,000 to 14,000 Btu/cuft. hr of furnace volume, and 63,000 to 80,000 Btu/sqft. hr of projected furnace wall area.

Not all coals have fouling tendencies. It varies with the ash analysis, and clear-cut relationships have not yet emerged. Research has demonstrated that alkali and sulphur compounds play a major role. Complex alkali sulphates form as superfine particles at temperatures well below the initial deformation temperature of the coal ash. These deposit as a thin, white layer on hot surfaces such as superheater tubes and serve as a bonding agent for larger particles. As the deposit temperature increases due to

reduced heat transfer, alkali silicates build up at an accelerating rate. Many boiler designers accept, as a rule of thumb, that if the alkali content ( $\text{Na}_2\text{O}$ ), exceeds 0.4% by weight of the dry coal the coal will have fouling tendencies. This assumes that there is always sufficient sulphur to react with the alkali to form alkali sulphates.

Of the alkali metals, sodium and potassium, the former is considered to be more troublesome because its compounds have lower melting temperatures, higher rates of activity, and are more effective in reducing slag viscosity than potassium compounds. Therefore, some designers and researchers feel that sodium content, rather than alkali content, is the best criterion of fouling properties. Still others argue that the percentage of water-soluble sodium compounds should be taken as the criterion, rather than total sodium content or total alkali content. The latter view is supported by results of short-term combustion tests at the CCRL. A sample of Saskatchewan lignite which had been washed and treated by an ion-exchange process to replace approximately two-thirds of the sodium with calcium, was found to have greatly reduced fouling tendencies compared to run-of-mine lignite.

Another important aspect of coal combustion is the influence of ash composition on corrosion of high-temperature surfaces such as superheaters, reheaters and supporting members. The same ash components which contribute to fouling, namely, compounds of sulphur, alkali and chlorine, may also cause corrosion. If alkali chlorides are present in tube deposits, they may react with  $\text{SO}_2$  to form alkali sulphates and  $\text{HCl}$ ; corrosion by chlorides is then likely to proceed if metal temperatures are above  $600^\circ\text{F}$ . If no chlorides are present, corrosion mechanisms may involve complex alkali iron sulphates, but this type of corrosion is only likely to be serious if metal temperatures exceed  $1100^\circ\text{F}$ . Since most North American coals do not contain significant quantities of chlorides, corrosion can usually be avoided by designing for maximum metal temperatures of  $1100^\circ\text{F}$ , and using austenitic alloy steels.

### 3.3.13 Effects of Physical Characteristics of Ash

Physical characteristics of ash logically include its fusibility and electrical resistivity, but these are of sufficient importance to warrant separate discussion. Other significant characteristics are the size, shape and hardness of the ash particles.

The potential for tube wastage by erosion increases with increasing ash content, but it also increases if the ash particles are large, sharp and hard. Coals with a low ash softening temperature are likely to have the ash particles rounded by melting in the flame, but this may encourage agglomeration into large particles. On the other hand, fine particles, particularly superfine particles produced when volatile ash components vapourize in the flame and later condense, increase fouling. Ash composition also plays a role in erosion; silica and alumina are naturally abrasive materials. The ash of European brown coal, for example, has a high sand content and special design measures are necessary to cope with erosion. The size to which the coal is ground is too closely governed by other considerations for this to be an effective method of controlling ash particle size. The designer must look to other means for dealing with abrasive ash, such as increasing the size of gas passages to reduce gas-stream velocities, placing expendable shields over the upstream side of vulnerable tube bundles, and providing settling chambers to remove coarse particles from the gas stream. It should be mentioned that erosion and corrosion often go hand-in-hand. Erosion may remove protective scales from the tubes, exposing bare metal to corrosive compounds.

Ash particle size also has a pronounced effect on the efficiency of dust collectors. If the fly ash consists mainly of relatively large, heavy particles, (greater than 10 microns diam.) mechanical separators such as multi-cyclones may be adequate. On the other hand, some types of mechanical collectors are prone to plugging by fine ash particles, which tend to agglomerate in the dry state on dust collector surfaces. Plugging is aggravated if the dust collector operates below the acid dewpoint of the flue gas.

Electrostatic precipitators collect fine particles more readily than coarse particles, but a small percentage of coarse particles may facilitate cleaning of the collector surfaces.

### 3.3.14 Effects of Electrical Resistivity of Ash

Electrical resistivity of fly ash is an important parameter of how readily it can be separated from the gas stream in electrostatic precipitators. If the resistivity is less than about  $10^7$  ohm-cm, the electrical force holding the dust deposit to the collector plates will be low, and substantial re-entrainment may occur. If it is more than about  $2 \times 10^{10}$  ohm-cm, the electrical field in the dust layer may exceed the breakdown strength, resulting in sparking and back corona. Then high-tension voltage must be reduced, and precipitator performance drops. There are various methods of measuring resistivity of dust samples in the laboratory, but the most reliable values are obtained from in-situ measurements.

Two distinct types of electrical conduction occur in dust. One is conduction by free electrons within the particles, which depends on a temperature and on the electron activation energy, which is a material property. The other is conduction over the particle surfaces via adsorbed moisture or chemicals such as sulphuric acid. Since adsorption increases with decreasing temperature, the two types of conduction are oppositely affected by gas-stream temperature. Thus, resistivity is a complex function of ash analysis, particle sizing, moisture and sulphur contents of the coal, combustion conditions, and gas temperature in the precipitator. It is likely that sulphur influences resistivity primarily through the formation of  $SO_3$  which is adsorbed by the ash particles, but the amount of  $SO_3$  formed depends on combustion conditions as well as sulphur content of the coal. Temperature effects can be dramatic. Results of in-situ resistivity measurements show that for a coal with 1.5% to 2% sulphur, resistivity may rise from  $10^9$  ohm.cm at  $225^\circ F$  to  $3 \times 10^{11}$  ohm.cm at  $280^\circ F$  and then drop to  $10^9$  ohm.cm at  $425^\circ F$ .



When reliable resistivity data are available, it is relatively easy to design electrostatic precipitators of the desired efficiency, or to predict the effects of a different coal on the efficiency of existing precipitators. However, when there are no resistivity data, designers must rely on the pragmatic experience that the fly ash from coals with less than 1.5% sulphur generally has resistivity in excess of  $10^{10}$  ohm.cm, and is therefore hard to collect, while fly ash from coals with more than 4% sulphur generally has a resistivity low enough to cause problems with re-entrainment. Sometimes  $SO_3$  is added to the gas stream to reduce the resistivity of fly ash from low-sulphur coals.

### 3.4 Slag-Tap Combustion Systems

#### 3.4.1 System Description

Slag-tap furnaces are designed to melt most of the ash in the furnace, so that it can be drained off as a liquid slag, rather than passing through the entire boiler as dry fly ash. This substantially reduces the problem of particulate emissions from the stack, but the furnace must be carefully designed to ensure that temperatures are high enough to make the ash fluid, without exceeding the temperature limitations of the refractory materials.

Slag-tap firing is common in western Europe, and there is a wide variety of furnace configurations. It is less common in North America, but there are several installations, including two in Canada, of the system shown in Figure 2. This design has a rectangular furnace necked in on two sides. The narrowest part of the furnace is called the throat, and pulverized coal is fired through directional-flame burners mounted on the lower slopes. Thus, the flames are opposed, but with a downward component, resulting in impingement over the tap hole, which is located in the centre of the furnace bottom.

The furnace floor is made up of tangent water tubes covered with super-duty refractory. The lip of the tap hole is raised a few inches above the furnace floor, so a pool of slag must form before tapping commences. The

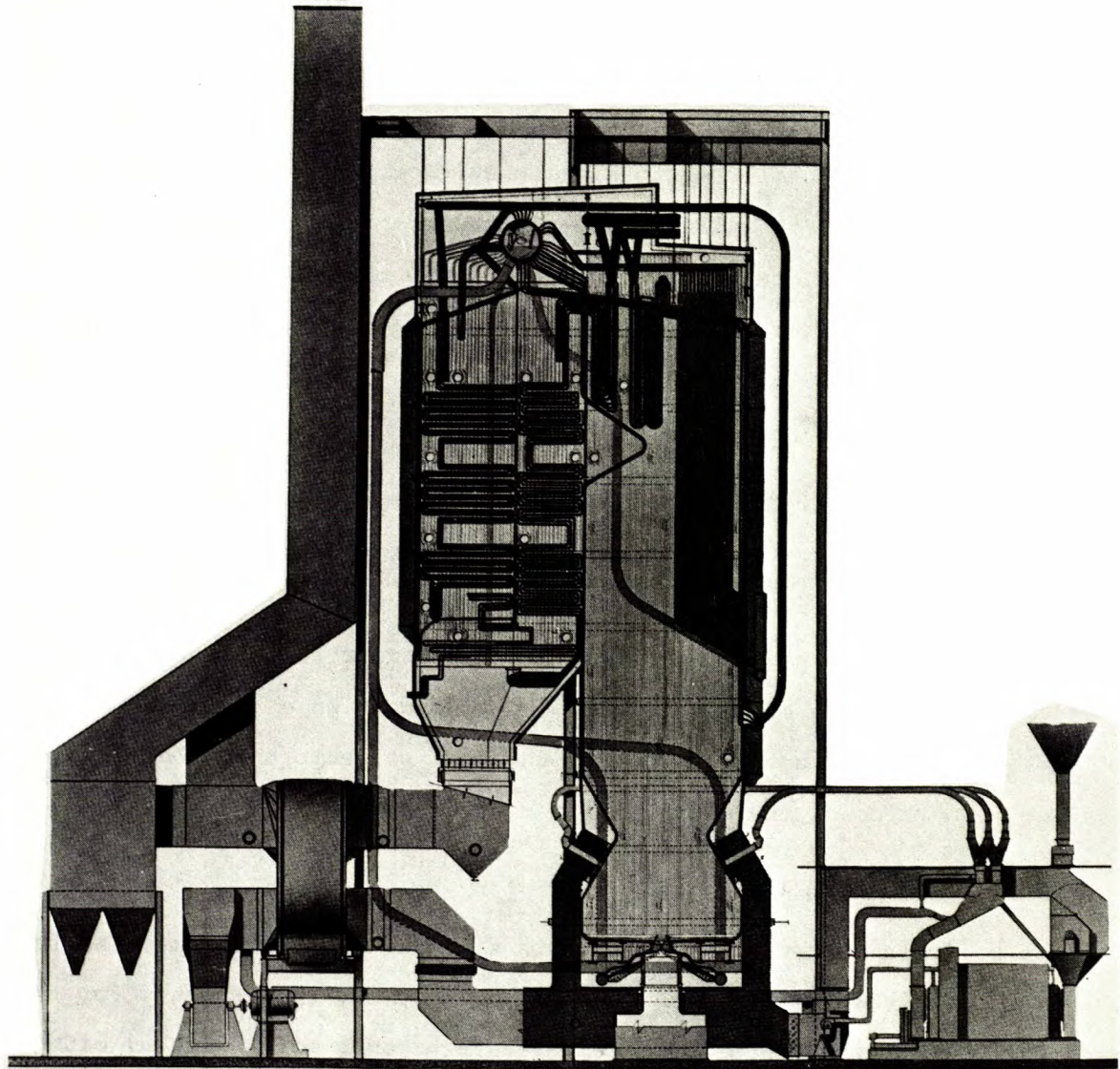


Figure 2. Pulverized-fired boiler with slag-tap furnace and opposed directional burners.

molten slag runs into a water-filled quench tank where it solidifies to form a hard, black, glassy material which is often suitable for road fill. The side-wall tubes below the throat are initially bare, but become covered with slag during operation. The thickness of the slag layer varies inversely with the firing rate.

The opposed placement of the burners and the restricted furnace volume below the throat contribute to high turbulence, rapid, stable ignition and intense combustion. Heat release rates in this region are about 60,000 to 90,000 Btu/cuft. hr of furnace volume, and 150,000 to 190,000 Btu/sqft. hr of projected wall area. Flames generally do not extend much beyond the upper expanded portion of the throat.

The upper part of the furnace is a radiant section similar to a dry-bottom furnace, except that the former is likely to be somewhat smaller for the same steaming capacity. The flue gases then enter conventional convection banks and heat recovery equipment. Normally up to 80% of the ash melts in the furnace and is drained off as slag. The remainder freezes to dry fly ash in the radiant section of the furnace, and that portion of it which is trapped in the convection bank hoppers and the dust collectors may be recycled to the slagging portion of the furnace as a convenient means of disposal.

#### 3.4.2 Effects of Moisture Content

The moisture content of coal affects slag-tap P-F systems much as it affects dry-bottom systems (See Section 3.3.2). However, the tendency for high moisture content to reduce flame temperature becomes more critical with slag-tap systems, because high temperatures must be maintained to melt the ash. Thus, a slag-tap system burning low ash fusion coal may have its turn-down ratio restricted as moisture content increases, or a similar system burning medium ash fusion coal with a high moisture content may only be able to slag the ash at full load. A more complete discussion relating to the maintenance of slagging conditions is given in Sections 3.4.9 and 3.4.10.

New slag-tap systems can be designed to cope with fairly high moisture levels by raising furnace temperature through means such as high combustion-air preheat and refractory-covered walls. In Europe, slag-tap furnaces have been operated on brown coal containing up to 50% moisture by sweeping the pulverizers with flue gas at up to 1800°F to substantially dry the coal, separating the gas from the pulverized coal prior to injecting the latter into the furnace, and either injecting the moist gas into the upper levels of the furnace, or venting it to atmosphere. However, such complications negate most of the advantages of slag-tap firing.

#### 3.4.3 Effects of Size Consist and Grindability

These effects are the same for slag-tap systems as for dry-bottom systems, and are discussed in Sections 3.3.3 and 3.3.4.

#### 3.4.4 Effects of Volatile Matter Content

An advantage of slag-tap systems lies in the fact that the high furnace temperatures, coupled with the incandescent masses of refractory and molten slag, provide a powerful stabilizing influence on ignition. Thus, these systems can generally cope with a lower volatile matter content than dry-bottom systems. However, the designer must ensure that ignition stabilizes near the burners, otherwise a pulsating form of ignition may occur, in effect a series of minor furnace explosions resulting in hazardous fluctuations in furnace pressures.

The tendency of low-volatile coals to produce long flames is somewhat mitigated by the high temperature and turbulence in slag-tap furnaces, but there is still a possibility of higher unburned combustile emission and changes in heat absorption patterns compared to high-volatile coals.

#### 3.4.5 Effects of Petrographic Constituents

In general, the comments in Section 3.3.6 apply to slag-tap systems as well, although some designs of slag-tap furnaces tend to trap particles on the surface of slag layers, thereby increasing residence time available for combustion.

#### 3.4.6 Effects of Ash Content

A major reason for developing slag-tap furnaces was to reduce the amount of fly ash that had to be dealt with. Since they remove 60% to 80% of the ash as slag, they are generally less sensitive to an increase in ash content than dry-bottom systems.

For example, if 100,000 lb/hr of coal with 10% ash are being burned, a dry-bottom system will produce about 10,000 lb/hr of fly ash, while a slag-tap system will produce 1000 to 2000 lb/hr of fly ash, and 9000 to 8000 lb of slag. If a coal of similar calorific value but with 12% ash is burned, the dry-bottom system will produce an additional 2000 lb/hr of fly ash, but the slag-tap system will only produce an additional 200 to 400 lb/hr of fly ash. The relative increase is the same in both cases, but the absolute increase is much smaller for the slag-tap furnace. Thus, in theory at least, changing to a coal of higher ash content should present little difficulty when slag-tap systems are involved.

Other factors may enter the picture. A substitute coal, whether of higher or lower ash content, may have different ash fusibility characteristics. If the fusion temperature is higher, there will be a tendency toward a higher proportion of fly ash. Most slag-tap systems can vary the furnace temperature, and thus the amount of ash slagged, to some extent by adjustment of the burners, but usually the amount of control is small. Also, the dust-collecting equipment may be of marginal design, and unable to cope with moderate increases in fly ash quantities without violating air quality standards. Even for slag-tap systems, the feasibility of using a coal with a different ash content than that for which the unit was designed must be evaluated carefully.

#### 3.4.7 Effects of Sulphur and Chlorine

These components affect slag-tap systems in much the same way as they affect dry-bottom systems. The comments in Sections 3.3.8 and 3.3.9 apply.

### 3.4.8 Effects of Organic Nitrogen Content

It was explained in Section 3.3.10 that the fuel-source nitrogen oxides are relatively unaffected by the firing system. However, air-source nitrogen oxides tend to increase with increasing flame temperatures. Since slag-tap systems are designed to produce high flame temperatures in order to melt the ash, nitrogen oxide emissions are likely to be high. Furthermore, the technique for minimizing nitrogen oxide emissions from dry-bottom systems are generally not applicable to slag-tap systems.

### 3.4.9 Effects of Ash Fusion Temperature

It has already been explained that dry-bottom systems are intended to operate with the ash in a dry state, therefore the initial deformation temperature of the ash is an important consideration in furnace design. Slag-tap systems are intended to melt the ash to a free-flowing fluid, therefore the ash fluid temperature is a more important characteristic than the initial deformation temperature. In general, slag-tap systems are suitable for coals with an ash fluid temperature of 2500°F or less, otherwise there may be difficulty in maintaining sufficient furnace temperature to keep the molten ash flowing freely. For a given calorific value, the lower the ash fluid temperature, the better will be the turn-down capabilities of the system. With bituminous coal having an ash fluid temperature of 2500°F, a good furnace design will permit continuous ash tapping down to 1/3 of full load.

Also important is the melting range; that is, the difference between initial deformation temperature and the fluid temperature. For some coals the melting range may be as little as 100°F and for others it may be as much as 600°F. It affects both furnace design and low-load operation, and in both cases, as far as slag-tap furnaces are concerned, the smaller the melting range the better.

As far as furnace design is concerned, it was stated earlier that slag-tap furnaces comprise two parts; a slagging section in which the coal is burned and the ash melted, and a radiant section in which the carried-over

portion of the ash is cooled to the dry state before it impinges on heat exchange surfaces. If the melting range is small, the radiant section need only reduce the gas temperature by 300°F to 400°F, but if the melting range is large, the gas temperature may have to be reduced by up to 1000°F to avoid slagging at the superheater or furnace exit. Thus, the size of the radiant section must be proportional to the melting range.

In most furnaces, temperatures drop as firing rate is reduced. Where difficulty in maintaining slagging temperatures limits the turn-down ratio of slag-tap furnaces, it may still be possible to operate at low load by reducing the firing rate to the point where the furnace temperature is below the initial deformation temperature of the ash. The furnace then operates as a dry-bottom system. This is feasible only if the ash fluid temperature is above about 2300°F, and the melting range is small, otherwise furnace temperatures may be too low for safe, reliable combustion. Prolonged operation with furnace temperatures in the melting range must be avoided, for if the ash is sticky but not free-flowing it will build up in the furnace, and block off the tap-hole. It may then become necessary to shut down the boiler and remove the slag with jack-hammers.

Manipulation of fuel firing rate and furnace temperature is restricted by steam temperature control when a steam turbine is involved.

#### 3.4.10 Effects of Ash Composition

The effects of ash composition on slagging, fouling and corrosion, as described in Section 3.3.12, also apply to slag-tap furnaces. There may be additional effects. Ash is a heterogeneous mixture of complex compounds. When these are melted together in a furnace and exposed to varying atmospheres, both oxidizing and reducing, the possibilities for chemical reaction are many. As reactions proceed, compounds may be formed that have properties different from those initially comprising the ash, and the ramifications may be extensive. For example, alkali silicates may be formed, which may volatilize and condense on superheater surfaces to initiate fouling. Other compounds may

attack the furnace refractory. In some cases, involving chemically reducing furnace conditions and ash with a high iron content, it was found that the slag-tap furnace operated much like a reverberatory furnace, producing pig iron. Unfortunately, the iron has a high density and a high melting temperature, therefore it tends to flow to the bottom of the furnace and freeze, making removal very difficult. Undesirable slag reactions such as these can largely be avoided by shaping the furnace bottom to drain the ash as quickly as it melts.

#### 3.4.11 Effects of Physical Characteristics of Ash

In connection with the physical characteristics of ash discussed in Section 3.3.13 it is worth mentioning that some designs of slag-tap furnaces tend to produce, in the dry ash fraction, a fairly narrow size range of particles, small enough to agglomerate readily by physical attraction. This can lead to troublesome deposits on heat exchange surfaces. One common method of coping with this problem is to adjust the burners to increase the proportion of dry ash carry-over. The increase is usually in the form of larger particles, which have sufficient abrasive force to minimize deposition.

Another physical characteristic of ash, of major significance to slag-tap systems, is the ash viscosity. Ash fusibility and its relationships with ash composition have already been discussed, and it was pointed out that the ash fusibility data are an incomplete guide to slagging characteristics. The fact that an ash is heated above its fluid temperature as determined in the ash fusion furnace does not mean that it will flow freely enough for trouble-free tapping in a slag-tap furnace. The viscosity of the slag is a complex function of the ash composition, a major factor being the effect of the furnace atmosphere in producing ferrous or ferric compounds, as discussed in Section 3.3.12.

The U.S. Bureau of Mines has developed a method for calculating slag viscosity from the results of spectrographic analysis of the coal ash. This has proved to be a fairly reliable guide for furnace designers. It has



been found that slags having a calculated viscosity of 250 poises or less at 2600°F generally tap freely, but if the viscosity is higher at the same temperature, sluggish tapping is likely.

The viscosity of molten coal ash in relation to temperature and atmosphere can also be determined by a physical test procedure. The apparatus consists of a platinum crucible which fits into a small, electrically-heated furnace, and a platinum bob which is rotated by an electric motor through a drive train which includes a stiff, calibrated wire. The atmosphere in the furnace can be controlled to provide chemically reducing or oxidizing conditions as desired. A sample of ash is placed in the crucible and heated until molten, then the bob is immersed in the ash and rotated while the temperature of the slag is controlled at various levels. The torsional deflection of the calibrated wire is determined optically and provides a measure of the slag viscosity.

#### 3.4.12 Effects of Electrical Resistivity of Ash

With respect to the electrical resistivity of ash, slag-tap systems require only one comment in addition to those in Section 3.3.14. Because slag-tap systems may produce a fly ash that is segregated with respect to sizing and composition, it is particularly desirable that resistivity measurements be made in-situ. Laboratory determinations made on an as-fired sample of ash may be entirely misleading.

### 3.5 Cyclone-Fired Systems

#### 3.5.1 System Description

The furnace of a dry-bottom P-F system must provide sufficient temperature and residence time to complete combustion of the coal particles, but must also reduce the gas stream temperature to less than the softening temperature of the ash. The cyclone combustor was developed in an attempt to separate these two, rather contradictory, functions, and leave the furnace with the single task of reducing the gas stream temperature. The resulting system is well-suited for the low grade, low ash fusion coals which constitute much of the North American reserves.

A boiler equipped with cyclone combustors is shown in Figure 3, while details of the cyclone are shown in Figure 4. The cyclone consists of water-cooled, refractory-lined cylinder, usually five to ten feet inside diameter, on an essentially horizontal axis. The discharge end is connected to the boiler furnace, and has a water-cooled re-entrant throat. Crushed coal is brought to the feed end of the cyclone, where it is picked up by a swirling flow of primary air which generates sufficient centrifugal force to throw most of the coal particles against the inside walls of the cylinder, where they are trapped in a thin layer of slag. Secondary air enters the cylinder tangentially with the same direction as the primary air, and a high velocity, approximately 300 fps. As it sweeps past the coal trapped on the walls, it continuously scrubs away the boundary layer of combustion gases, promoting very rapid combustion.

Heat release rates within the cyclone range from 500,000 to 900,000 Btu/cuft. hr, but because the inside walls are insulated by a layer of chrome ore refractory, heat absorption rates are low; 40,000 to 100,000 Btu/sqft. hr. Consequently, gas temperatures may exceed 3000°F, and coals with an ash softening temperature of up to 2500°F can usually be slagged without difficulty. Centrifugal forces keep most of the ash from being entrained by the gas stream, and the re-entrant throat prevents the ash from escaping into the furnace, except through tap holes under the throat. Only fine ash particles or droplets, representing 5 to 15% of the total ash, escape through the throat with the combustion gases.

Since combustion is essentially completed within the cyclone, the furnace serves only to cool the gases to the point where the fly ash is in solid state. Two types of furnace are commonly used. The screened furnace, as shown in Figure 3, has primary and secondary furnaces separated by a bank of screen tubes which serve to collect some of the carried-over slag by impingement. The open furnace is a simple water-cooled cavity much like the radiant section of a conventional P-F furnace.

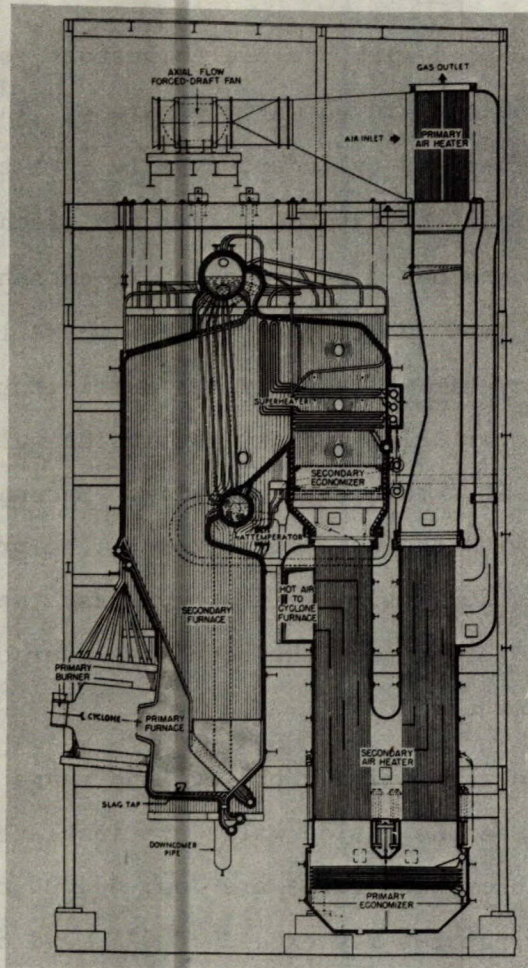


Figure 3. Crushed coal, cyclone furnace boiler.

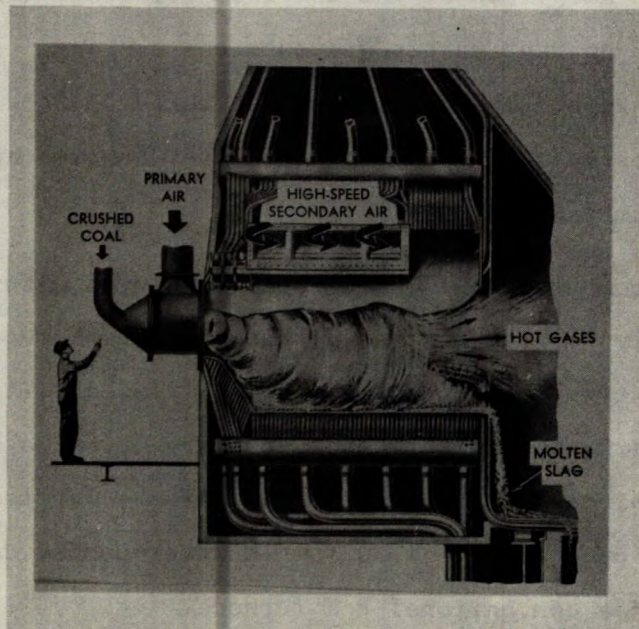


Figure 4. Crushed coal cyclone combustor.

Cyclone combustors are normally built for an input range of 100 million to 500 million Btu/hr. Typically, cyclone-fired boilers are equipped with two to eight cyclones each, depending on steaming capacity.

A major advantage of the cyclone combustor is that it burns crushed, rather than pulverized coal. Thus the capital, operating and maintenance costs of pulverizers are avoided. This is to some extent offset by the extra power required to produce the high secondary-air velocity. Compared to dry-bottom P-F systems, cyclone-fired systems are likely to have a higher power requirement when burning high-grindability bituminous coals, but a lower power requirement when burning low-grindability sub-bituminous coals or lignites.

Confusion sometimes arises because European combustion engineers use the term "cyclone firing" to denote a substantially different combustion system. The European cyclone is also a slag-tap system, but it utilizes several pulverized-coal burners firing tangentially through the sides or roof of a large cylinder on a vertical axis. The foregoing discussion has concerned itself only with the North American cyclone combustor.

### 3.5.2 Effects of Moisture Content

Increasing moisture content reduces flame temperature in cyclones as in slag-tap furnaces, and thus places a lower limit on the firing rate required to maintain satisfactory tapping. However, since cyclone-fired boilers always have two or more cyclones, which can be operated independently, tapping can be maintained at low loads by shutting down some cyclones and firing the others at full capacity. Thus, turn-down ratio is more likely to be governed by the ability to control superheat temperature than by ability to maintain slagging. Coals with up to 40% moisture have been successfully burned in cyclone-fired boilers.

### 3.5.3 Effects of Size Consist

The preferred size consist of coal for cyclone combustors is at least 95% through a 1/4 in. screen, and no more than 10% through a 200-mesh

screen. Coarser sizing reduces the combustion rate, and finer sizing increases the fly ash carry-over. Coarser coal can readily be crushed to the desired size consist, and conventional mining operations do not usually produce coal too fine for cyclone firing.

#### 3.5.4 Effects of Grindability

A coal with low grindability will require more power for crushing, just as it requires more power for pulverizing. Since crushing requires only a fraction of the power required for pulverizing, grindability is not a significant characteristic as far as cyclone firing is concerned.

#### 3.5.5 Effects of Volatile Matter Content

The comments in Section 3.4.4 are generally applicable to cyclone combustors. To maintain the high combustion rates required in cyclones, the volatile matter content should exceed 15%. Somewhat lower-volatile fuels can be burned by increasing combustion air temperature or by firing small quantities of oil or gas to support combustion.

#### 3.5.6 Effects of Petrographic Constituents and Ash Content

These effects are essentially the same for slag-tap and cyclone systems, and are discussed in Sections 3.4.5 and 3.4.6.

#### 3.5.7 Effects of Sulphur Content

Cyclone combustors typically operate with fairly low excess air; 10% to 15% when burning coal. This tends to inhibit the formation of SO<sub>3</sub>, and consequently reduces low-temperature corrosion problems. On the other hand, the reduction in SO<sub>3</sub> may adversely affect the electrical resistivity of the ash.

#### 3.5.8 Effects of Chlorine Content and Organic Nitrogen Content

With respect to chlorine content, the comments in Section 3.3.9 apply to cyclone combustors, and with respect to organic nitrogen content, the comments in Sections 3.3.10 and 3.4.8 apply.

### 3.5.9 Effects of Ash Fusion Temperature and Ash Composition

Here, too, the response of cyclone combustors is similar to slag-tap furnaces and the comments in Sections 3.4.9 and 3.4.10 apply.

### 3.5.10 Effects of Physical Characteristics of Ash

The tendency of some slag-tap furnaces to produce small fly ash particles in a narrow size range was described in Section 3.4.11. This is particularly true of cyclone combustors. Although 85% to 95% of the ash in the coal is normally slagged in the cyclone, the fly ash which does pass through the boiler consists typically of particles ranging from sub-micron to about 15 microns in diameter, generally spherical in shape. These can cause problems because of their tendency to agglomerate through a variety of physical and chemical mechanisms such as Bernoulli's theorem, Brownian motion, Van der Waal's force of attraction, static electrification, bonding by adsorbed layers, and surface tension of liquids condensed on the particles. Agglomeration may occur on heat exchanger surfaces, in ductwork, and in dust collectors. In some cases plugging of dust collectors has occurred, and emission problems resulted when fly ash agglomerated on the walls of the breeching and chimney, then broke loose in large flakes which were carried up the chimney and fell in the vicinity of the plant. Corrosion may also occur if the fly ash adsorbs sufficient SO<sub>3</sub> to render it acidic.

The foregoing difficulties can be largely avoided by equipping the boiler with electrostatic precipitators, and ensuring that heat exchange surfaces are kept above the acid dewpoint.

### 3.5.11 Effects of Electrical Resistivity of Ash

In this respect, cyclone-fired systems require no comments in addition to those in Sections 3.3.14 and 3.4.12.

### 3.6 Summary of Coal Properties Affecting Pulverized Firing

The foregoing discussion of how variations in coal properties influence the performance of P-F systems invites the conclusion that the

complexity of the subject places satisfactory combustion of any coal on the borders of the miraculous. In fact, experts in the field will recognize that this paper offers only a brief outline of the technological limitations. Individual effects of coal properties have been described, but their interactions have scarcely been touched on. For example, moisture affects grindability. It also affects flame length, and thus flame temperature, and thus the ability to melt the ash in slag-tap or cyclone-fired systems. There are complex relationships between ash fusibility, ash viscosity, ash composition and furnace atmosphere which influence boiler corrosion, pollutant formation and electrical resistivity of fly ash. The coal properties discussed represent nothing more than a series of parameters which have been found empirically to offer some guidance to system performance. Their value is limited, but they provide the best information presently available. The complexity of the subject is such that a completely rational understanding is slow to emerge.

Fortunately, while the full spectrum of coals found in this country displays a formidable array of awkward properties, it is seldom that they all occur in a single coal. Over the past half-century there has been sufficient success in designing systems to accommodate the more common combinations of coal properties to make P-F systems the backbone of coal combustion technology. They will undoubtedly maintain their pre-eminence for at least the next two or three decades, but their major weakness is clearly this: they are sensitive to changes in a wide variety of coal properties, thus a plant designed for a particular coal may suffer serious impairment of performance if it is forced to burn another coal. As we enter an era in which fuel sources become increasingly unreliable, we must look for combustion systems that are relatively insensitive to coal properties.

#### 4. COAL PROPERTIES IN RELATION TO COAL-IN-OIL FUELS

##### 4.1 Nature and Advantages of Coal-in-Oil Fuel

The use of coal-in-oil as a boiler fuel is currently attracting considerable interest for three reasons. Firstly, a continuing shortfall of

industrial fuel oil is anticipated; secondly, these slurries can be readily burned in many oil-fired boilers (as well as in boilers converted from coal to oil) using commercially available hardware; and thirdly, the oil reduces the sensitivity of combustion systems to the properties of coals which influence ignition, flame propagation and ash deposition.

Research on coal-in-oil slurries has demonstrated that up to 35% by weight of pulverized coal and up to 60% by weight of crushed coal can be blended in oil to produce slurries having high fluidity, slow settling rates and rapid particle re-entrainment characteristics. It has also been shown that the combustion efficiency and the pollutant emissions from coal-in-oil flames are controlled primarily by the coal properties described in Section 3. For this reason, the following sub-sections are concerned mainly with coal properties as they affect the behaviour of the slurry. Coal properties, associated with the combustion of, and the pollutant emissions from, coal-in-oil slurries are only referred to when their effect is significantly different from coal combustion.

#### 4.2 Slurry Behaviour

Slurry behaviour is primarily influenced by the properties of the individual coal or coal ash particles. These properties, which are inter-dependent, are density, swelling, size, porosity, wettability and moisture.

##### 4.2.1 Density and Swelling

High particle densities result in accelerated settling and retarded re-entrainment of sediment in slurry handling equipment. It follows that low density particles - i.e., those with a specific gravity less than 1.3 - are easier to maintain in suspension.

In the case of high-ash coals, high particle densities are invariably associated with the ash constituents. Thus, slurry stability is improved by the partial removal of ash during grinding or crushing.



High-density, low-ash coals will generally produce unstable slurries, except in some cases where the coal particles swell in the presence of oil. Coal swelling, by increasing particle size, effectively reduces particle density and enhances the slurry stability.

#### 4.2.2 Coal Particle Size

Fine particles, particularly those less than  $20\mu\text{m}$ , are difficult to re-entrain from sediment because particle cohesion increases as particle size decreases. On the other hand, particles larger than  $20\mu\text{m}$  tend to produce a weakly cohesive sediment which can be re-entrained easily.

Large increases in the concentration of fine particles in the slurry are undesirable in that slurry viscosity can increase to the point of exhibiting semi-solid or plastic flow. When this occurs, pump energy requirements increase rapidly and small orifices and narrow valve channels plug frequently. Fortunately, most pulverizers and crushers employed in practical combustion systems produce a wide range of particle sizes with only a small weight fraction below  $20\mu\text{m}$ . Nonetheless, superfine, monosize particles such as dust collector residues can be used in coal-in-oil slurries, but a reduction in solids loading is necessary in order to produce a fluid rather than a plastic slurry.

#### 4.2.3 Particle Porosity

Highly porous particles, being much lower in density than non-porous particles, enhance slurry stability. This is true even if oil penetrates the pore structure and creates a slight increase in apparent particle density. With oil in the pores, the particles tend to settle slowly producing a soft, easily re-entrainable sediment.

Low porosity or non-porous particles usually have a high density and are difficult to stabilize in slurries.

#### 4.2.4 Particle Wettability

Wettability, the tendency of a particle surface to become oil-wetted or olephilic, affects the ease with which coal particles can be blended and stabilized in oil slurries. This property is influenced primarily by the presence of polar organic surface groups that attract rather than repel oil. If the particles strongly reject contact with oil, the slurries will settle very quickly and the sediment will be very hard regardless of particle size. Such a condition will occur when polar groups are absent in the original coal or when coals have had their polar groups destroyed by oxidation.

The absence of polar groups can, to some extent, be offset by the addition of small amounts (ca 2% by wt) of a polar liquid such as water, varsol or tannic acid to the coal. Liquids of this type have been used to improve the stability of coal-in-oil slurries, but the best liquid and the optimum addition to a specific coal can only be determined by experiment. In some cases sophisticated surfactants are beneficial, but treatment costs are high.

Lignite coals are usually easy to blend and stabilize in oil because their cellulosic constituents have an affinity for oil. Conversely, coke particles are difficult to suspend and re-entrain in oil unless they are first treated with a polar liquid, because all cellulosic constituents have been driven off, and the pores may be partially blocked by carbon dust or ash.

#### 4.2.5 Moisture

High external moisture in coal may present problems when slurries are made from oils that require preheating for handling and combustion. For example, preheating residual oil with coal containing over 10% moisture can result in more than a 40% increase in volume due to frothing. This phenomenon may not be overly critical in the storage tank, but if large volumes of froth are pumped to the furnace, combustion performance will deteriorate and flame failures are highly probable.

#### 4.3 Slurry Combustion

Coal-in-oil flames, being much shorter and more intense than pulverized coal flames, provide less residence time to burn out coal particles. This characteristic, which is due to the high effective volatile matter content in coal-in-oil fuels, means that the fixed carbon in the coal particles must be highly reactive in order to achieve good burn-out.

Coals that are high in fusinite or semi-fusinite, are grossly unsuitable for coal-in-oil fuels because these forms of fixed carbon, being graphitic in structure, are virtually non-combustible.

#### 4.4 Pollutant Emissions from Slurry

The major pollutants emitted from coal-in-oil flames will be essentially the same as those from pulverized-coal flames. Sulphur oxide and fly ash concentrations can be calculated from the combined coal and oil analyses while nitrogen oxides concentrations, which are dependent on fuel nitrogen as well as air nitrogen oxidation, should be slightly lower than for coal alone. Pollution control technology for pulverized-coal boilers can be applied to boilers fired with coal-in-oil without change.

### 5. FLUIDIZED-BED COMBUSTION SYSTEMS

#### 5.1 System Description

The fluidized-bed combustion system may turn out to be the most significant advance in combustion technology since pulverized firing was introduced. It offers the advantages of economy, efficiency, low pollutant emission, and perhaps most important of all, insensitivity to coal properties. Furthermore, it is applicable to small commercial boilers as well as large utility steam generators. So far it has only been demonstrated experimentally in fire-tube boilers of about 1600 lb/hr steaming capacity, but there seem to be no insuperable barriers to scaling up.

Fluidized beds have been used in the chemical industry for many years in processes requiring contact between gases and solids. The principle is simple; a bed of granular material is supported in a cylinder on a perforated plate, and air or some other gas is forced through the perforations at sufficient volume and pressure to cause the bed material to behave as a fluid. That is, it assumes a boiling action as it is partially lifted by the bubbles of gas passing upwards through it. This creates intense mixing in the bed and it becomes an excellent medium for transferring heat or bringing together chemical reactants. Two common applications are catalytic crackers in petroleum refining, and production of sulphuric acid by roasting of sulphide ores.

In applying the fluidized bed to combustion systems, advantage can be taken of both its mixing and heat transfer characteristics. Figure 5 shows a vertical fire-tube boiler equipped with a fluidized-bed combustion system. The bed material may be crushed refractory, coal ash, or any other solid material with properties suitable for some specific purpose, such as ability to react with sulphur. The particle size range is usually 0.5 to 5mm, and the bed depth is typically 0.3 to 2 m. Combustion air, preferably preheated, is introduced through perforations in the plate supporting the bed. The velocity through the bed required to fluidize varies with particle size, but is usually in the range of 0.5 to 7 m/s. Crushed coal, usually -2 mm particle size, but possibly in the form of lumps up to 3 or 4 cm diameter, is introduced into or onto the bed. The burning capacity is essentially determined by bed area and pressure.

For start-up the bed must be preheated to temperatures which will support combustion of the coal. One way to accomplish this is to pass flue gas from auxiliary burners through the bed. A temperature of 750 to 800°C is sufficient to ignite most coals; the system can then be operated on coal only, and usually the bed is maintained at a fairly constant temperature ( $\pm 10^\circ\text{C}$ ) somewhere between 800°C and 900°C. These are much lower temperatures than are encountered in P-F flames or stoker fire-beds, thus slagging of the ash

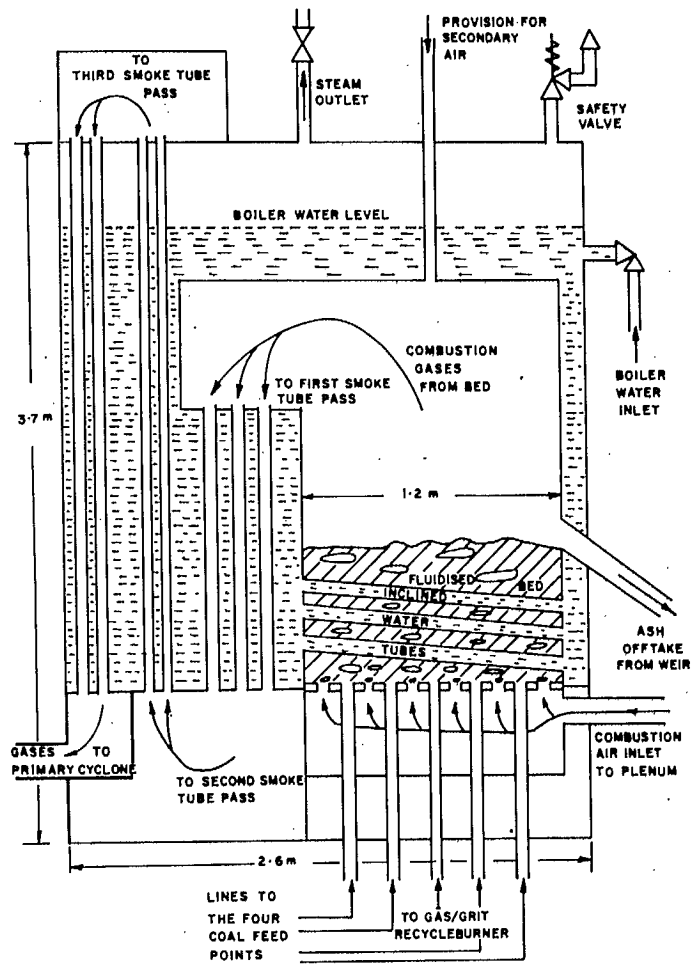


Figure 5. Schematic of a fluidized-bed combustion system.

is largely avoided. Furthermore, in steady-state operation, coal is injected into the bed at such a rate that it does not usually comprise more than 5% of the total bed. Being thus diluted about twenty to one with inert material, it does not agglomerate and cake in the manner so troublesome to underfeed stokers. The residence time of coal in the bed is in the order of minutes, compared to seconds or fractions of a second in P-F systems.

Because of the intense mixing in the bed, incoming coal and combustion air are rapidly brought up to bed temperature and complete combustion can be achieved with moderate excess air. The burning fuel and combustion products in turn transfer heat to the bed material, and both the bed material and the combustion products transfer heat to boiler tubes immersed in the bed or to waterwalls containing the bed. The rate of heat transfer to tubes in a fluidized bed is about five times greater than that from combustion gases to tubes in a conventional furnace, thus there is a substantial reduction in heat exchange area for a given steaming capacity.

Combustion gases leave the top of the bed essentially at bed temperature, entraining with them fine particles of ash and bed material. They then pass through conventional boiler banks which reduce the temperature by convective transfer to normal stack temperatures. The entrained solids are removed by a dust collector, and are normally recycled to the bed to reduce the carbon content. Most of the coal ash remains in the bed and is discharged, together with bed material, over a weir which serves to maintain a constant bed height.

The volume of a fluidized-bed is small compared to that of a suspension-fired furnace of equal heat input. Fluidized-beds are therefore amenable to pressurized combustion, which further reduces the volume requirements and further increases the heat transfer rates. Figure 6 shows the estimated volume requirements of atmospheric and supercharged fluidized-bed systems for 660 MW compared to a conventional P-F boiler. It should be kept in mind that fluidized-bed combustion systems, like conventional systems, require convective heat transfer surfaces to reduce the flue gas temperature

from combustion temperature to stack temperature. But the differential for the fluidized-bed is about  $750^{\circ}\text{C}$  while for conventional systems it is about  $1250^{\circ}\text{C}$ .

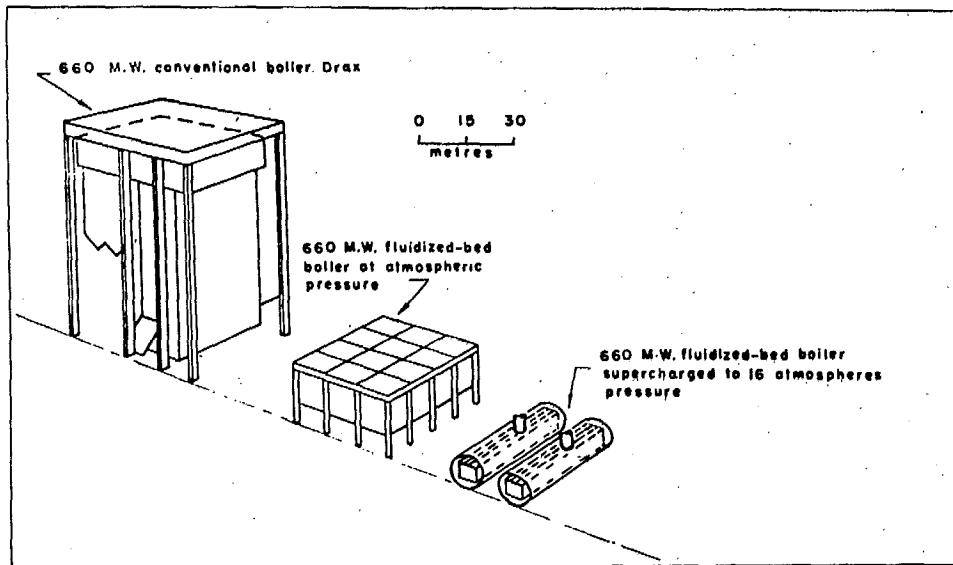


Figure 6. Size comparison of low- and high-pressure fluidized-bed boilers with a conventional boiler. After Hoy and Roberts.

Fluidized-beds are not without their disadvantages. Because heat transfer rates in the bed are so high, the immersed boiler tubes are easily damaged by excessive bed temperatures. On the other hand, combustion ceases if the bed temperature drops too low. Therefore, the bed must be maintained within rather narrow temperature limits, and this complicates the process of controlling output. It may be necessary to control the heat absorption rate as well as the firing rate.

Another characteristic of fluidized-bed is that relatively little variation can be tolerated in the velocity of the fluidizing air. If it is too high, entrainment of particulates is excessive and loss due to unburned carbon is high. If it is too low, fluidizing becomes sluggish, coarse material in the bed segregates, and heat transfer is impaired. If, on turndown, air flow is held constant while fuel flow is decreased, excess air levels become unacceptably high. The possibilities of achieving acceptable turndown by allowing part of the bed to slump are being investigated.

The combustion air must be introduced at a substantial pressure in order to fluidize the bed. In pilot-scale tests with a bed at atmospheric pressure, combustion air at 9 in. WC was required to fluidize a bed of 0.4 m depth, but a pressure drop of 40 in. WC through the distributor plate alone may be necessary.

For pressurized systems much higher combustion air pressures are necessary, and cycles combining gas turbines with fluidized beds appear attractive.

Further characteristics of fluidized-bed combustion systems are perhaps best discussed by considering the list in Section 3.2 of coal properties affecting P-F systems. This will enable a direct comparison of the advantages claimed for fluidized-bed combustion systems over more conventional technology.

## 5.2 Coal Properties Affecting Fluidized-Bed Combustion Systems

### 5.2.1 Effects of Coal Moisture

Coal moisture content should have little effect on combustion in a fluidized-bed as long as the calorific value is sufficient to evaporate the moisture and maintain the bed temperature. Whether high-moisture coals would require increasing residence time by increasing the bed thickness or reducing the fluidizing velocity has not yet been determined experimentally, but sewage sludge containing 50% moisture has been successfully burned in a fluidized bed.



### 5.2.2 Effects of Size Consist and Grindability

These effects are relatively minor, since fluidized-bed systems burn crushed, rather than pulverized coal. In this respect, fluidized-beds compare roughly to cyclone combustors.

### 5.2.3 Effects of Volatile Matter Content, Petrographic Constituents and Ash Content

Since combustion occurs within the fluidized-bed rather than in a suspended flame envelope, ignition stability is not a problem. Increasing volatile matter content would tend to lower the temperature at which the bed is self-sustaining. Since the average residence time in the bed is in the order of minutes, combustion of relatively unreactive fuel constituents should be possible, although when burning char or coal with a high fusinite content the carbon content of the ash might be higher than with more reactive coals. The ash content of the coal has little effect on the concentration of combustibles in the bed. It is believed that even such high-ash, low-calorific-value fuels as unprocessed tar sands and oil shales can be burned, with the only penalty being perhaps a slightly higher loss due to unburned carbon.

### 5.2.4 Effects of Sulphur Content

Possibly the single greatest advantage claimed for fluidized-bed combustion systems is the ability to burn high-sulphur coal with minimal SO<sub>2</sub> emissions and virtually no SO<sub>3</sub> emissions, without resorting to gas scrubbing plants. This is accomplished simply by using limestone (CaCO<sub>3</sub>) or dolomite (CaCO<sub>3</sub> + MgCO<sub>3</sub>) as the bed material. As SO<sub>2</sub> is formed in the bed, it reacts with the bed material to form CaSO<sub>4</sub>, MgSO<sub>4</sub>, and CO<sub>2</sub>. Fresh bed material is continuously added, and the spent material is withdrawn in the ash stream. Since the sulphates of calcium and magnesium are non-toxic, the spent material can be dumped without hazard. Technology also exists to recover the sulphur if this is economically feasible.

Research in the UK has shown that when operating a fluidized-bed combustion system with limestone, crushed to -10 mesh size and supplied at a rate of 2-1/4 times the stoichiometric ratio of calcium to sulphur, 80% to 99% of the sulphur in the fuel was trapped in the bed. Substantially better sulphur removal could be achieved by using a finer size of limestone. With coal containing two to three per cent sulphur, it is estimated that stack emissions from fluidized-bed combustion systems can be limited to 100 ppm of SO<sub>2</sub> at additional costs of 1% on capital and 3% on generation costs.

#### 5.2.5 Effects of Chlorine Content

Experience to date indicates that beds of limestone and dolomite are not very effective in removing chlorine compounds. However, there is a possibility that other materials could be added to the bed for this purpose. Furthermore, if the bed can be operated at temperatures below 800°C, the chlorine-bearing compounds are unlikely to decompose.

#### 5.2.6 Effects of Organic Nitrogen Content

The relatively low temperatures at which combustion proceeds in a fluidized-bed effectively suppress the formation of air-source nitrogen oxides. It would appear that they also reduce the formation of fuel-source nitrogen oxides. In pilot-scale tests with coal in the UK, a fluidized-bed system produced 60 to 180 ppm of NO<sub>x</sub>, compared to 400 to 800 ppm for a conventional P-F plant.

#### 5.2.7 Effects of Ash Fusion Temperature

Clinkering is not likely to occur in a fluidized-bed if the ash reaches its initial deformation temperature, but is likely to occur if the ash softening temperature is reached. Thus, the latter value may impose a limitation on allowable bed-temperature. Experience to date indicates that some particles within a fluidized-bed may be 100°C higher than the average temperature. Therefore, a fluidized-bed operating at an average temperature of 900°C should not experience clinkering with coals having an ash softening temperature greater than 1000°C (1832°F). Furthermore, if a refractory bed

material is used, softened ash particles will be too dilute to form clinkers. Slagging of the heat transfer surfaces downstream of the fluidized-bed is not likely to occur. Serious clinkering in the bed would develop first.

#### 5.2.8 Effects of Ash Composition

There is a possibility that with certain coals, ash components with a low sintering temperature may be selectively elutriated from the fluidized-bed, and lead to fouling of downstream heat exchange surfaces. Experience with fluidized-bed combustion systems has not yet been extensive enough to verify this.

#### 5.2.9 Effects of Physical Characteristics of Ash

Fluidized-bed combustion systems are expected to reject most of the ash via the ash weir, and thus reduce the potential loading on the dust collectors. However, if the ash is very friable, the abrasive action of the bed may reduce the ash to such small particles that most of it is elutriated. Deposition and dust collection problems would then be comparable to dry-bottom P-F systems.

#### 5.2.10 Effects of Electrical Resistivity of Ash

It is presently believed that fluidized-bed combustion systems can be operated with cyclone dust collectors rather than electrostatic precipitators. However, if the latter are required in certain instances, due, for example to a friable ash, then the electrical resistivity of the ash will have the same effects as for conventional combustion systems.

#### 5.2.11 Effects of Coal Caking Properties

Caking properties, as measured by the Free Swelling Index have been discussed in connection with stoker-fired systems (Section 2). Caking normally has no effect on P-F systems, and it is unlikely to occur in a fluidized-bed because the coal is diluted about 20 to 1 with ash and inert bed material. However, it may occur in the coal feed spouts to the bed, and may either block the feed, or result in large lumps of caked coal, reducing

the combustion rate in the bed. Experience indicates that the problem can be overcome by cooling the feed spouts.

### 5.3 Summary of Fluidized-bed Combustion Systems

The foregoing discussion makes it difficult not to become excited about the potential of the fluidized-bed as a combustion system which is both insensitive to coal properties and adaptable to the full size range, from small commercial heating applications to large electricity generation stations. Unfortunately, the apparent benefits cannot be realized immediately because the technology is not fully developed. Experience to date totals about 17,000 hr of operation, mostly in Great Britain, and mostly on pilot-scale systems having a bed area of less than 0.5 m<sup>2</sup>. A system having a bed area of 0.75 m<sup>2</sup>, and pressurized at 3 to 5 atmospheres has been operated for over 1000 hr. A few somewhat larger systems have been installed in shell boilers on an experimental basis.

While the pilot-scale results generally verify the advantages claimed for fluidized-bed combustion systems, satisfactory solutions to the problems of turndown and control have yet to be demonstrated. Small-scale systems may be commercially available in one or two years, but large-scale systems are not likely to be available for at least ten years. A major UK manufacturer is presently converting a boiler in the 5 to 10 MW range to fluidized-bed firing, using a 100 ft<sup>2</sup> bed, subdivided into four sections which can operated independently to provide turndown. It is expected to be ready for operation early in 1975. This, too, is primarily an experimental unit, and the results may be of great significance to the Canadian coal industry.

6. BIBLIOGRAPHY

6.1 Textbooks and Handbooks

Shields, Carl D. "Boilers, Types, Characteristics and Functions". Published by F. W. Dodge Corporation, New York, USA, 1961

Field, M. A., et al. "Combustion of Pulverized Coal". Published by The British Coal Utilization Research Association, Leatherhead, Surrey, England, 1967

Johnson, A. J. and Auth, G. H. "Fuels and Combustion Handbook". Published by McGraw-Hill Book Company, Inc. New York, USA, 1951

Thring, M. W., "The Science of Flames and Furnaces". Published by John Wiley & Sons, Inc., New York, USA, 2nd Edition 1962

Nelson, H. W., et al "Corrosion and Deposits in Coal and Oil-fired Boilers and Gas Turbines". Published by The American Society of Mechanical Engineers, New York, USA, 1959

"Steam Its Generation and Use". Published by The Babcock and Wilcox Company, New York, USA, 37th Edition 1955

Spiers, H. M. "Technical Data on Fuel". Published by The British National Committee, World Power Conference, 201 Grand Buildings, Trafalgar Square, London WC 2 Sixth Edition 1962

Beér, J. M. and Chigier, N.A. "Combustion Aerodynamics". Published by Applied Science Publishers Ltd., Ripple Road, Barking, Essex, England. 1972

Francis, Wilfred "Fuels and Fuel Technology". Published in two volumes by Pergamon Press, Oxford, England, 1965

de Lorenzi, Otto "Combustion Engineering". Published by Combustion Engineering Company Inc., New York, USA, 1st Edition 1948

Oglesby, Sabert Jr., and Nichols, G.B. "A Manual of Electrostatic Precipitator Technology Part I - Fundamentals and Part II Application Areas". Published by the Southern Research Institute, Birmingham, Alabama, USA, 1970

Swartzman, E. "Analysis Directory of Canadian Coals, 2nd Edition" and Swartzman, E., and Tibbetts, T.E. Analysis Directory of Canadian Coals - Supplement No. 1". Published by the Fuels Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada, No. 836, 1953 and No. 850, 1955 respectively

Friedrich, F. D. and Hayden, A.C.S. "A Combustion Handbook of Canadian Fuels, Volume 3 - Coal". Published by the Department of Energy, Mines and Resources, Ottawa, Canada, Mines Branch Monograph 882, 1974

"1972 Annual Book of ASTM Standards, Part 19: Gaseous Fuels; Coal and Coke". Published by the American Society for Testing Materials, 1916 Race Street, Philadelphia, Pa., USA, 1972

#### 6.2 Conference and Symposium Proceedings

Members Conferences of the International Flame Research Foundation, held approx. every three years. Proceedings published by the International Flame Research Foundation, Eindhoven, Holland

International Combustion Symposium, held biennially. Proceedings published by the Illinois Institute of Technology, Chicago, Illinois, USA

Canadian Conferences on Coal, held annually. Proceedings published by the Department of Energy, Mines and Resources, Ottawa, Canada

Proceedings of the Boyer Conference, May 1963. Published by the Department of Mines and Technical Surveys, Ottawa, Canada

Proceedings of the North American Fuel Technology Conference, June 1970. Available from the Institute of Combustion and Fuel Technology of Canada, 35 Rochester Avenue, Toronto, Ontario, Canada

Proceedings of the Symposium on the Science and Technology of Coal, March 1967. Published by the Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada

Johnson, H.R., and Littler, D.J. (Editors). "The Mechanism of Corrosion by Fuel Impurities". Proceedings of the International Conference held at the Marchwood Engineering Laboratories, Marchwood, Hampshire, England, May 1963. Published by Butterworth and Co. (Canada) Ltd., Toronto, Canada 1963

### 6.3 Papers and Journal Articles

#### 6.3.1 Stokers and P-F Systems

"Power from Coal-A Special Report, Parts I, II and III", Power, Vol. 118, Nos. 2, 3 and 4. Feb, Mar and Apr, 1974. Published by McGraw-Hill, New York, USA

Mitchell, E.R., Friedrich, F.D., and Gauthier, G.A. "Combustion of Eastern Canadian Coal in Thin Fires on a Spreader Fired Air-Cooled Oscillating Grate", Mines Branch Technical Bulletin TB 1, Department of Energy, Mines and Resources, Ottawa, Canada, 1959

Mitchell, E.R., Friedrich, F.D., and Lee, G.K. "Research on the Application of Eastern Canadian Coal to Large Stokers", Mines Branch Technical Bulletin TB 14. Department of Energy, Mines and Resources, Ottawa, Canada, 1961

Lee, G.K. and Skulski, J.Z. "An Index of Ash Clinkering and the Influence of Additives on Eastern Canadian Coal", Mines Branch Technical Bulletin TB 19, Department of Energy, Mines and Resources, Ottawa, Canada, 1961

Tibbetts, T.E. and Lloyd, T.A. "Survey of Canadian Commercial Coals, Nova Scotia-1964", Fuels and Mining Practice Division, Divisional Report FMP 65/33 Prep. Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada, 1964

Tibbetts, T.E. and Lloyd, T.A. "Survey of Canadian Commercial Coals, Alberta and British Columbia-1964", Fuels and Mining Practice Division, Divisional Report FMP 65/53 Prep. Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada, 1964

Tibbetts, T.E. "Evaluation of Canadian Commercial Coals: Saskatchewan, Alberta and British Columbia-1971", Mines Branch Information Circular IC 291, Department of Energy, Mines and Resources, Ottawa, Canada, 1972

Tibbets, T.E. and Montgomery, W.J. "Evaluation of Canadian Commercial Coals: 1972 Saskatchewan, Alberta and British Columbia", Mines Branch Information Circular IC 305, Department of Energy, Mines and Resources, Ottawa, Canada 1973.

Coykendall, L.H., and Loughin, P.R. "Boiler and Furnace Designed for Spreader Stoker Firing", Transactions of the ASME, Vol. 76, No. 6, pp 873-882. August 1954.

Miller, E.C. "Future Trends in Stoker Design", ASME Paper No. 55-FU-1. Published by The American Society of Mechanical Engineers (ASME), United Engineering Center, 345 East 47th Street, New York, N.Y. 10017, USA, 1955

Messaros, F.C. "New Concepts in Stoker Design", ASME Paper No. 57-A-273. Published by the ASME, 1957

Tate, B.E. "Properties of Coal - Their Influence on Performance of Coal-Burning Apparatus", ASME Paper No. 52-SA-54. Published by the ASME, 1952

Van Tassel, W., and Miller, E.C. "Spreader Stoker Firing North Dakota Lignite for 66 Megawatts". Published by the American Power Conference, Illinois, Institute of Technology, Chicago, Illinois, USA, 1962

Collins, W.J. "Small and Medium Size Cyclone Furnace Boilers" ASME Paper No. 54-FU-3. Published by the ASME, 1954

Bayles, A.L. "Effects of Particle Size on Firing Pulverized Solid Fuel in Boilers", ASME Paper No. 57-A-276. Published by the ASME, 1957

Piper, J.D., and Van Vliet, H., "Effect of Temperature Variation on Composition Fouling Tendency and Corrosiveness of Combustion Gas from a Pulverized-Fuel-Fired Steam Generator", ASME Paper No. 57-A-281. Published by the ASME, 1957

Holdup, E.D. "Sound Methods of Solid Fuel Evaluation for Use in Thermal Power Stations", ASME Paper No. 57-FU-1. Published by ASME, 1957

Bross, W. "First Cyclone Furnace Boiler in Southeast". ASME Paper No. 58-FU-3. Published by ASME, 1958



Duzy, A.F. "American Coal Characteristics and Their Effects on the Design of Steam Generating Units", ASME Paper No. 59-A242. Published by ASME, 1959

Finney, C.S., and Spicer, T.S. "The Influence of Particle Size and Volatile Content on the Ignitibility of Pulverized Bituminous Coal", ASME Paper No. 62-WA-195. Published by ASME 1962

Barnhart, D.H., and Cantieri, W.F. "Test Procedure to Predict Relative Fouling Characteristics of Coal", ASME Paper No. 63-WA-249. Published by ASME, 1963

Mitchell, E.R., et al "Research on the Use of Pulverized Coal in Firing Industrial Steam Boilers", Fuels and Mining Practice Division, Internal Report FMP 61/152 MECH, Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada, 1961

Orning, A.A., Smith, John F., and Schwartz, Cecil H. "Minor Products of Combustion in Large Coal-Fired Steam Generators", ASME Paper No. 64-WA/FU-2. Published by ASME, 1964

Lee, G.K., and Mitchell, E.R. "Agglomeration of Superfine Fly Ash in Cyclone-Fired Boilers of the Nova Scotia Light and Power Company, Ltd", Fuels and Mining Practice Division Internal Report FMP 62/43 MECH, Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada, 1962

Friedrich, F.D. "Combustion Systems Used in Germany for Large Boilers", Fuels and Mining Practice Division, Divisional Report FMP 65/101 MECH, Mines Branch, Department of Energy, Mines and Resources, Ottawa, Canada, 1965

Harris, W.C. "Operation and Maintenance Experience of Cyclone-Fired Boilers". Published by the Nova Scotia Light and Power Company, Ltd., Halifax, Nova Scotia, Canada, 1966

Friedrich, F.D., Lee, G.K., and Mitchell, E.R. "Combustion Fouling Characteristics of Two Canadian Lignites", ASME Paper No. 71-WA/CD-3. Published by ASME, 1971

Wiedersum, G.C. Jr., Brokel, W.E., and Sensenbaugh, J.D. "Corrosion and Deposits in Low-Level Economizers", ASME Paper No. 61-WA-138. Published by ASME, 1961

Levy, Arthur, and Merryman, Earl L. "Sulphur Chemistry and Its Role in Corrosion and Deposits", ASME Paper No. 62-WA-124. Published by ASME, 1962

Essenhigh, Robert H. "The Influence of Coal Rank on the Burning Times of Single Captive Particles", ASME Paper No. 62-WA-35. Published by ASME, 1962

Orning, A.A., Schwartz, C.H., and Smith, J.F. "A Study of the Minor Products of Coal Combustion", ASME Paper No. 64-PWR-4, Published by ASME, 1964

Guner, M.I., Lovell, H.L., and Spicer, T.S. "Factors Affecting the Results of the Hardgrove Grindability Test and a Proposed Method of Correction", ASME Paper No. 64-WA/FU-3. Published by ASME, 1964

Richards, Charles E., and Beck, Lawrence O. "Availability of Large Fossil Fuel Fired Power Generating Units". ASME Paper No. 65-PWR-8. Published by ASME, 1965

Hedley, A.B., Brown, T.D., and Shuttleworth, A. "Available Mechanisms for Deposition from a Combustion Gas Stream", ASME Paper No. 65-WA/CD-4". Published by ASME, 1965

Gronhovd, G.H., Wagner, R.J., and Wittmaier, A.J. "Comparison of Ash-Fouling Tendencies of High and Low-Sodium Lignite from a North Dakota Mine". Published by the American Power Conference, Illinois Institute of Technology, Chicago, Illinois, USA, 1966

Reid, William T. "Basic Problems in the Formation of Sulfates in Boiler Furnaces". ASME Paper No. 66-WA/CD-1. Published by ASME, 1966

Reese, J.T., and Greco, Joseph. "Experience With Electrostatic Fly-Ash Collection Equipment Serving Steam-Electric Generating Plants", ASME Paper No. 67-WA/APC-3. Published by ASME, 1967

Murthy, C. Rajasekara "On the Settling of Dust Particles Borne by Hot Chimney Plumes", ASME Paper No. 68-WA/APC-3. Published by ASME, 1968.

Attig, R.C., and Duzy, A.F. "Coal Ash Deposition Studies and Application to Boiler Design". Published by the American Power Conference, Illinois Institute of Technology, Chicago, Illinois, USA, 1969

Duzy, A.F. and Rudd, A.H. "Steam Generator Design Considerations for Western Fuels". Published by the American Power Conference, Illinois Institute of Technology, Chicago, Illinois, USA, 1971

Bonafede, G., and Kiss, L.T. "Study of Ash Deposits from Brown Coal Fired Boilers With the Aid of Scanning and Transmission Electron Microscopy", ASME Paper No. 73-WA/CD-7. Published by ASME, 1973

Wilson, J.S., and Redifer, M.W. "Equilibrium Composition of Simulated Coal Combustion Products: Relationship to Fireside Corrosion and Ash Fouling", ASME Paper No. 73-WA/CD-6. Published by ASME, 1973

"Standard Definitions of Terms Used for the Petrographic Description of Coal (Macroscopic and Microscopic)", ASTM Designation D 2796. Published by the American Society for Testing Materials, 1916 Race Street, Philadelphia, Pa., USA, 1974

### 6.3.2 Fluidized-Bed Combustion Systems

Wright, S.J., Ketley, H.C., and Hickman, R.G. "The Combustion of Coal in Fluidized Beds for Firing Shell Boilers". J. Inst. Fuel, Vol. 42, No. 6, pp 235-239. June 1969

McLaren, J., and Williams, D.F. "Combustion Efficiency, Sulphur Retention and Heat Transfer in Pilot-Plant Fluidized-Bed Combustors", J. Inst. Fuel Vol. 42, No. 8, pp 303-308. Aug 1969

Bishop, J.W., et al. "Status of the Direct Contact Heat Transferring Fluidized Bed Boiler", ASME Paper No. 68 WA/FU-4. Published by ASME, 1968

Reid, William T. "Basic Factors in the Capture of Sulfur Dioxide by Limestone and Dolomite", ASME Paper No. 69-PWR-5. Published by ASME, 1969

Locke, Brian "Fluidized Combustion for Advanced Power Generation with Minimal Atmospheric Pollution". Published by Combustion Systems Ltd., London, England, 1973