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THE COMBUSTION PROPERTIES OF WESTERN CANADIAN COALS

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by

G. K. Lee,* F. D. Friedrich** and H. Whaley**

ABSTRACT

The influence of the various physico-chemical properties of western Canadian thermal coals on flame characteristics, ash deposition and pollutant formation during combustion are described. Emphasis is placed on dry, pulverized systems because they will continue to be widely used around the world for the foreseeable future. Slagging boilers, although restricted to low-ash fusion coals, are also briefly reviewed.

Fluidized-bed combustion will likely emerge as a major technology development over the next decade, especially for industrial space heating and processing. Its potential advantages and applications are explained with particular reference to the utilization of highly-variable, very-low quality coals and coal rejects.

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INTRODUCTION

In 1981, the production of western Canadian thermal coal reached 23×10^6 tonnes, with exports accounting for slightly less than 10% of the total. By 1990, the demand for these coals is expected to rise to 50×10^6 tonnes with about 20% or 10×10^6 tonnes being marketed offshore, mainly in the Pacific Rim and western Europe.

The successful utilization of these coals, which range from lignite through to semi-anthracite is, however, dependent on two closely interrelated factors - the physico - chemical properties of the coals and the operational characteristics various combustion systems. These factors can be accommodated when a system is designed to burn coals of known quality. But when an existing system is required to burn substitute coals that are not well defined, extreme care must be taken to ensure that the coal properties and the system design are reasonably compatible.

This overview paper (a) describes the principal suspension firing systems in which western Canadian coals are being, or are likely to be burned and (b) gives a detailed summary of the influence of various coal properties on fuel handling, combustion performance, ash deposition and pollutant emissions. Special emphasis has been placed on dry firing systems because of their widespread, international acceptability. Slagging systems which are less common and fluidized-bed systems which are now being demonstrated are also reviewed.

SUSPENSION FIRING OF COAL

Principles of Combustion

Pulverized firing is at present the most important technology for converting coal to useful energy and it is likely to remain so for the next 20 to 30 years. Basically, the process involves grinding coal to a very fine powder, typically 75% less than 74 μm, which is then pneumatically transported to a burner array with 20% or less of the total combustion air. The remaining combustion air is added at the burner where the cloud of coal particles is ignited by recirculated furnace gases or hot refractory. By judicious use of burner aerodynamics and furnace geometry, the time, temperature and turbulence conditions can be optimized to provide stable flames, with efficient burn-out of the coal particles.

The effect of burner aerodynamics on flame geometry is shown in Figure 1 and a simple model of a burning coal particle is illustrated in Figure 2.

Furnace Technology

Most pulverized-coal-fired systems employ dry ash removal (dry bottom systems), although, slag or liquid ash removal (wet bottom systems) is sometimes employed for low ash fusion coals.

Dry bottom furnaces are large water-cooled chambers having a hopper-shaped bottom and an array of burners mounted in either the front wall, in opposite walls or in each corner, as shown in Figures 3 and 4 respectively. Roof mounted burners are used in Europe but are less common in North America.

Combustion is initiated and completed in the furnace, and the products of combustion travel up the furnace into the convective heat transfer zones. After passing through the superheater, reheater, economizer and air heater, the gases are cleaned, usually in electrostatic precipitators, before being exhausted through the stack. Most of the ash travels through the entire boiler to the gas cleaning equipment, although about 20% of the input ash settles out in the furnace hopper and in hoppers under the convection zones.

Wet bottom furnaces have been designed for burning either pulverized or crushed coal. Pulverized fired systems may employ a) opposed-inclined b) tangential or c) roof burners, while crushed coal is burned in cyclone combustors mounted in the front wall of a radiant furnace. These systems, remove about 75% of the input ash as slag, and provide high boiler availability with low ash fusion coals. Two types of wet bottom furnaces are shown in Figures 5 and 6.

Because of their complexity, suspension firing of coal is only economic for systems burning 5 to 500 tonnes of coal per hour. Their application is therefore limited to the large industrial and electric utility markets.

PROPERTIES OF WESTERN CANADIAN THERMAL COALS

General Properties

Western Canadian thermal coals range in rank from lignite, through sub-bituminous and high-volatile bituminous, to low-volatile bituminous and semi-anthracite. Table 1 shows the ASTM Classification System for ranking coals and Tables 2 and 3 summarize the physico-chemical properties of five commerical coals from different coal regions.

Influence of Coal Properties on Combustion

The following sections describe the effect of the major coal properties, shown in Table 4, on both the combustion process and the combustion residues.

Moisture

The total moisture in coal is composed of free or surface moisture and inherent or internally bound moisture.

Coal with surface moisture in excess of 8%, particularly if it is fine or contains a large amounts of clay-type minerals, tends to agglomerate into large cohesive lumps that are difficult to handle. At sub-zero temperatures, these handling problems are accentuated by massive frozen blocks of coal that may require thawing and crushing.

Inherent moisture, which can range from 2% for high rank coals to 30% for lignite, is combined with the coal substance and does not effect handling. With only inherent moisture present, the coal appears to be dry and is generally dusty and free-flowing.

Moisture in coal, whether surface or inherent, impairs combustion performance by a) reducing pulverizer capacity, b) retarding ignition, c) decreasing flame stability, (d) increasing flame length and furnace volume, e) increasing induced draft fan requirements and f) causing corrosion in the colder regions of the boiler. Moreover, each 1% increment in total coal moisture reduces boiler efficiency by 0.1%.

Ash

Ash is the solid inert residue that remains after combustion of the carbon, hydrogen and sulphur in coal. The mount of ash is typically less than the mineral matter in the "as received" coal because a number of mineral components may be volatilized at flame temperatures.

Ash contents exceeding 15% by weight, by diluting the combustible coal constituents, can adversely affect pulverizer capacity, flame stability, heat transfer patterns and the combustible carry-over in fly ash. Furthermore, the higher the ash content, the more inert material must be collected in the boiler system and conveyed to disposal. If, for example, the ash content of a coal were to increase from 10% to 15%, the pulverizer would only have to grind 5% more coal to provide the same heat input to the boiler, but the boiler ash system would have to handle 57.5% more ash.

Volatile Matter

The portion of the coal that vapourizes when heated is defined as volatile matter. Using the ASTM Method, volatile matter contents range from >35% for a high-volatile bituminous to <18% for a low-volatile bituminous coal on a dry, mineral free basis; lignites and sub-bituminous coals are intermediate between these values.

It is important to note that: a) the actual volatile matter evolved during combustion can be as much as 25% higher than that given by the ASTM Method due to the ultra-rapid heating of coal particles in flames b) some of the volatile matter may be non-combustible H_2O, CO_2 or N_2 derived from the decomposition of mineral species and c) the type and quantity of the early volatiles varies with coal rank with CO, CO_2 and H_2O being evolved primarily from low rank coals and CH_4 and higher gaseous hydrocarbons being evolved primarily from high rank coals; d) late volatiles from all coals consist mostly of tarry compounds with the volatile tar yields being lower for bituminous than for low-rank coals.

Increases in both the total combustible volatile matter content and in the ratio of early to late volatiles produces improvements in ignition, flame stability and carbon burn-out as well as decreases in flame length and furnace size.

With low-volatile coals, special care must be taken to minimize flame instability, the risk of furnace explosions and poor carbon burn-out, particularly in water-cooled furnaces. In practice, satisfactory combustion performance can usually be achieved by adding refractory to the burner zone, by using an auxillary fuel to assist ignition and by increasing furnace size to increase burn-out. Low-volatile coals are therefore excellent fuels for kilns and refractory process furnaces.

Fixed Carbon

Fixed carbon is the char or coke that remains after evolution of volatile matter from coal. It should not be confused with the carbon content of coal, as determined by ultimate analysis, which also includes volatile matter carbon.

The speed of burn-out or reactivity of this carbonaceous residue is a critical parameter in designing burners and furnaces because the time-temperature profile of a flame significantly affects furnace heat transfer patterns. In general, the char or coke fraction consumes up to 90% of the time required for complete burn-out of a coal particle.

Char or coke resistivity varies with coal rank. Low rank coals invariably yield non-swelling, highly porous chars that burn readily. Bituminous coals, however, may be non-swelling or swelling. The non-swelling coals produce chars that tend to decrease in reactivity with increases in coal oxidation whereas the swelling coals produce highly porous, hollow coke particles or "cenospheres" which burn internally as well as externally. With swelling coals, the coke diameter in an oxidizing atmosphere and is about 10% larger than the parent coal, but this increase is not considered to have a major effect on the rate of coke burn-out.

Experience has shown that bituminous coals generally require finer grinding than low-rank coals for satisfactory burn-out and that oxidized bituminous coals are less reactive than unoxidized bituminous coals.

Maceral Forms

The maceral constituents of coal have a pronounced effect on combustion performance, and to some extent, the relative proportions of the different macerals present can be used to predict how easy a coal will burn. Although the maceral forms vary widely, depending on the source material of the plants and the geological history of the coal seam, three main groups-vitrinite, exinite and inertinite, are routinely identified by petrographic examination.

Vitrinite, which is derived from large fragments of wood and bark, usually contains little mineral matter. It expands when heated, exposing a large surface area that burns readily. When oxidized vitrinite does not swell and does not burn freely.

Exinite consists mainly of coalified spores, pollens and algae. It is high in resin and burns rapidly.

Inertinite is made up of fusinite and semi-fusinite, two components that appear to be derived from partially oxidized or charred walls of plant cells. It is characterized by a low-volatile content and a graphitized form of carbon which burns slowly without swelling. Sustained high temperatures are required to ensure complete combustion of inertinite.

Grindability

The energy required to grind a coal to a given fineness, usually 70% to 80% less than 75 μm, depends on total coal moisture, coal structure, mineral content and mineral hardness. The effect of each of these factors on grindability is too complex to evaluate separately, but a relative measure of the energy required for comminution in ball-race or roller-race type mills is given by the widely used Hardgrove Grindability Index (HGI). An index of 100, typical of a Rocky Mountain bituminous coal, denotes an easily ground coal whereas an index of 35, typical of an Alberta sub-bituminous coal, denotes a difficult coal to grind.

The HGI cannot be related directly to mill throughput, but it does provide a relative indication of the deterioration or improvement in mill performance that will occur if a change in coal supply to an existing boiler is contemplated. For example, mill throughput would decrease with substitute coals having either a) the same calorific value but a lower HGI than the design coal or b) the same HGI but a lower calorific value than the design coal.

An ample reserve in pulverizing capacity should be incorporated in all new boiler designs that may be subject to coal switching.

Calorific Value

The calorific value of a coal in North America is based on its higher heating value. In this determination the latent heat due to the combustion of hydrogen to water is added to the sensible heat even though the latent heat is not recovered in operating boilers.

European practice, however, defines the calorific value of the coal in terms of its net heating value or the higher heating value less the latent heat due to the combustion of hydrogen.

Accordingly, a given coal will have a reduced calorific value and a higher boiler efficiency in Europe than in North America.

Ash Fusion Temperature

The fusion or melting characteristics of coal ash are universally used to estimate the sintering (fouling) or melting (slagging) tendency of fly ash deposits. Since most of the ash that leaves a pulverized coal flame is molten or plastic, it is essential that the burner and furnace arrangement be designed to maximize solidification of ash particles prior to its contact with any boiler surfaces.

As ash fusion temperatures decrease, furnace volumes must be increased proportionally to prevent the build-up of intractable sinters or slag deposits. The most critical boiler zones are the furnace exit and the superheater where build-up of deposits can block the gas passages in a few hours. As shown in Figure 7, boilers designed for high moisture, low ash fusion Saskatchewan lignite are about 110% larger in volume than for a low-moisture, high-ash fusion bituminous coal.

Ash fusion data based on the ASTM Method, is a measure of the average behaviour of all ash components and is only an approximate guide to slagging potential. Many minor components, which are liquid at temperatures below the fluid temperature of the bulk ash may cement dry ash into a cohesive mass. As shown in Figure 8, selective deposition of ash components in boilers often results in a wide variation in ash fusion temperatures downstream of the burner.

One simple indicator of potential slagging (T_{ps}), incorporates the temperature spread between the minimum initial deformation (IT_{min}) and the maximum hemispherical ash softening (HT_{max}) temperatures as shown in Table 5. Usually fusion temperatures in a reducing atmosphere are lower than in an oxidizing atmosphere.

Elemental Oxide Composition of Ash

Eight major elemental oxides in coal ash (Al_2O_3, SiO_2, CaO, Fe_2O_3, MgO, Na_2O, K_2O and TiO_2) have been used with some success to predict both fouling and slagging of fly ash.

The degree of fouling has been found to depend roughly on the sodium oxide content of the ASTM ash as shown in Table 5. In recent work with low-rank coals, the organically bound sodium fraction has been identified as a better indicator of fouling potential than total sodium, but an empirical correlation has not yet been developed.

A popular indicator of ash slagging potential is the basic percentage of the coal ash oxides. This index, which is obtained by calculating the percentage of the basic oxides in the total ash, is defined as:

$$\text{Basic Oxides, \%} = \frac{CaO + Fe_2O_3 + Na_2O + K_2O}{CaO + Fe_2O_3 + Na_2O + K_2O + Al_2O_3 + SiO_2 + TiO_2}$$

Figure 9 shows the influence of the basic oxides in the ash from various rank coals on the hemispherical ash softening temperature in a reducing atmosphere. An examination of these curves indicates that lignitic and sub-bituminous coal with $SiO_2/Al_2O_3 >> 1$ achieve minimum softening temperatures with about 35% basic oxides whereas sub-bituminous coals with $SiO_2/Al_2O_3 \overset{\sim}{<} 1$ and western bituminous coals achieve minimum softening temperature with about 50% basic oxides.

The temperature ranges near the bottom of Curves 1 and 2 in Figure 9, should be avoided for drying firing systems but should be emminently suitable for slagging combustion.

A number of sophisticated methods are available for more accurate estimation of fouling and slagging; however, they require tedious, expensive experimental work.

Control of fouling has been achieved by intermittent additions of limestone which apparently dilutes the sticky build-up of ash particles by producing dry, layered deposits that are amenable to soot blowing. Slag control is much more difficult to achieve with additive additions because the melting and liquid propereties of the slag are altered by chemical reactions between the ash and additive. Insufficient additive treatment could accelerate fouling or slagging whereas excess additive treatment besides being expensive, contributes unnecessarily to the amount of ash in the combustion system.

Mineral Transformation During Combustion

The original mineral matter in coal is usually transformed in the flame into radically different sizes and species, that may impact on boiler availability.

Superfine dust, produced by volatilization of sodium and potassium compounds, can react with iron and sulphur to produce low-melting complexes that either initiate corrosion or act as a bonding agent to accelerate deposit build-up. If dry, a preponderance of fly ash in the 0.1 to 3.0 μm size range may adversely affect dust collector performance.

On the other hand, certain types of clay in coal are converted in the flame from soft, superfine particles into hard, coarse particles of abrasive mullite. With high-clay coals the concentrations of mullite or other abrasive compounds in the flue gas will result in serious tube erosion unless protective shields are used or gas velocities are kept low.

Sulphur

Western Canadian coals of all ranks generally contain less than 1% sulphur on a dry basis. During combustion sulphur in higher rank coals is almost totally converted to SO_2 with about 2% of the SO_2 being oxidized to SO_3. With lower rank coals all of the SO_3 and up to 70% of the SO_2 may be neutralized by alkaline and alkaline earth constituents in the parent coal ash.

Thus, condensed SO_3 is not a problem with low sulphur coals because concentrations are too low to cause corrosion of low-temperature boiler surfaces.

SO_2 emissions from either high or low rank coals can be significantly reduced by the injection of powdered limestne or alkaline compounds through or around the burner. Over 50% of the available SO_2 can be trapped by Ca/S mol ratios of 2 to 3.

The substitution of a low-sulphur for a high-sulphur coal or the continuous use of limestone with a high sulphur coal to control SO_2 emissions can, however, adversely affect precipitator performance. For example, the collection efficiency of a precipitator designed for a 3% sulphur coal may be reduced by up to 30% when SO_3 is absent in the flue gas.

Chlorine

The chlorine in western Canadian coals is mostly present as inorganic salts and is normally less than 0.1%. At this level chlorine has no detrimental effect on boiler availability but when levels exceed 0.3% corrosion of boiler tubes will occur. For this reason the use of chloride salts to prevent freezing of wet coal warrants a thorough evaluation before implementation.

Nitrogen

A major precursor of acid rain, NO, is produced by the oxidation of coal nitrogen in flames. About 80% of the total NO emitted during combustion is generated from fuel nitrogen with the balance being formed by fixation of nitrogen in the combustion air. Experimental research has shown that 25% to 40% of the fuel nitrogen is converted to NO and that most of this NO is generated during the combustion of nitrogen evolved with the volatile coal fraction. The nitrogen in the char or coke fraction, which rarely exceeds 20%, is only a minor source of NO.

These mechanistic studies of NO formation from pulverized coal flames have resulted in the development of staged combustion systems which provide a fuel for rich zone for the rapid evolution of volatile fuel nitrogen followed by an oxidizing zone having a temperature regime that is low enough to minimize conversion of air nitrogen to NO, but is still high enough to produce acceptable char or coke burn-out. A staged burner concept for simultaneous reduction of both NO_x and SO_x is shown in Figure 10. Although developed for front wall firing the same concept is applicable to tangential firing. It should be noted that the absolute degree of NO reduction with tangential firing, which is already an inherently low NO producer, may not be as great as for front wall firing.

Slagging Systems

Except as noted in this section, the effects of coal properties on combustion, as described for dry firing, are also applicable to slagging systems.

Slagging systems differ from dry systems in that furnace temperatures must be high enough to allow the removal of 70% or more of the ash as a liquid. Key factors that impair slag flowability are fuel moisture levels which lower flame temperatures and ash composition which decrease slag fluidity.

The main advantages of slagging systems are:

a) low ash fusion coals can be burned without decreasing boiler availability;
b) high-inertinite, low-volatile coals can be burned with stable flames and good burn-out and
c) dust collectors are only required to handle 20% to 30% of the input ash.

The problem areas with slagging systems include:

a) slag freezing due to minor excursions in ash composition;

b) large amounts of dry, superfine fly ash, with a narrow size range that agglomerates into cohesive deposits on heat transfer surfaces, in ducting and in dust collectors and

c) inability to burn moderate and high ash fusion coals.

Fluidized-Bed Combustion

This is a new technology which is on the verge of commercial application. It offers the advantages of economy, efficiency, low pollutant emission, and perhaps most important of all, insensitivity to coal properties. Furthermore, it seems to be applicable to small commercial boilers as well as large utility steam generators. Although fluidized-bed combustors have been in commercial use for about ten years as incinerators for various waste products, to date they have been fired with coal only in small pilot plants and in prototype steam boilers.

In a fluidized-bed combustor, a bed of granular material is placed in a container with a perforated bottom. Air or some other gas is forced through the perforations at a 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 upward flow of gas bubbles as shown in Figure 11. This creates intense mixing and, if there is a thermal gradient, rapid heat exchange.

To initiate combustion, the fluidizing medium must contain oygen, and the bed must be preheated to the ignition temperature of the fuel. When these two conditions are met, fuel introduced into the bed will burn rapidly because of the intense mixing, even though its concentration relative to the bed material may be very low. It is, therefore, relatively easy to control the temperture at which combustion proceeds. A bedtemperature of 800°C to 900°C is adequate for complete combustion, but is below the ash fusion temperature of most coals; thus, problems related to slagging of the ash are avoided.

If crushed limestone is used as a bed material, it will react with and capture much of the sulphur in the fuel. Thus, the fluidized-bed combustor offers an effective technique for reducing SO_2 emissions.

The rate of heat transfer to heat exchange surfaces exposed to or immersed in the fluidized bed is about five times greater than that from combustion gases to tubes in conventional furnaces; this permits a substantial reduction in heat exchange area for a given steaming capacity.

Fluidized-bed combustion has the potential for widespread application in the Canadian energy picture in that it can efficiently burn high-sulphur fuels, high-ash coaly waste, unreactive chars and cokes from oil sand refining and biomass fuels such as wood refuse. Although the technology is not yet fully developed, systems burning up to 15 tons of coal per hour may be commercially available in one to two years, but large utility-size systems burning upwards of 50 tons per hour are not likely for 5 to 10 years.

CLOSURE

The safety, availability and efficiency of conventional industrial and utility combustion systems are strongly dependent on the physico-chemical properties of the coal being burned. Existing installations designed for a specific coal will usually tolerate only minor excursions in coal quality and still perform at rated capacity.

In the design of new suspension firing systems, allowance should be made for burning off-specification coals. This is particularly important because coals from captive mines may deteriorate in quality and export coals of the desired quality may not always be available.

Future technologies for large-scale coal burning, to be successful, must be relatively insensitive to wide swings in fuel properties. Fluidized-bed combustion is one developing technology which shows promise of being able to cope with variable quality, low-grade fuels.

TABLE 1 - SUMMARIZED CLASSIFICATION OF COAL BY RANK

VM*	FC*	Class	Group (rank)	Calorific value**	
				Btu/lb	MJ/kg
8	92	Anthracitic(1)	Anthracite		
14	86		Semianthracite		
22	78	Bituminous(2)	Low volatile bituminous		
31	69		Medium volatile bituminous		
			High volatile A bituminous	14,000	32.6
			High volatile B bituminous	13,000	30.2
			High volatile C bituminous	11,500	26.7
		Subbituminous(4)	Subbituminous A(3)	10,500	24.4
			Subbituminous B	9,500	22.1
			Subbituminous C	8,300	19.3
		Lignitic(4)	Lignite A	6,300	14.7
			Lignite B		

*Dry, mineral-matter-free basis; VM = Volatile matter; FC = fixed carbon.
**Moist, mineral-matter-free basis.

(1) Nonagglomerating; if agglomerating classified as low volatile bituminous.

(2) Commonly agglomerating.

(3) If agglomerating classified as high volatile C bituminous

(4) Nonagglomerating.

TABLE 2

TYPICAL PROPERTIES OF WESTERN CANADIAN COALS

RANK	PROXIMATE ANALYSIS, %						CV	HGI
	M	A	VM	FC	S	N	MJ/KG	
LIGNITE	27	10	30	33	0.6	0.9	18.1	51
SUB-BITUMINOUS	20	12	28	40	0.2	0.7	19.4	43
HIGH VOLATILE BITUMINOUS	11	12	33	44	0.5	1.6	25.8	46
MEDIUM VOLATILE BITUMINOUS	8	21	55	16	0.3	1.0	26.2	91
LOW VOLATILE BITUMINOUS	5	13	20	62	0.3	1.1	28.4	100
SEMI-ANTHRACITE	7	10	11	72	0.7	1.6	29.6	82

TABLE 3

TYPICAL ASH PROPERTIES OF WESTERN CANADIAN COALS

PROPERTY	COAL RANK					
	LIG	SUB-BIT	HVBIT	MVBIT	LVBIT	SEMI-ANTH
ASH COMPOSITION, %						
CaO	17	13	8	2	1	1
MgO	4	1	2	<1	<1	1
Fa_2O_3	4	5	5	2	3	3
Na_2O	8	3	<1	<1	<1	<1
K_2O	<1	<1	1	<1	<1	2
Al_2O_3	27	24	21	29	30	26
SiO_2	32	48	55	62	61	63
TiO_2	<1	<1	<1	<1	<1	2
SO_3	10	3	3	<1	<1	1
ASH FUSION TEMP, °C						
REDUCING ATM						
INITIAL	1160	1320	1120	1480	1480	1480
HEMISPHERICAL	1215	1385	1230	+	+	+
FLUID	1270	1430	1250	+	+	+
OXIDIZING ATM						
INITIAL	1360	1335	1205	1480	1480	1480
HEMISPHERICAL	1425	1390	1315	+	+	+
FLUID	1450	1445	1420	+	+	+

TABLE 4

COAL PROPERTIES INFLUENCING COMBUSTION

1. Moisture
2. Ash
3. Volatile Matter
4. Fixed Carbon
5. Maceral Forms
6. Grindability
7. Calorific Value
8. Ash Fusion Temperatures
9. Ash Composition
10. Mineral Transformations
11. Sulphur
12. Chlorine
13. Nitrogen

TABLE 5

POTENTIAL SLAGGING TEMPERATURE

SLAGGING CATEGORY	POTENTIAL SLAGGING TEMPERATURE, ^{o}C
LOW	> 1340
MEDIUM	1340-1230
HIGH	1230-1150
SEVERE	< 1150

POTENTIAL SLAGGING TEMP., ^{o}C

$$= \frac{HT_{MAX} + 4IT_{MIN}}{5}$$

WHERE HT_{MAX} = MAXIMUM HEMISPHERICAL SOFTENING TEMPERATURE

IT_{MIN} = MINIMUM INITIAL DEFORMATION TEMPERATURE

TABLE 6

ASH FOULING INDEX		
FOULING CATEGORY	% Na_2O IN ASH	
	$\frac{CaO + MgO}{Fe_2O_3} \leq 1$	$\frac{CaO + MgO}{Fe_2O_3} > 1$
LOW	< 0.5	< 2.0
MEDIUM	0.5-1.0	1.0-6.0
HIGH	1.0-2.5	6.0-8.0
SEVERE	> 2.5	> 8.0

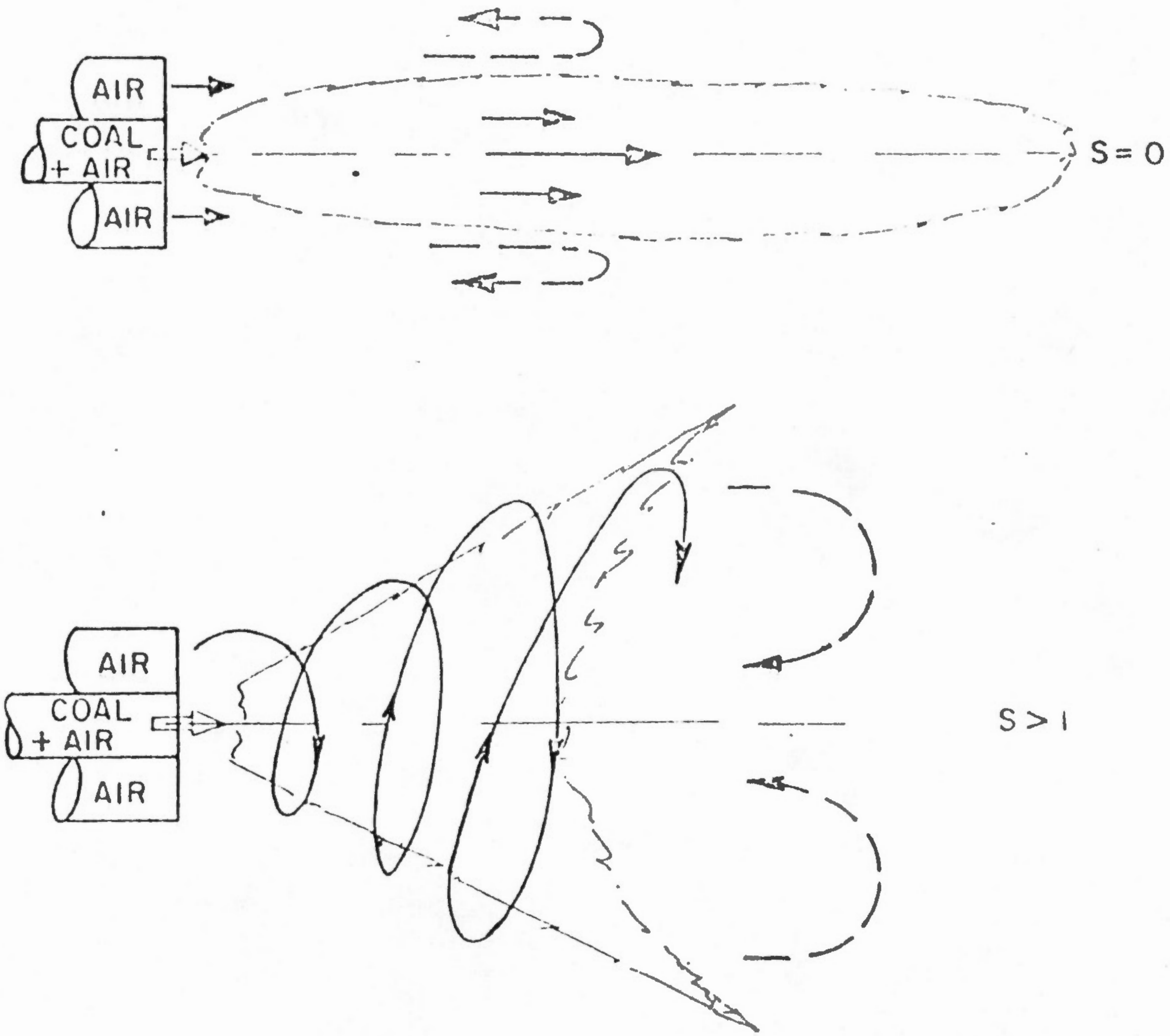


FIGURE 1: EFFECT OF SWIRL ON FLAME GEOMETRY

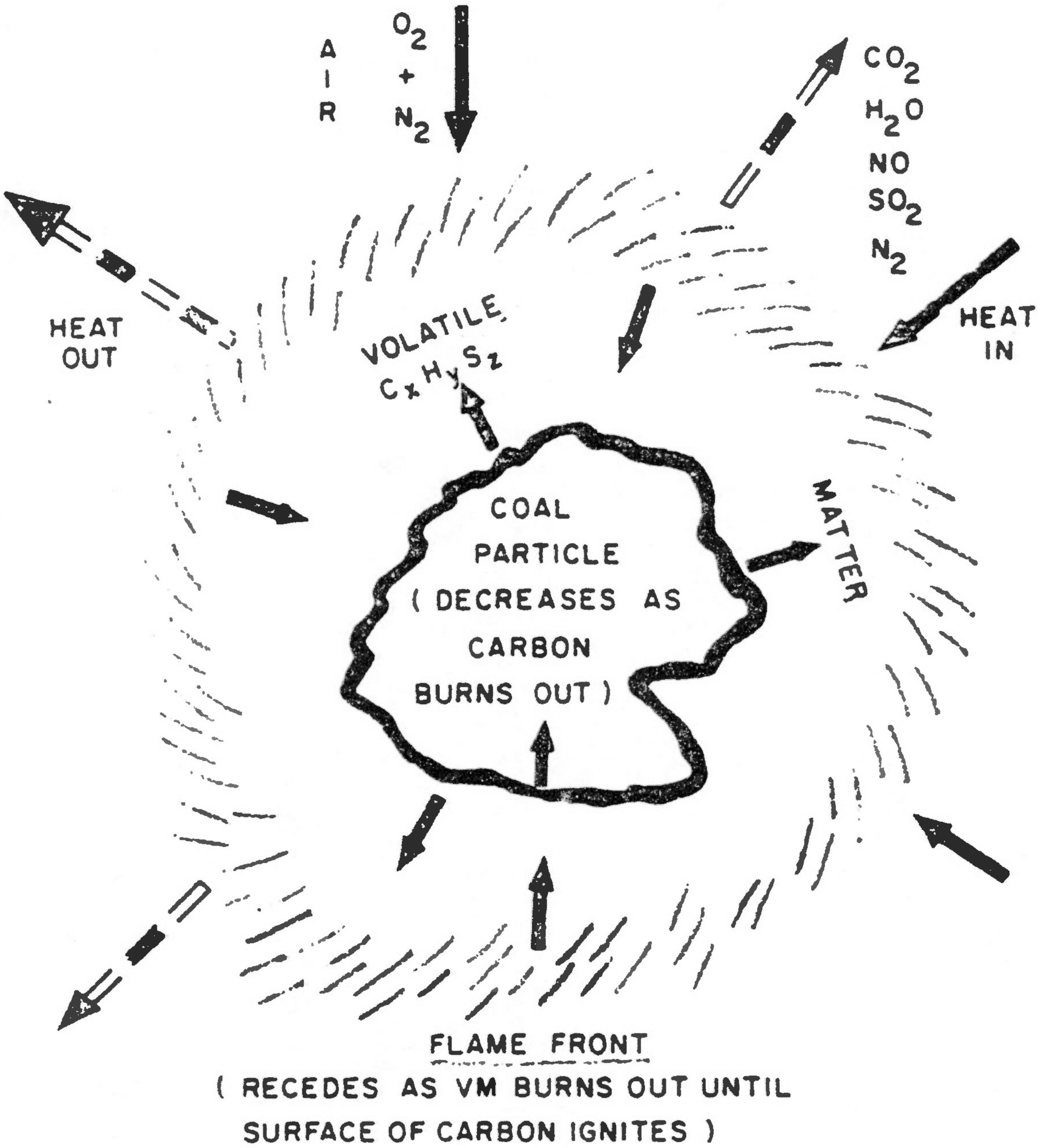


FIGURE 2 - SIMPLE COMBUSTION MODEL OF BURNING COAL PARTICLE

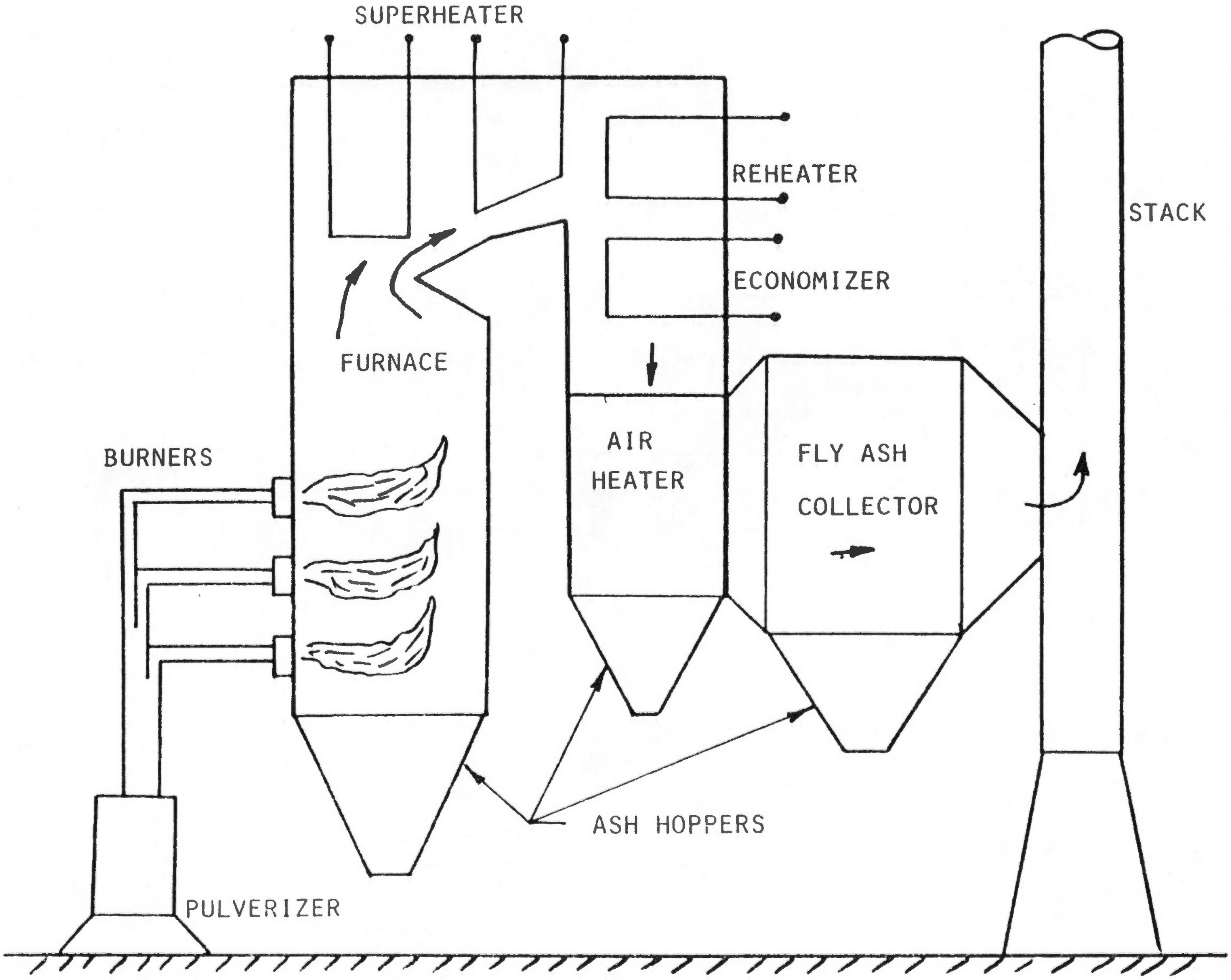


FIGURE 3 - FRONT-WALL FIRED BOILER

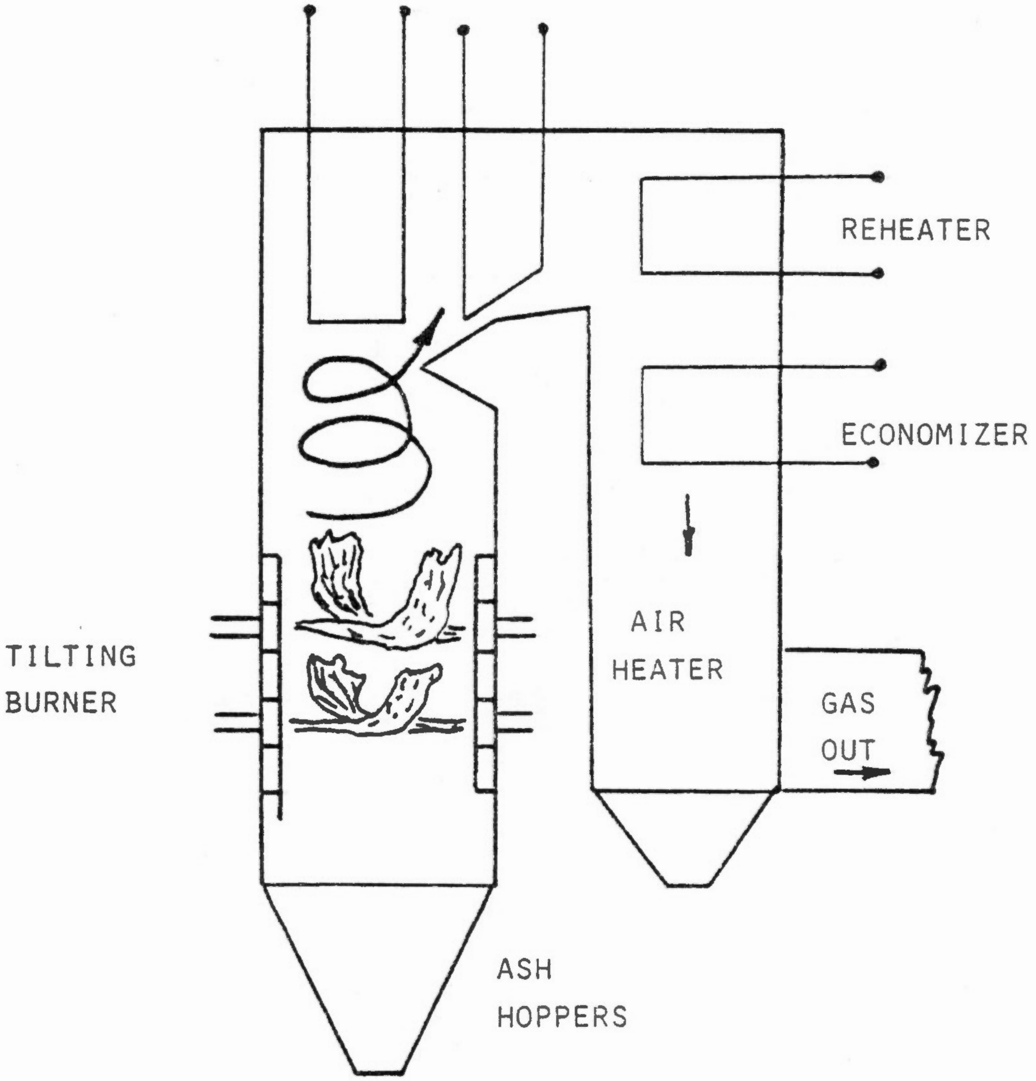


FIGURE 4 - CORNER-FIRED BOILER

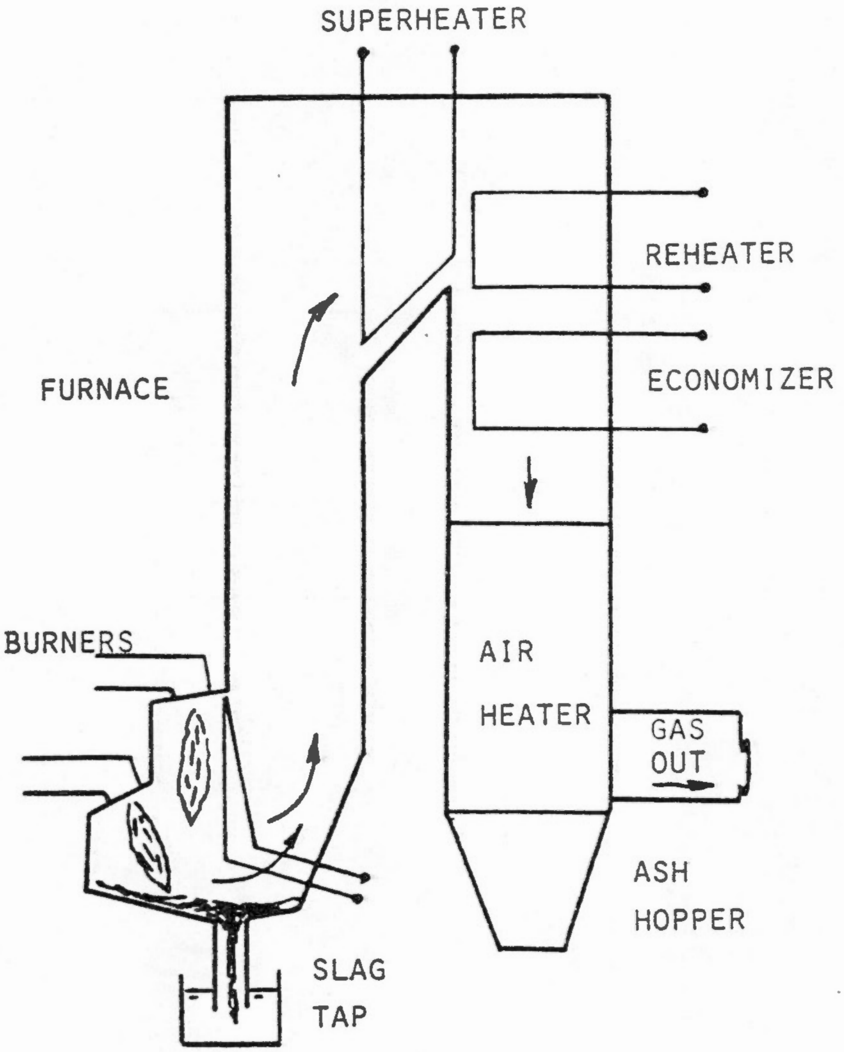


FIGURE 5 - ROOF-FIRED BOILER-WET BOTTOM

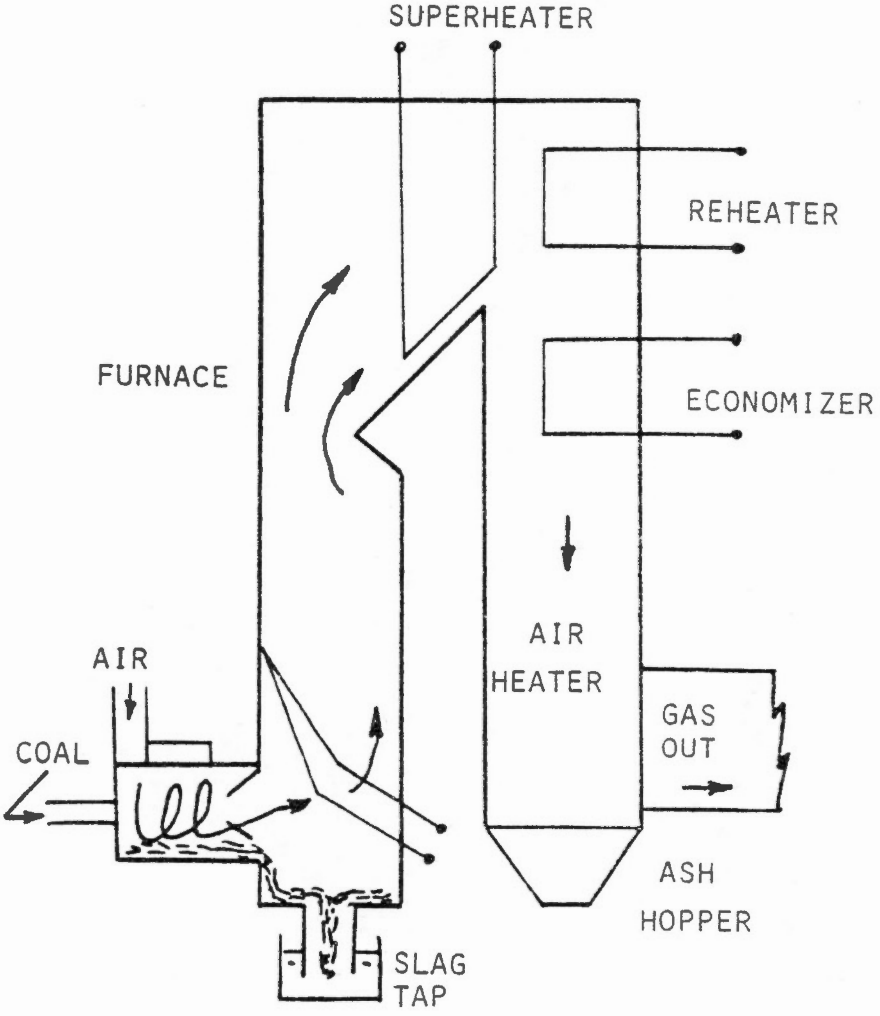
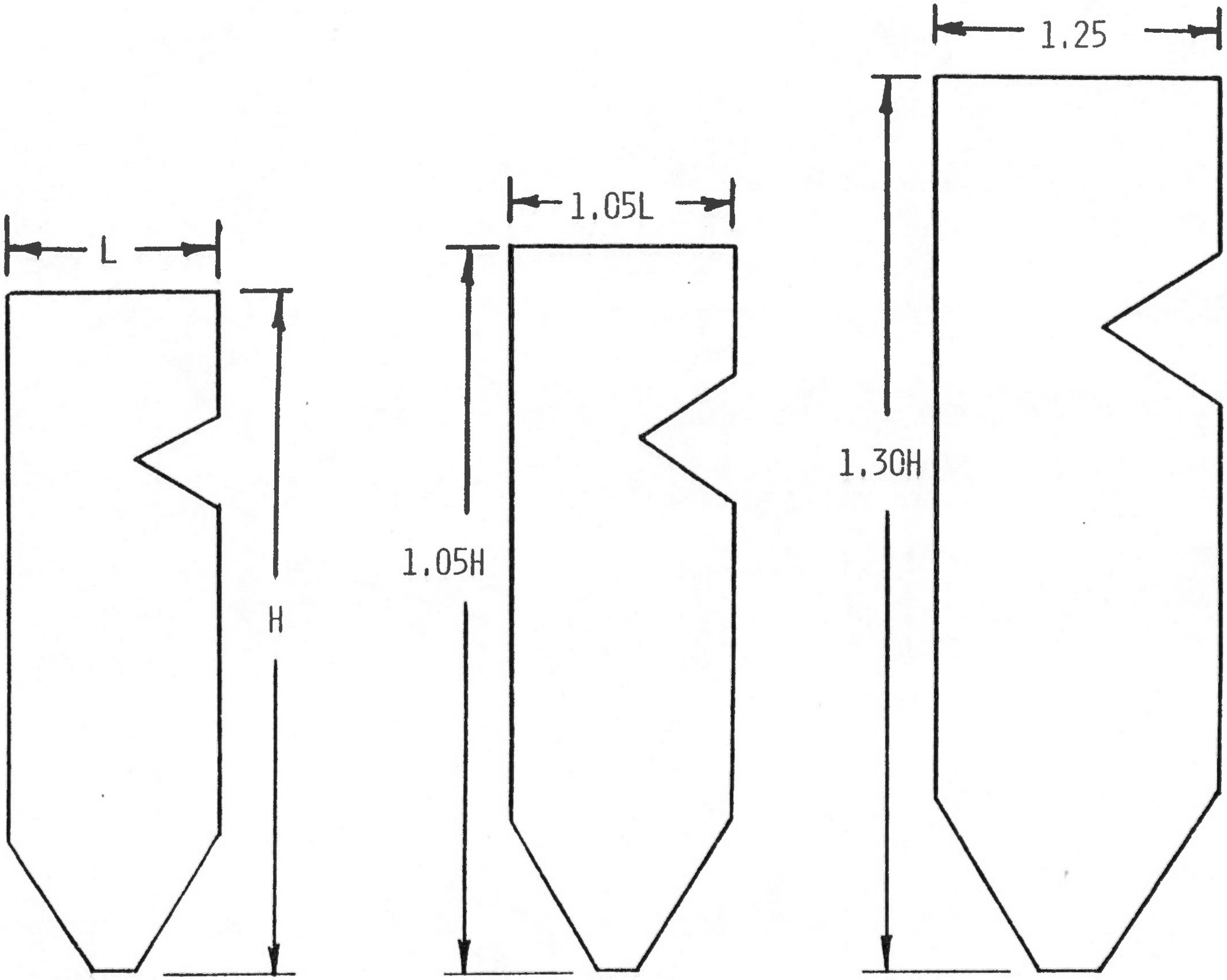


FIGURE 6 - CYCLONE-FIRED BOILER



MV BITUMINOUS

SUB-BITUMINOUS

LIGNITE

FIGURE 7 - RELATIVE FURNACE SIZES FOR DIFFERENT COAL RANKS

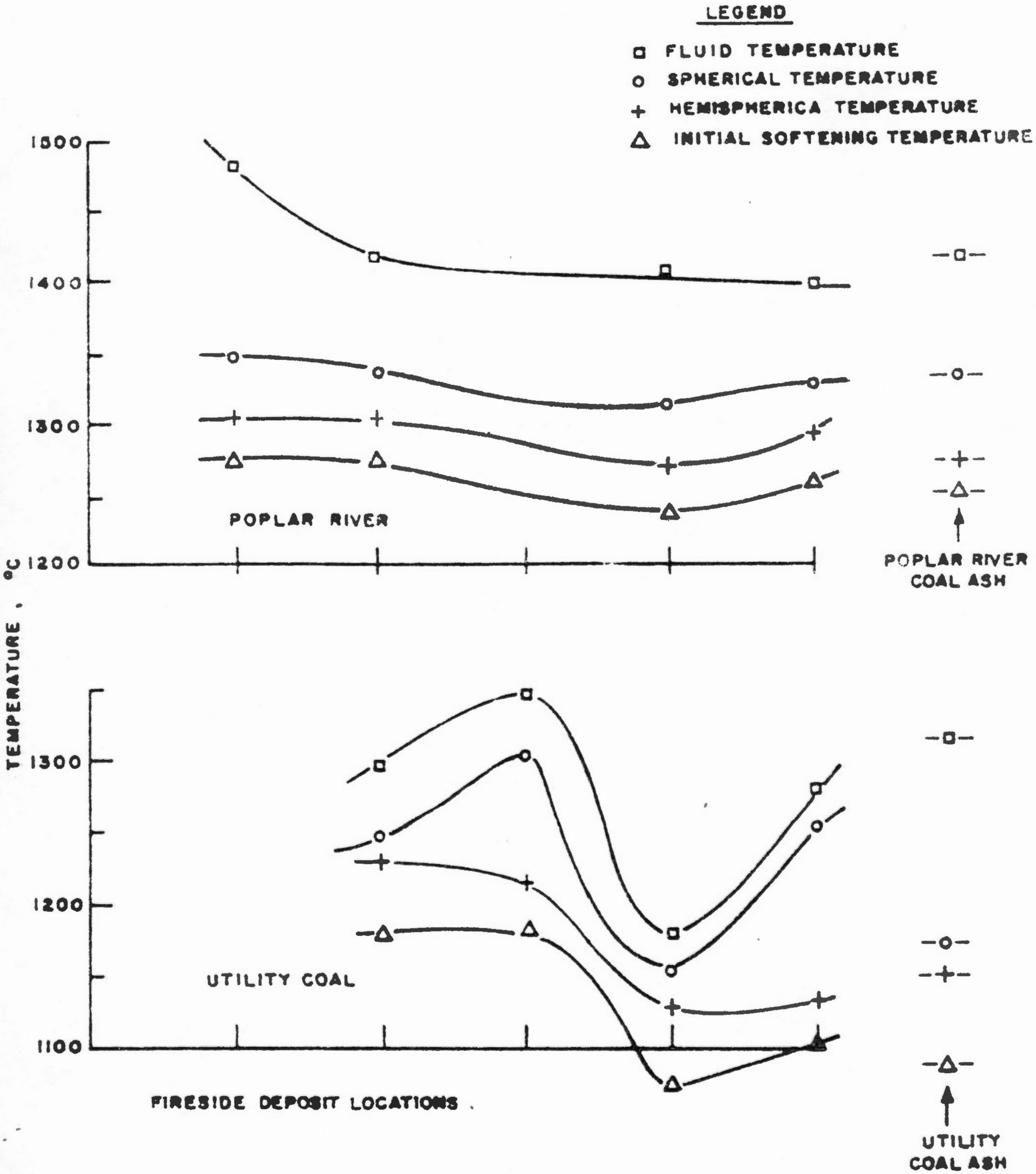
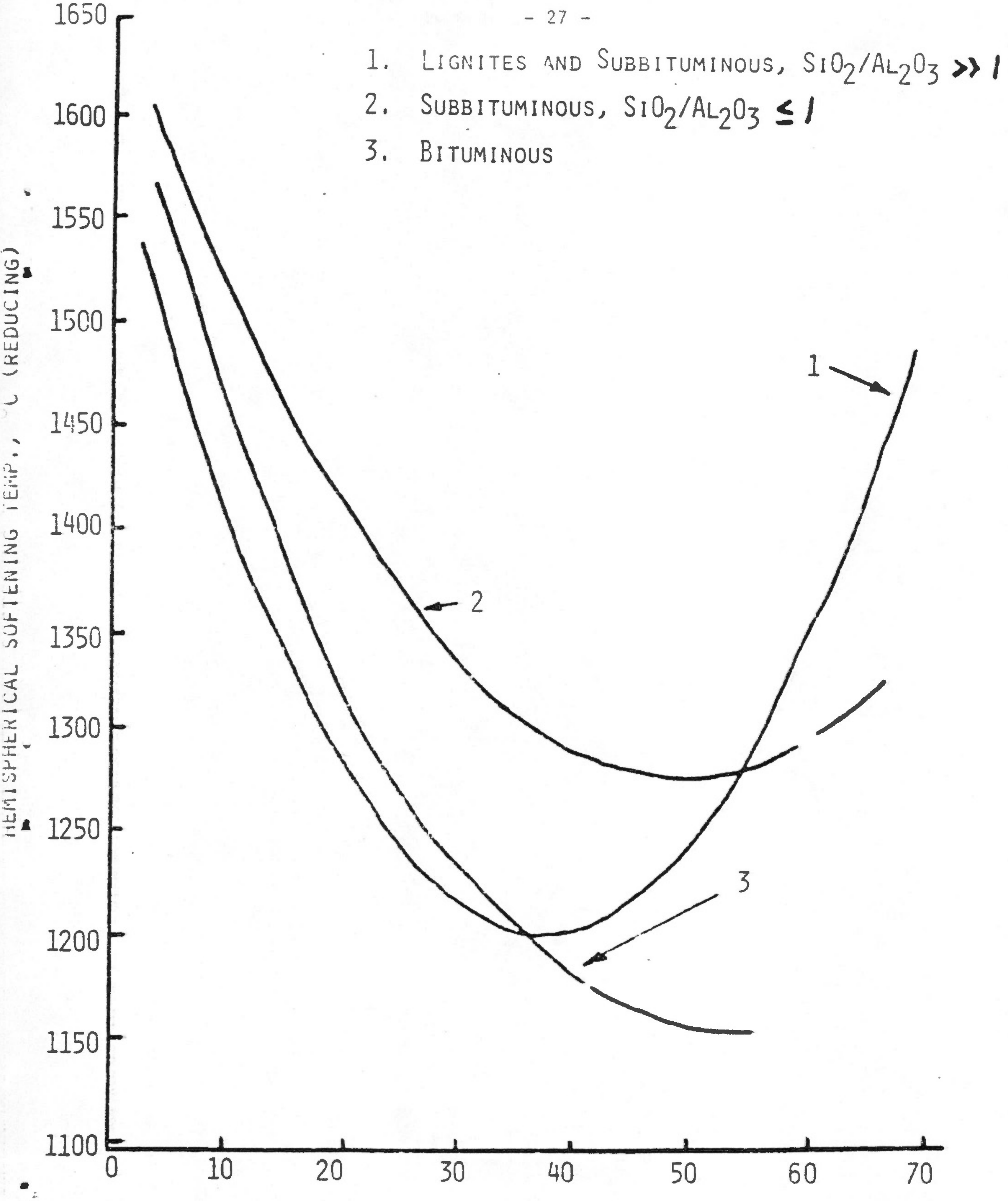


FIGURE 8 - FUSION TEMPERATURES OF DEPOSITS AT VARIOUS BOILER LOCATIONS



$$\frac{\text{BASIC}}{\text{BASIC + ACIDIC}} = \frac{(Fe_2O_3 + CaO + MgO + Na_2O + K_2O)}{Fe_2O_3 + CaO + MgO + Na_2O + K_2O + Al_2O_3 + SiO_2}, \%$$

IGURE 9 -

INFLUENCE OF BASIC CONSTITUENTS IN ASH ON ASH SOFTENING TEMPERATURES FOR DIFFERENT COALS.

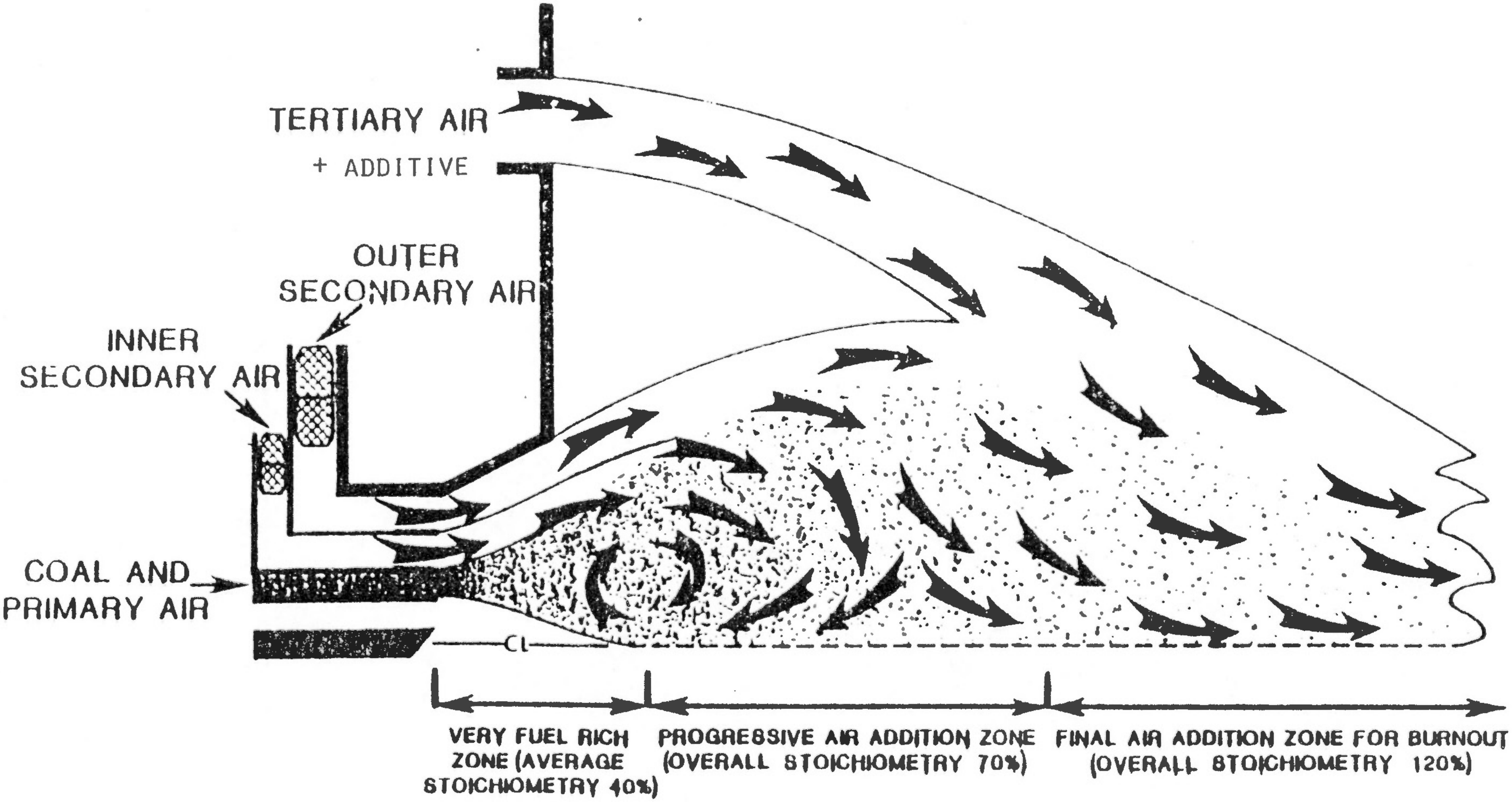


FIGURE 10 - STAGED MIXING BURNER CONCEPT FOR SIMULTANEOUS REDUCTION OF SO_X AND NO_X

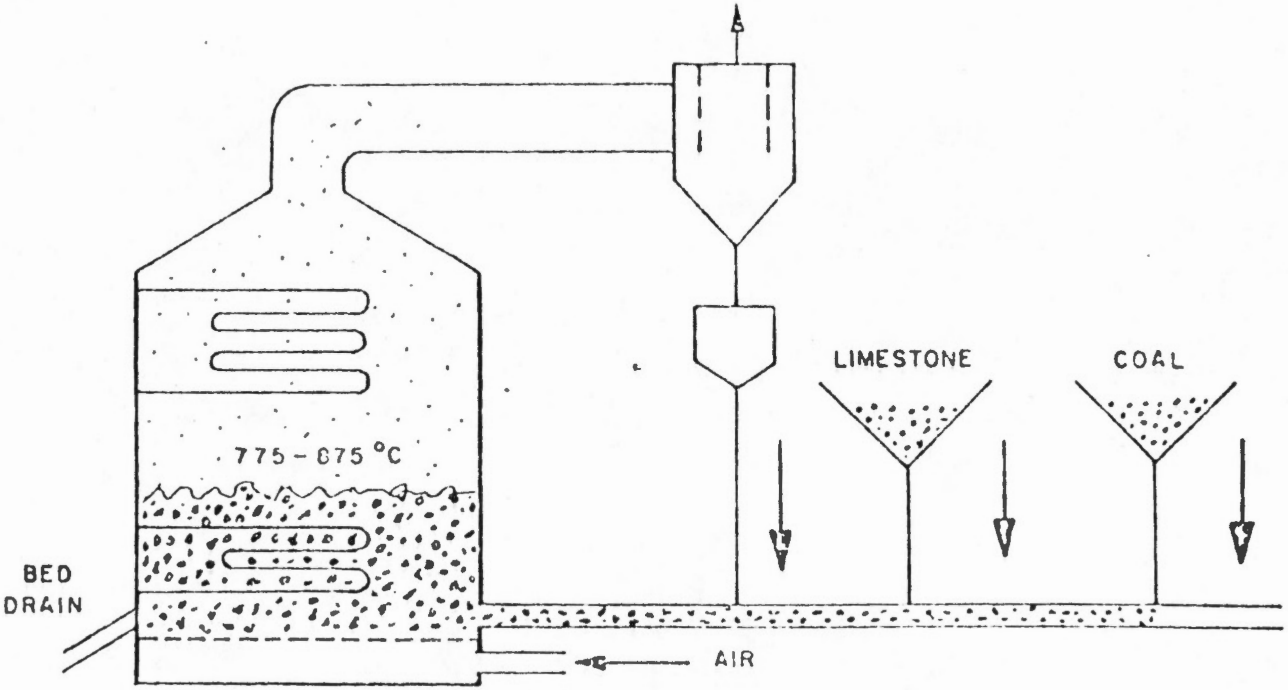


FIGURE 11 : SCHEMATIC OF FLUIDIZED-BED COMBUSTOR