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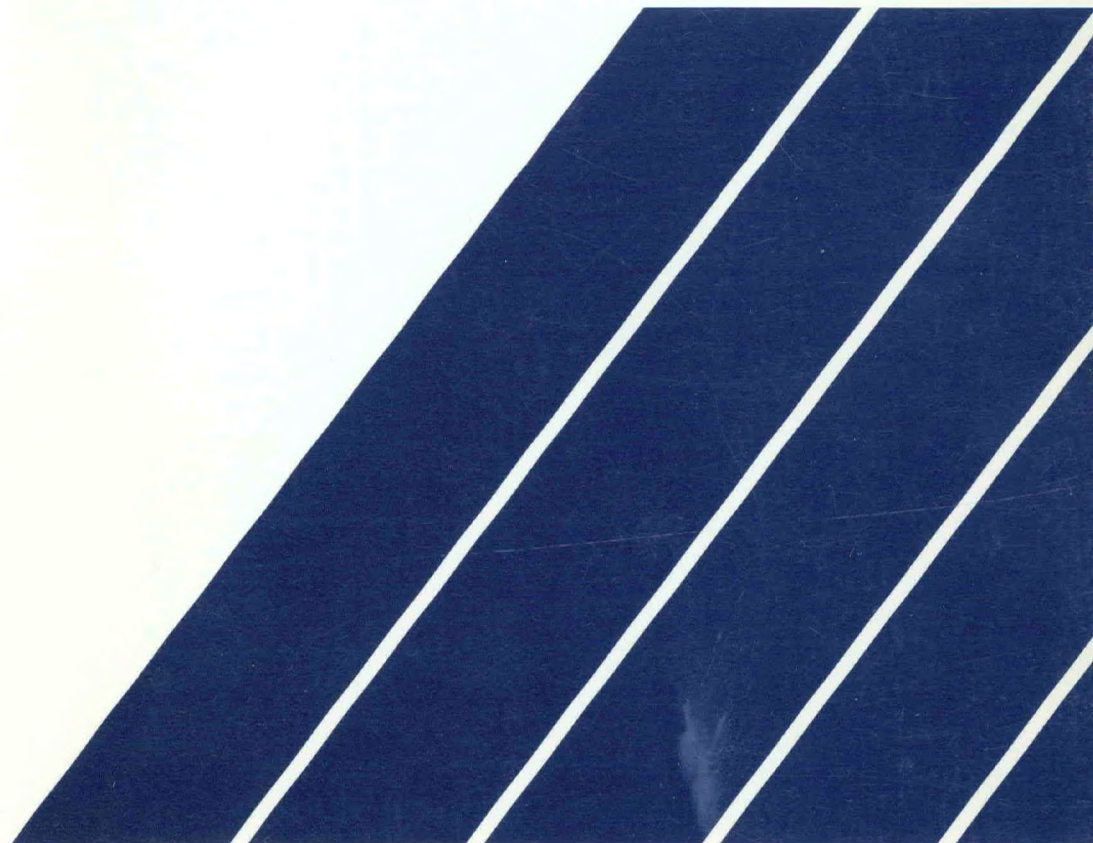
COMBUSTION OF PIPELINEABLE COAL-WATER SLURRIES

H. Whaley, K.V. Thambimuthu, G.N. Banks
and J.K.L. Wong

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COMBUSTION OF PIPELINEABLE COAL-WATER SLURRIES

by

H. Whaley*, K.V. Thambimuthu**, G.N. Banks** and J.K.L. Wong***

ABSTRACT

The use of liquids or fluids to transport coal through pipelines is not
new, nor is the application of coal liquid slurries as fuels in industrial
combustion systems. However, it does appear that there are a number of
conflicting areas which preclude coals from performing well in a pipeline
transportation mode and as a coal-liquid fuel (CLF). Many factors influence
the flow of coal as a slurry inside a pipe whether it be over long distances
or from the storage tank to the burner. To disperse coal particles in water
to form a slurry that will not only atomize well to give high combustion
efficiencies, but also can be readily pumped over long and short distances may
be a very difficult task. Higher rank coals perform well in pipeline
transportation slurries. They require less additives to stabilize and
disperse the coal particles in the water to form the slurry. However, from a
combustion viewpoint, higher rank coals are more difficult to ignite and burn,
mainly due to their lack of volatility. Conversely, as the rank decreases,
the increased volatility enhances ignition and combustion, making a good coal
slurry fuel. They are, however, not as good a pipeline slurry because of the
lower thermal loading (thermal content per unit mass of material being
conveyed) and the fact that they require more additives to produce the desired
rheological properties for pipelining.

As part of a continuing program to evaluate the pipelineability and
combustibility of CLF, pipelineable slurries made from two Western Canadian
foothills coals were assessed in CANMET's pilot-scale research boiler. A
commercial CLF was used as a reference fuel. These combustion tests indicated
that there were some difficulties in ignition, flame stability and combustion
with both pipeline slurries. The better combustion performance of the two
pipeline slurries was achieved with that having the lowest thermal loading and
consequently the poorest properties for pipelining. One of the major problems
with both batches of slurry was their settling in transit which led to
agglomeration of particles and inevitably to the poor atomization and
combustion efficiency. Subsequent tests, conducted at CANMET on a properly
managed fuel shipment, showed excellent atomization and combustion
characteristics.

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COMBUSTION DE SUSPENSIONS CHARBON-EAU TRANSPORTABLES PAR PIPELINES

par

H. Whaley*, K.V. Thambimuthu**, G.N. Banks** et J.K.L. Wong***

RÉSUMÉ

L'utilisation de liquides ou de fluides pour transporter du charbon par des pipelines n'est pas nouvelle, tout comme l'application de suspensions de charbon dans un liquide comme combustibles dans les systèmes de combustion industriels. Toutefois, il existe, semble-t-il, un certain nombre de domaines où le transport efficace par pipeline et l'utilisation de suspensions de charbon sont impossibles. Nombreux sont les facteurs qui influent sur l'écoulement du charbon en suspension dans une canalisation, tant pendant le transport à grande distance qu'au cours du transport entre un réservoir de stockage et un brûleur. La dispersion des particules de charbon dans de l'eau en vue de préparer une suspension qui s'atomise bien, qui constitue un combustible très efficace et qui peut être facilement pompée sur des distances tant grandes que petites peut représenter une tâche très difficile. Les charbons de rang élevé permettent de préparer des suspensions facilement transportables par pipelines, les quantités d'additifs nécessaires pour stabiliser et disperser les particules de charbon dans l'eau étant alors moindres. Toutefois, du point de vue de la combustion, les charbons de rang élevés'enflamment et brûlent plus difficilement, principalement en raison de leur faible volatilité. Inversement, comme une diminution de rang se traduit par une accroissement des caractéristiques d'inflammation et de combustion, les suspensions préparées avec des charbons de rang moins élevé constituent de bons combustibles. Toutefois, ces suspensions sont plus difficilement transportables par pipelines, en raison de leur charge thermique plus faible (quantité de chaleur par unité de masse de suspension transportée) et des plus grandes quantités d'additifs qu'il faut ajouter pour obtenir les propriétés rhéologiques voulues pour le transport par pipelines.

Dans le cadre d'un programme permanent d'évaluation de la transportabilité et de la combustibilité des suspensions de charbon, nous avons étudié des suspensions transportables par pipelines, préparées à partir de deux charbons provenant des contreforts de l'Ouest canadien, dans la chaudière pilote du CANMET. Nous avons utilisé comme combustible de référence une suspension commerciale. Selon les résultats des essais de combustion, les deux suspensions étudiées présentaient certaines difficultés pour ce qui est de l'inflammation, de la stabilité de la flamme et de la combustion. La suspension qui présentait les meilleures caractéristiques de combustion était également celle qui possédait la plus faible charge thermique et, par conséquent, celle qui était la plus difficilement transportable par pipelines. La précipitation des particules de charbon pendant le transport, qui entraînait l'agglomération des particules et se traduisait inévitablement par une atomisation et une combustion peu efficaces, constituait l'un des principaux problèmes observés avec les deux suspensions étudiées. Les caractéristiques d'atomisation et de combustion, déterminées au cours d'essais ultérieurs réalisés au CANMET avec un lot de combustible traité de façon appropriée, étaient excellentes.

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INTRODUCTION

Under an agreement between Canada and Germany, the Canada Centre for Minerals and Energy Technology (CANMET) and the Alberta Office of Coal Research and Technology (AOCRT) collaborated with the German government in a research, development and demonstration program on coal slurry manufacture, transportation by pipeline and utilization in boilers. The objective of this program was to use Alberta foothills bituminous coals as a feedstock for producing coal-water slurries for pipelining and combustion applications. Another paper being presented at this conference deals with the manufacturing and pipelining aspects of the project (1). The Combustion and Carbonization Research Laboratory (CCRL) of CANMET's Energy Research Laboratories evaluated the combustion performance of two coal-water slurries prepared from Alberta foothills coals. A commercial coal-liquid fuel (CLF) prepared from Eastern Canadian bituminous coal was used as a reference fuel. A 5000 tonne sample of this reference CLF had been used for a demonstration test-burn in a 20-MWe compact oil-designed boiler in Charlottetown, PEI. (2) and in a coal-water fuel burner demonstration at Chatham, NB (3).

COAL PROPERTIES AFFECTING PIPELINING AND COMBUSTION

The best choice for a pipelineable slurry is a high-rank bituminous coal because it has the highest calorific value and hence maximizes the energy transported per unit weight. It is also clear that high-rank coals require a lower quantity of additives to stabilize and disperse the coal particles in the slurry due to their low oxygen/carbon (O/C) atomic ratio, which relates to moisture absorption and porosity as noted below. However, from a combustion viewpoint, higher rank coals are more difficult to ignite and burn due to their lower volatility and higher carbon/hydrogen (C/H) ratio. The devolatilization products of high-rank coals do not tend to support ignition phenomena, especially when water is present in the proportions required for pipelining or transportation to the burners as a liquid.

The skeletal structure and apparent densities of candidate coals should be measured mainly to determine porosity. The porosity usually affects the distribution of surface and pore moisture in the CLF, Fig. 1 and 2. A higher porosity, and hence a greater concentration of pore moisture would reduce the solids loading and ignition stability of the slurry (4). Because porosity is often linked to a tendency for increased oxidation, the oxygen content may also serve as an indicator. In addition, the oxygen content increases the amount of chemical additive required to produce a CLF with an acceptable rheology. In most cases, a high oxygen content will also reduce the calorific value and the coal volatiles that are so crucial to the ignition stability of the fuel.

Since it is difficult to delineate natural coals by rank alone, coal selection may be achieved by evaluating all or some of the following parameters:

- fixed carbon, hydrogen and C/H ratio
- combustible, volatile content
- composition and calorific value of the volatiles evolved in an inert atmosphere
- higher heating value
- inert maceral content, i.e., stable forms of carbon
- oxygen content
- free swelling index

In evaluating a coal for combustion as a slurry, ignition stability of the fuel is the most critical requirement for its efficient combustion in a boiler. For coal-liquid fuel (CLF), the moisture content and coal volatility are the most significant fuel selection parameters for good ignition stability. The fuel moisture delays ignition by retarding droplet drying and heating, whereas the coal volatile content and composition determine the onset of fuel ignition and flame propagation at the burner mouth.

Typically, an increased moisture content in the CLF usually dictates a higher volatile content coal and higher calorific value gaseous products (from devolatilization) for stable ignition. For conventional 70% solids CLF,

intermediate-rank, bituminous coals with a volatile content >30 wt % are necessary for the stable ignition of CLF. These requirements also vary somewhat with the fuel spray quality, and burner design parameters such as length to diameter ratio of the quarl. Due to the absence of a reliable data base on high moisture generic CLF, it is necessary to evaluate ignition behaviour in pilot-scale combustion tests.

Another important aspect of slurry combustion is the overall fuel carbon conversion efficiency which is determined by gas temperature, excess oxygen, and residence time available for char burnout in the boiler. For CLF, the moisture can reduce the flame temperatures by up to $200^{\circ}C$ and this has a great bearing on char burnout. For retrofit applications in an oil-designed boiler, the higher gas volume required for coal combustion and the smaller boiler volume reduces the char residence time. With these negative effects for which little can be done, it is important to select coals with less stable forms of carbon. This selection may be expedited by a petrographic evaluation of candidate coals.

Besides the above parameters, carbon burnout in CLF combustion is also affected by the morphology of the char and ash particles. A recent study has shown that coarse char cenospheres formed in the CLF flame envelope contribute significantly to the unburnt carbon emissions from the boiler (5). This effect is caused by entrainment of the low apparent density chars. It was found that the carbon emissions from the boiler could be improved by coal selection to reduce the free swelling index and by improved fuel atomization (3).

Ash behaviour has been shown to be quite different when comparing CLF with pulverized coal (6). The sintering temperatures (or ash fusion temperatures) in an oxidizing and reducing environment are important in determining the slagging and fouling propensity of the ash. High sintering temperatures minimize the tendency to slag on furnace panels, and in forming hard sintered deposits on heat transfer tubes which could be difficult to remove by soot blowing. The sintering temperatures are often determined by the chemical composition of the ash, and increase with the acid oxide ratio, i.e., the fraction of SiO_2/Al_2O_3 and decrease with the base percentage, i.e., the total fraction of Fe_2O_3, CaO, MgO, Na_2O and K_2O. Usually, a minimal tendency for ash slagging and fouling established in a pulverized coal firing

environment would be an adequate criterion for safe application as a CLF. However, due to the fundamentally different morphology of the CLF ash (5), pilot-scale combustion tests to evaluate the ash properties are recommended. Where practical, the fuel ash content should be minimized to reduce the risk of erosion damage in the boiler, for improved heat transfer and reduced frequency of operation of soot blowers.

Table 1 and Fig. 3 to 5 show the proximate and ultimate analyses of the two coals which have been formulated into slurries for pipelining applications. The analyses of the parent coal feedstock for the CBDC Carbogel is also given for comparison, since considerable boiler operating experience in Canada exists with this fuel. Table 2 and Fig. 6 show the C/H ratio and also the fuel ratio, fixed carbon/volatile matter (FC/VM), of the various coals. The high-volatile bituminous (HVB) coal has a serious drawback due to low calorific value and high oxygen content. In terms of pipelining it is debatable whether it could be considered, since the amount of thermal content per unit weight is much lower due to the high oxidation level. On the other hand the medium-volatile bituminous (MVB) coal is a poor combustion candidate because of its lower volatile content, and the volatiles being of higher O_2 content means poorer ignition stability. For these reasons a blend of these two coals was considered for testing (slurry B).

From the combustion and transportation viewpoints the coals can be provisionally ranked as follows:

	Combustion	Pipeline transportation
1)	CBDC	MVB
2)	HVB	CBDC
3)	MVB	HVB

Additional analyses involving detailed petrographic examination, porosity, free swelling index and composition volatiles are required, as are combustion evaluations in pilot-scale equipment and pipeline loop testing before a definite conclusion can be reached.

Coals deemed appropriate in terms of the above criteria and other properties described below should then be evaluated in pilot-scale tests to assess their slurry ability, transportation and combustion performance.

SLURRY QUALITY ASSESSMENT

Two pipelineable coal slurry products, which were manufactured in Germany, were shipped to CANMET's Bells Corners Complex near Ottawa. The shipment, comprising 40 100-L drums of each product was stored in a heated enclosure to prevent freezing prior to the combustion tests. During boat and truck transport from Germany to Canada, the two slurries had been shipped in a thermally-controlled container maintained above 5°C to prevent freezing. One product, slurry A, was prepared from a medium-volatile bituminous Alberta foothills coal containing a stablizer to prevent the coal particles from settling. The other product, slurry B, a 60/40 blend of the same medium-volatile bituminous coal and a high-volatile bituminous Alberta coal, did not contain a stablizer because of the inherent stabilizing properties of the high-volatile bituminous coal. Slurry A contained 30.3% and slurry B contained 32.4% water respectively. Both of the Alberta coal feedstocks have been burned successfully at CANMET as pulverized-coal fuel.

From particle size distribution (PSD) data provided by Germany for the parent coals, it was expected that 90% of slurry A would contain coal particles less than 75 μm, whereas the blend would be coarser with about 80% of particles less than 75 μm. However, PSD conducted on the CLF used at CCRL showed that the blend was much finer than anticipated. Figures 7 and 8 show the German PSD data compared with that measured by CCRL. The figures suggest that much of the coarser material (>100 μm) in the blend, slurry B, had not been successfully transferred from the drums to the day tank prior to the combustion tests. The effect on the combustion tests is not known but it may be speculated that the coarser particles, had they been in the "as-fired" slurry, would not have improved combustion quality, since larger particles normally take longer to burn.

Examination of the slurry products on their arrival at CANMET indicated that the unstabilized slurry B was more viscous than the stabilized slurry A. This was confirmed by rheology and spray atomization tests undertaken by the Nova Scotia Research Foundation Corporation (NSRFC) (7). When the stabilized slurry was discharged into the day tank it was noted that about 3 cm of soft sediment remained on the bottom of each drum. This sediment was then transferred from the drums to the day tank, where it was readily resuspended by a low speed mechanical mixer.

Personnel from Germany and AOCRT were present to observe the transfer of the unstabilized slurry blend to the day tank for the combustion evaluation. Although these drums had been turned upside down on arrival, there was still about 15 cm of hard sediment remaining in the bottom of the drums. This sediment was resuspended in the day tank, but with much more difficulty than was encountered with the stabilized slurry.

The reference CLF, containing 32% water and prepared by the Cape Breton Development Corporation (CBDC), had been at CANMET for over a month and no observable settling had occurred. Transfer to the day tank was achieved with negligible residue remaining in the storage drums.

PARENT COALS

The CLF were prepared from coals containing about 7% ash and over 28% volatile matter. The proximate and ultimate analyses of the parent coals for each CLF are given in Table 1.

ATOMIZATION CHARACTERISTICS

The test protocol used and the data obtained from the spray atomization tests done at room temperature for the slurries and the reference CLF are described elsewhere (4). The atomization theory and data reduction methodology developed for CLF (4, 5) are summarized as follows:

Sub-Sonic Regime

The sub-sonic spray droplet correlations usually take the form:

$$SMD/Do = A \, W_e^{-n} \, (1+(F/A))^m \qquad\qquad \text{Equation 1}$$

where
- SMD = Sauter mean droplet diameter, μm
- Do = atomizer liquid orifice, μm
- F, A = fuel and air mass flowrates, kg/s
- W_e = Weber Number, a dimensionless group representing the ratio of disrupting aerodynamic force to the cohesive surface tension force as noted previously (4)

A, n and m are constants determined from model fits of the experimental data (Table 3).

Sonic Regime

As the flow in the orifice approaches sonic velocity the correlation takes the form:

$$SMD/Do = A \, W_e^{-n} \qquad\qquad \text{Equation 2}$$

in which A and n are constants with different values determined from model fits of the experimental data (Table 4).

Spray Data

Figure 9 shows the correlations of spray quality data for the reference CLF and Fig. 10 to 13 show the data for the slurries. Separate correlations were possible in both sonic and sub-sonic regimes with the reference CLF (Fig. 9a and 9b). However, Fig. 10 shows a poor correlation in both regimes for the two pipeline slurries. Fig. 11 indicates that the fuel index, m, determined for slurry A is 1.45, and for slurry B, 1.13. The reference CLF has an m index of 0.86 and an additional dependence on W_e, which indicates that atomization uses less energy to produce smaller droplets. The higher index value for slurry A indicates a less efficient atomization process, which produces coarser droplets and inevitably poorer combustion performance

than the reference CLF or slurry B. Tables 3 and 4 show the relevant atomization parameters for all three slurries.

Figures 12 and 13 show the variable air and fuel rate spray data for slurries A and B respectively.

COMBUSTION TEST PROCEDURES

Combustion tests were conducted in CCRL's pilot-scale research boiler (PSRB) using the roof-fired "J" configuration shown in Fig. 14. A qualitative assessment of combustion performance was obtained from:

- ignition stability
- flame shape and size
- sparkler density
- ash distribution characteristics
- carbon in ash

Each slurry, including the reference fuel, was fired at about 2.0 GJ/h in a 6 h combustion test. As mentioned earlier, the reference CLF was selected as a baseline fuel because it has been successfully burned in both the CCRL pilot-scale research boiler and in a 20-MWe utility boiler at Charlottetown, PEI. (2). In the latter case, the reference CLF had been manufactured from the same coal feedstock using the same process, but had been cleaned to a lower ash level than that used at CCRL in the present study (3.5% vs 6.9%).

OBSERVATIONS

Test results on the three slurries indicated that ignition was very unstable for slurry A and only marginally satisfactory for slurry B. Unlike the stable flame produced by the reference CLF, the slurry flames (which were not anchored to the burner quarl) were long and ragged, extending the full length of the furnace bottom into the base of the boiler (Fig. 14). A very

heavy concentration of sparklers was observed, particularly with slurry A. Both slurries showed a much higher production of furnace bottom ash and char than the reference fuel which produced virtually no bottom ash under similar combustion conditions. The unstabilized slurry B produced less bottom ash and char on a volume basis than the stabilized slurry A. Table 5 compares the combustion data for each.

Figure 15 shows the amount of combustible in the ash samples deposited at various locations in the boiler. These data must be qualified by noting that the slurries deposited more ash in the PSRB system than the reference CLF and the distribution was quite different. Table 6 shows the distribution and quantity of ash in the PSRB system for the 5% O_2 combustion trials.

The main difference between the reference CLF and the pipeline slurries was the lower overall ash deposition and the reduced proportion in the furnace bottom section for the reference fuel. This result is comparable with that obtained at Charlottetown in the 20 MWe boiler, where deposited ash has been negligible, i.e. bottom ash and tube deposits. The higher concentration of furnace deposits with the pipeline slurries is consistent with the atomization data and the poorer ignition and combustion efficiency.

CONCLUSIONS

In tests on two pipeline slurries made from Western Canadian bituminous coals, it was found that:

1. Examination of slurry B suggested that many of the larger particles (>100 μm) remained in the drums when the CLF was transferred to the CCRL day tank. This did not occur with the reference CLF or the slurry A.
2. Atomization data indicate that the two pipeline slurries will produce larger droplets than the reference CLF and will require more atomizing fluid and higher pressures to attain an optimum spray quality.
3. The two pipeline slurries had poor to marginal ignition stabilities and poor flame characteristics, probably resulting from poorer spray quality when compared with the reference CLF.

4. There was a noticeable improvement in combustion performance with slurry B compared with slurry A, probably due to the improved spray quality and higher volatility.

Subsequent combustion tests undertaken on a pipeline slurry which had been properly managed during transportation to CCRL, i.e. continually agitated, eliminated many of the problems experienced in these tests and good combustion results were obtained.

ACKNOWLEDGEMENT

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Table 1 - Analyses of parent coals

	High-volatile coal, HVB	Medium-volatile coal, MVB	CBDC coal
Proximate, wt % dry			
Ash	8.3	7.7	6.9
Volatile matter	34.3	28.7	34.4
Fixed carbon (by diff.)	57.4	63.6	58.7
Ultimate, wt % dry			
Carbon	72.1	81.2	78.9
Hydrogen	4.5	4.6	4.9
Nitrogen	1.1	1.2	1.6
Sulphur	0.3	0.2	2.2
Ash	8.3	7.7	6.9
Oxygen (by diff.)	13.7	5.1	5.5
Calorific value, MJ/kg	29.0	33.1	33.1

Table 2 - Miscellaneous coal evaluation parameters

Coal type	HVB	MVB	CBDC
C/H ratio	15.95	17.58	16.10
Fuel ratio	1.67	2.21	1.71

Table 3 - Sub-sonic spray data

CLF	A	n	m
Slurry A	0.03	0	1.45
Slurry B	0.005	0	1.13
Reference	0.08	0.3	0.86

Table 4 - Sonic spray data

CLF	A	n
Slurry A	-	0
Slurry B	-	0
Reference	70.54	0.96

Table 5 – Comparison of combustion data of pipelineable
slurries with those of reference fuel

	Slurry A		Slurry B		Reference CLF	
	1	2	3	4	5	6
Moisture in CLF, wt %	30.3	30.3	32.4	32.4	32.0	32.0
CLF rate, kg/h	91.3	91.5	98.9	98.3	87.3	87.8
Thermal input, MJ/h	2106	2111	2103	2090	1965	1976
Atomizing air						
Temp, °C	28.0	24.8	25.8	24.3	25.0	21.0
Flowrate, kg/h	29.4	30.0	29.2	29.8	29.8	23.0
Combustion air temp, °C	247	226	245	222	235	201
Flue gas analyses, dry volume basis						
O_2 %	5.0	2.0	4.9	2.0	5.0	2.0
CO_2 %	14.0	17.4	16.0	17.5	14.2	16.0
CO ppm	44	25	39	36	31	47
NO ppm	542	554	548	684	656	728
SO_2 ppm	171	204	161	214	1296	1269
Furnace exit temp, °C	975	966	992	984	903	879
Combustible in fly ash, wt %	15.9	14.3	12.2	10.7	11.3	30.0
Bottom ash, approx.						
Depth, cm	> 15	> 18	> 9	> 12	> 0.5	> 1
Char, %	High	Very high	Moderate	High	Very low	Low

Table 6 – Per cent distribution of ash in PSRB combustion system*

	Slurry A	Slurry B	Reference CLF
Furnace bottom (FB)	40	40	25
Furnace wall (FW)	10	10	12
Superheater tubes (SHT)	0	0	0
Flue pipe and heat exchangers (END)	27	26	36
Electrostatic precipitator (ESP)	23	24	27
Total weight, kg	15.0	17.6	8.4

* 5% O_2 in flue gas tests
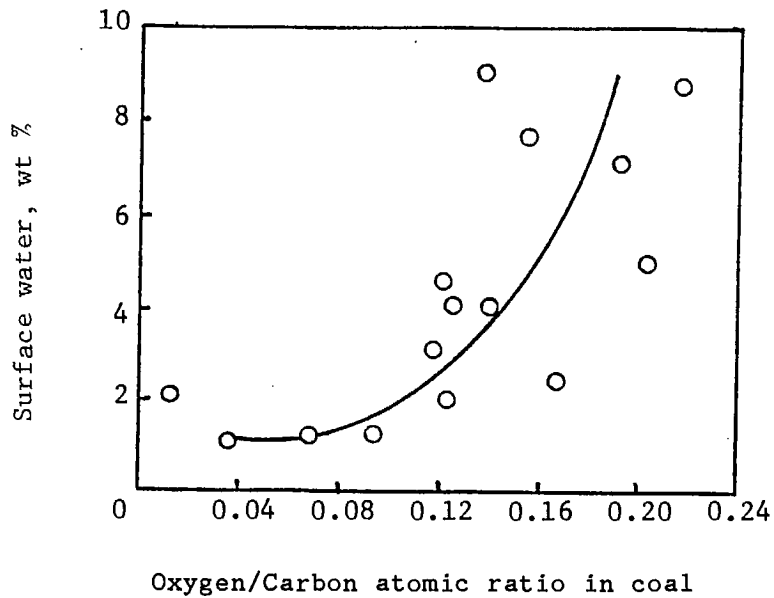
Fig. 1 – Relationship between O/C atomic ratio and amount
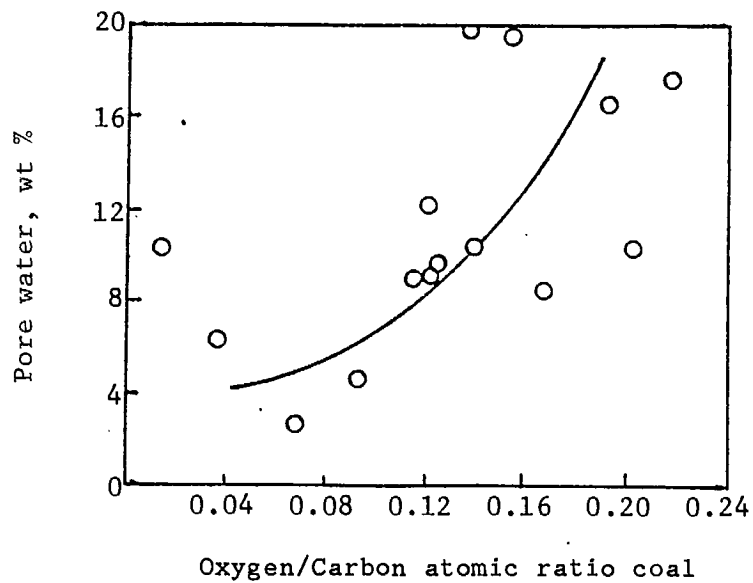   of surface moisture on coal particles

Fig. 2 – Relationship between O/C atomic ratio and amount
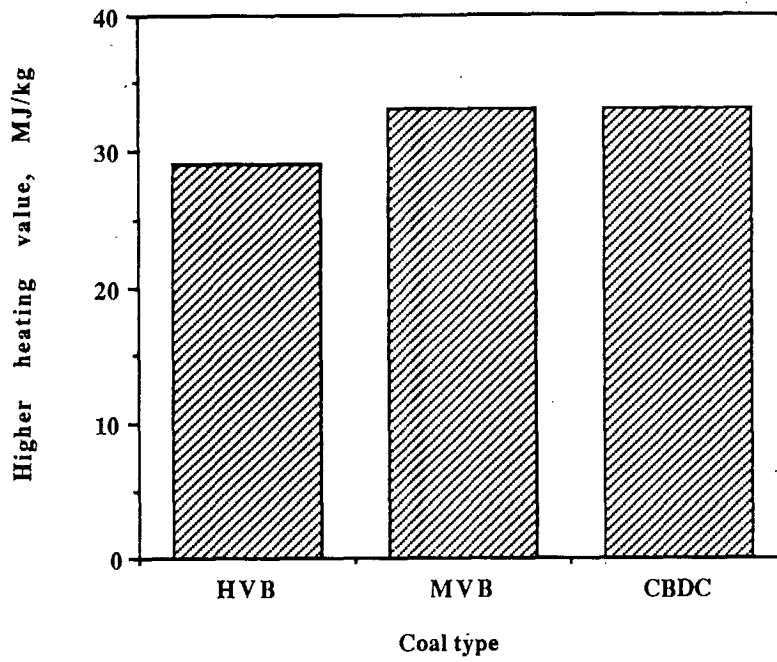   of water absorbed within coal particle pores
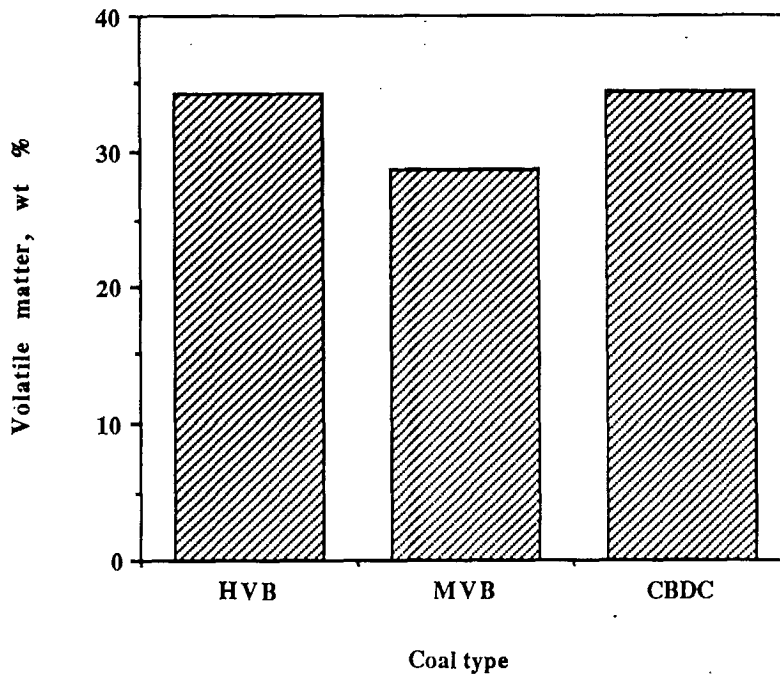
Fig. 3 - Coal heating value
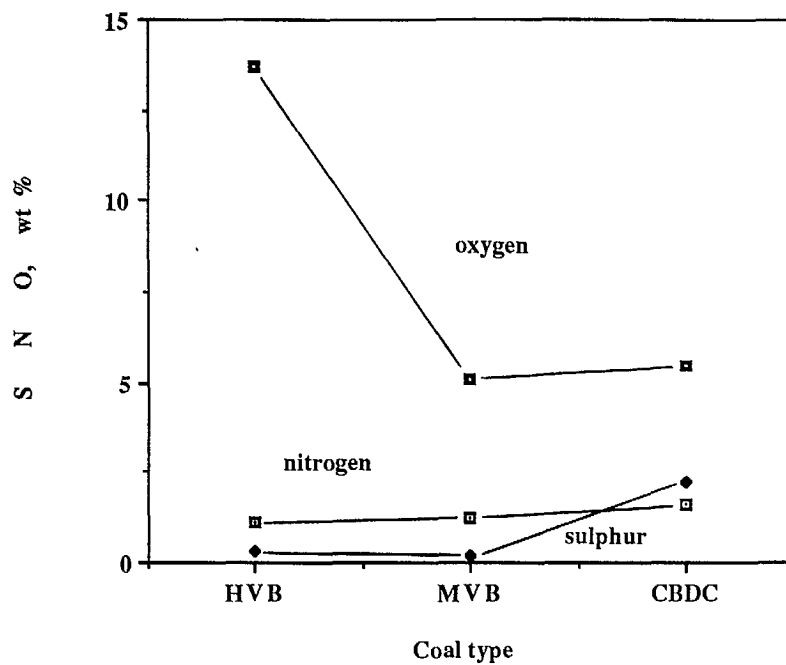

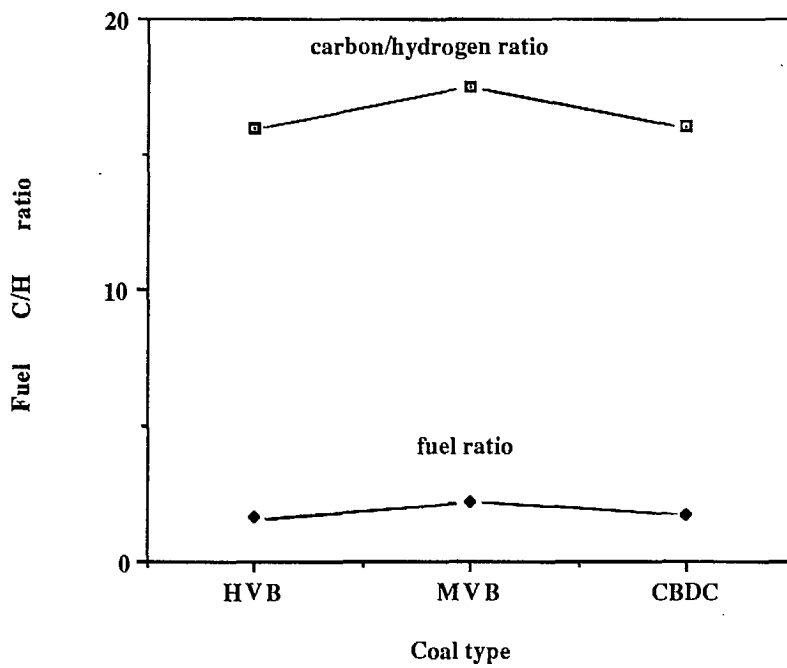
Fig. 4 - Coal volatile matter

Fig. 5 - Coal S, N, O

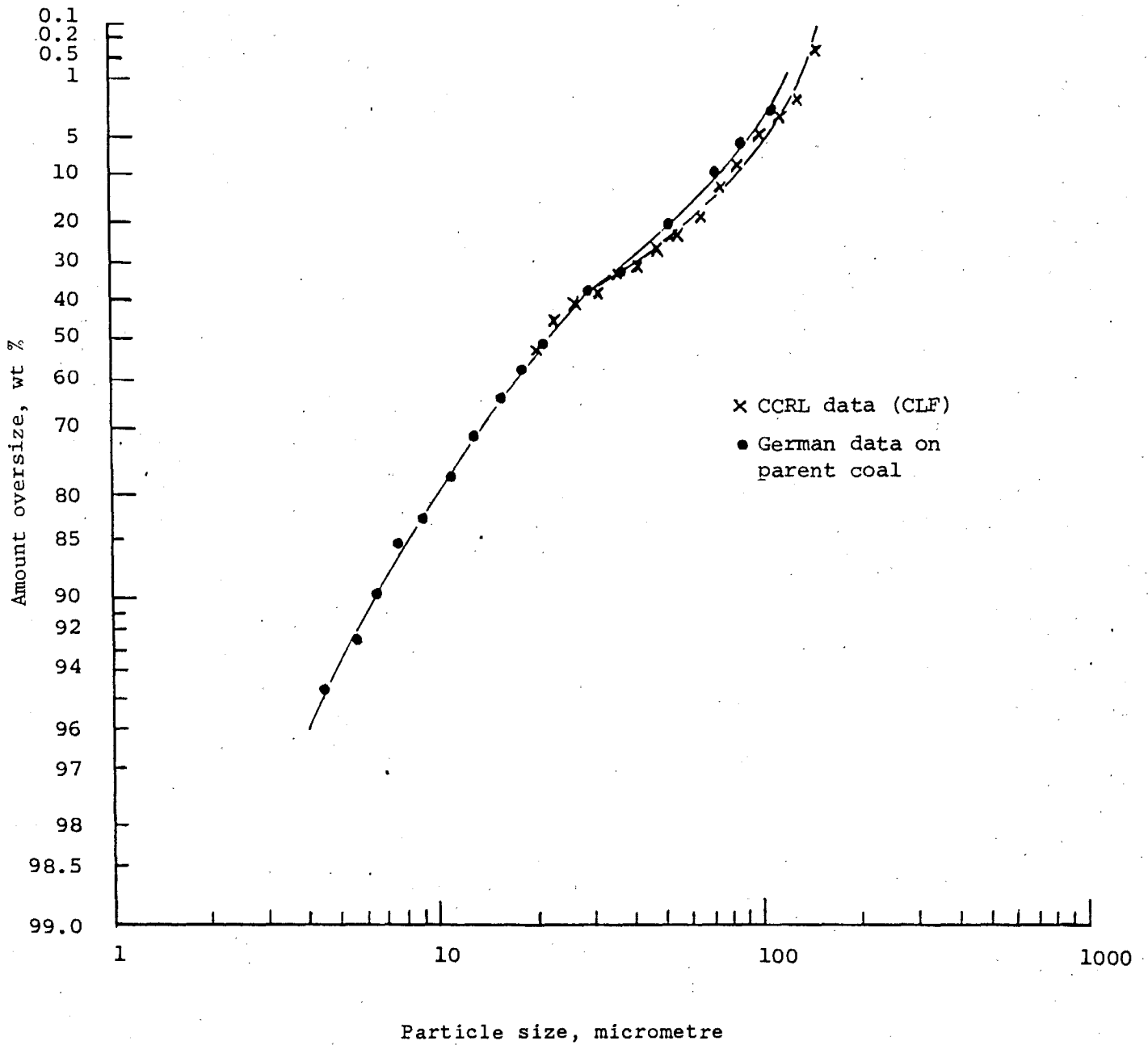

Fig. 6 - Coal fuel and C/H ratio

Fig. 7 – Particle size distribution of slurry A
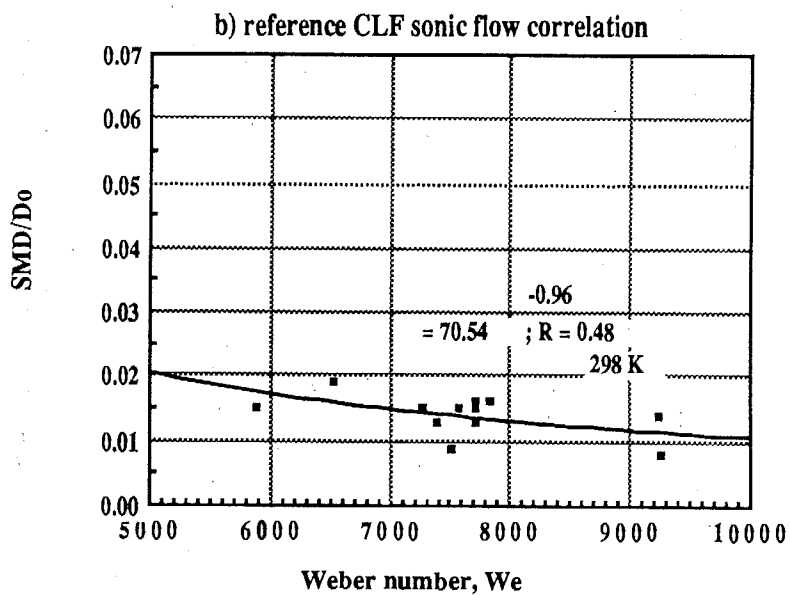
Fig. 8 – Particle size distribution of slurry B

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a) reference CLF sub-sonic flow correlation

b) reference CLF sonic flow correlation
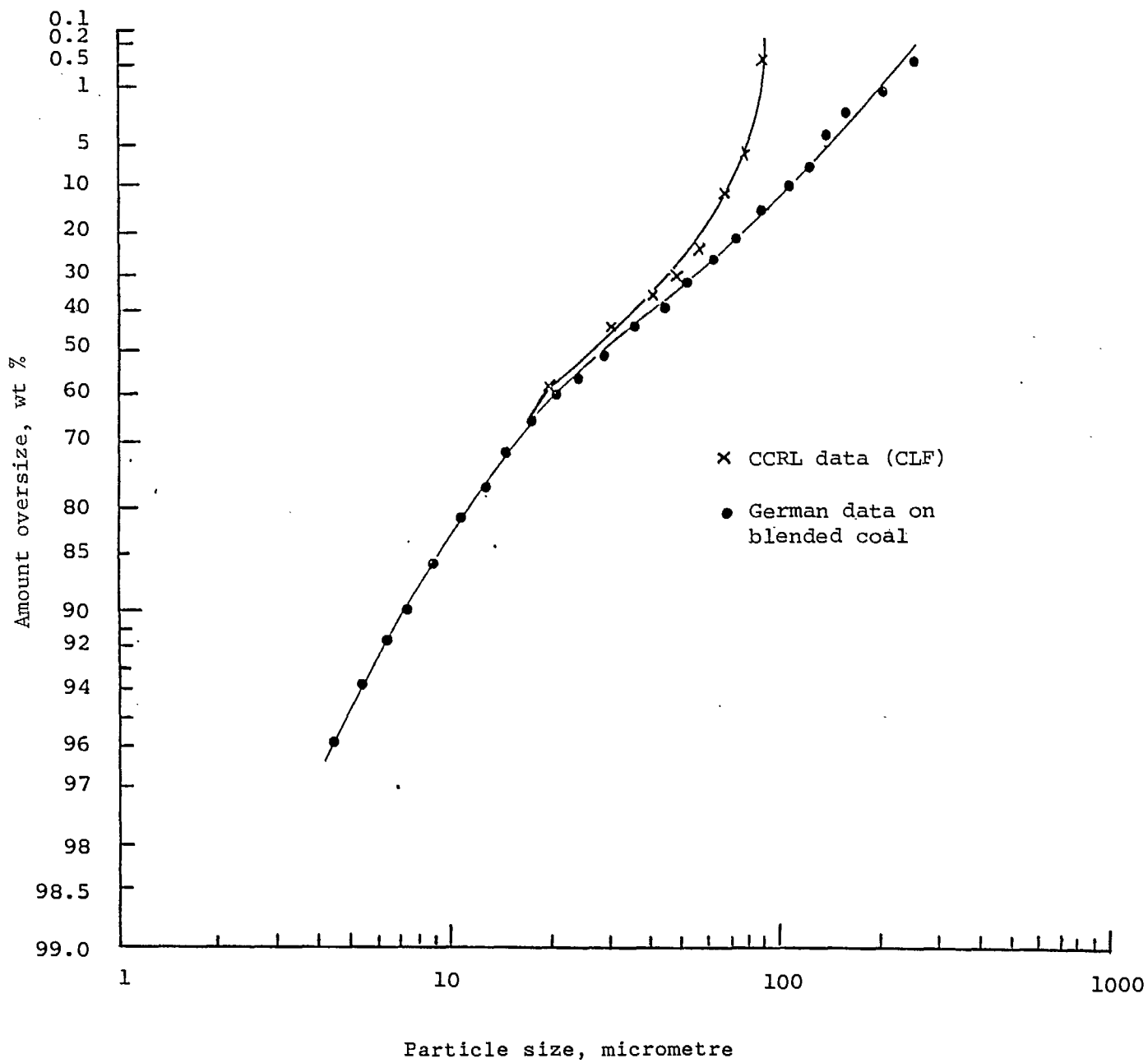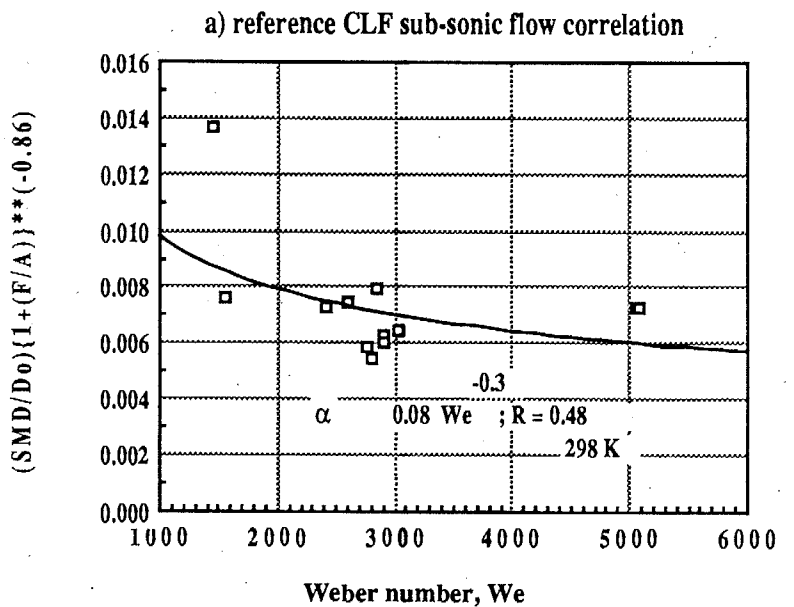
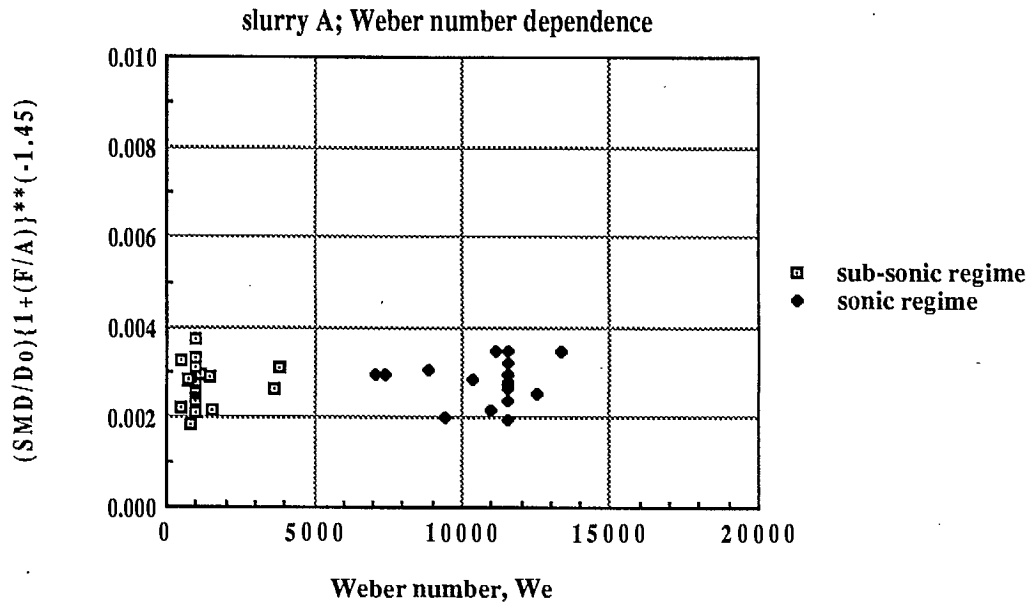
Fig. 9 - Correlations of spray quality data, reference CLF

slurry A; Weber number dependence

$(SMD/D_0)\{1+(F/A)\}**(-1.45)$

Weber number, We

□ sub-sonic regime
● sonic regime

slurry B; Weber number dependence

$(SMD/D_0)\{1+(F/A)\}**(-1.13)$

Weber number, We

□ sub-sonic regime
● sonic regime
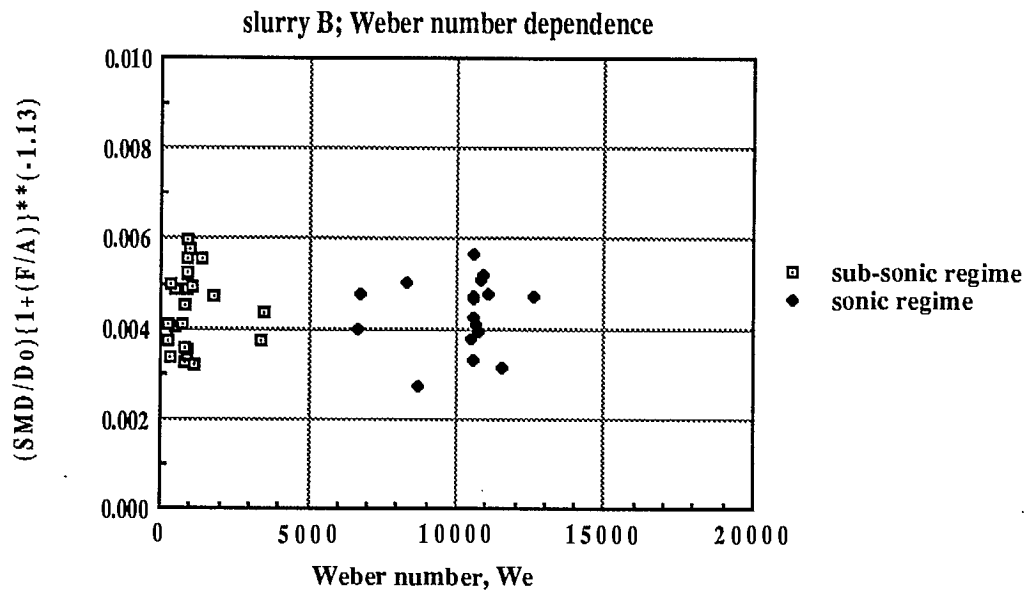
Fig. 10 - Correlations of spray quality data, CLF
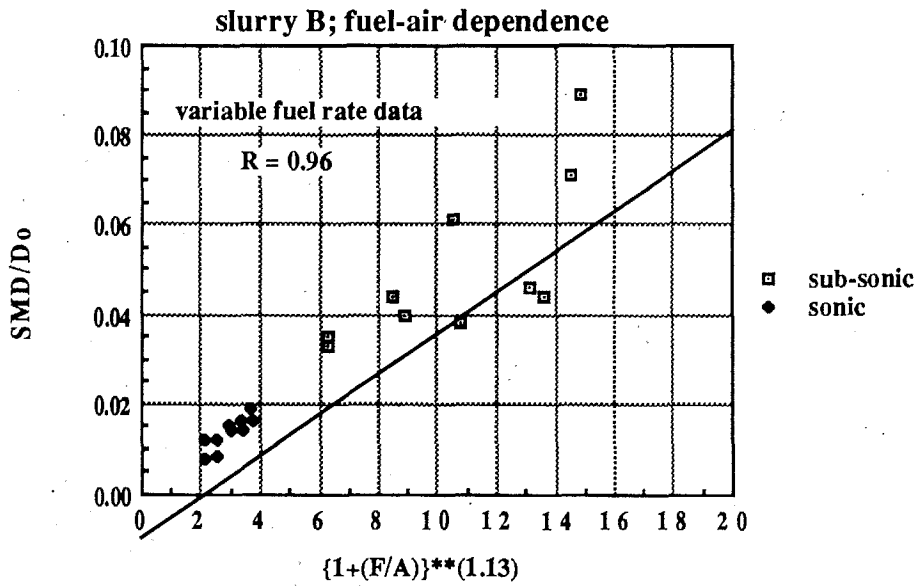
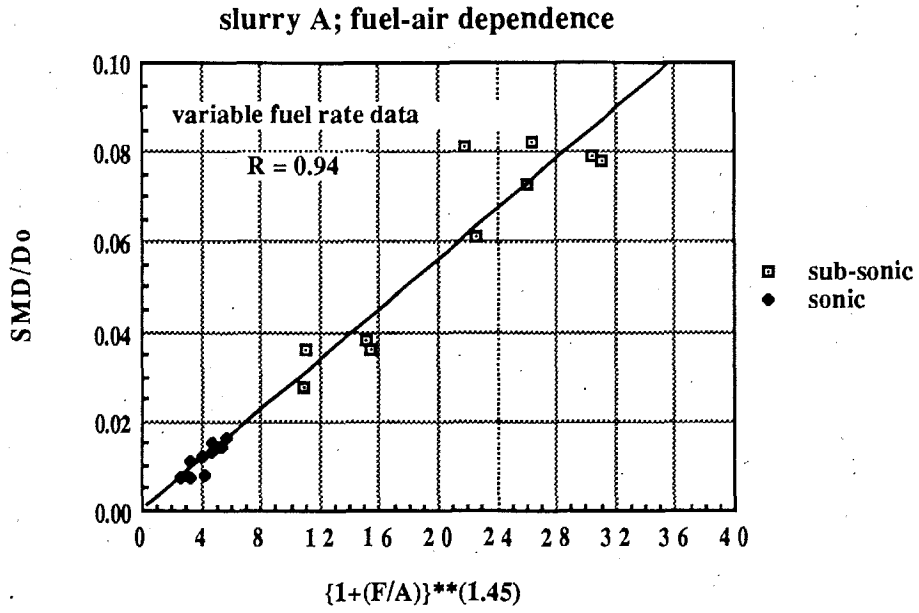Fig. 11 - Spray data, fuel-air dependence, CLF

variable air rate data

Fuel 13*10^(-3) kg/s

□ sub-sonic regime
● sonic regime

variable fuel rate data

Air Flowrate
□ 2*10^(-3) kg/s
● 9*10^(-3) kg/s
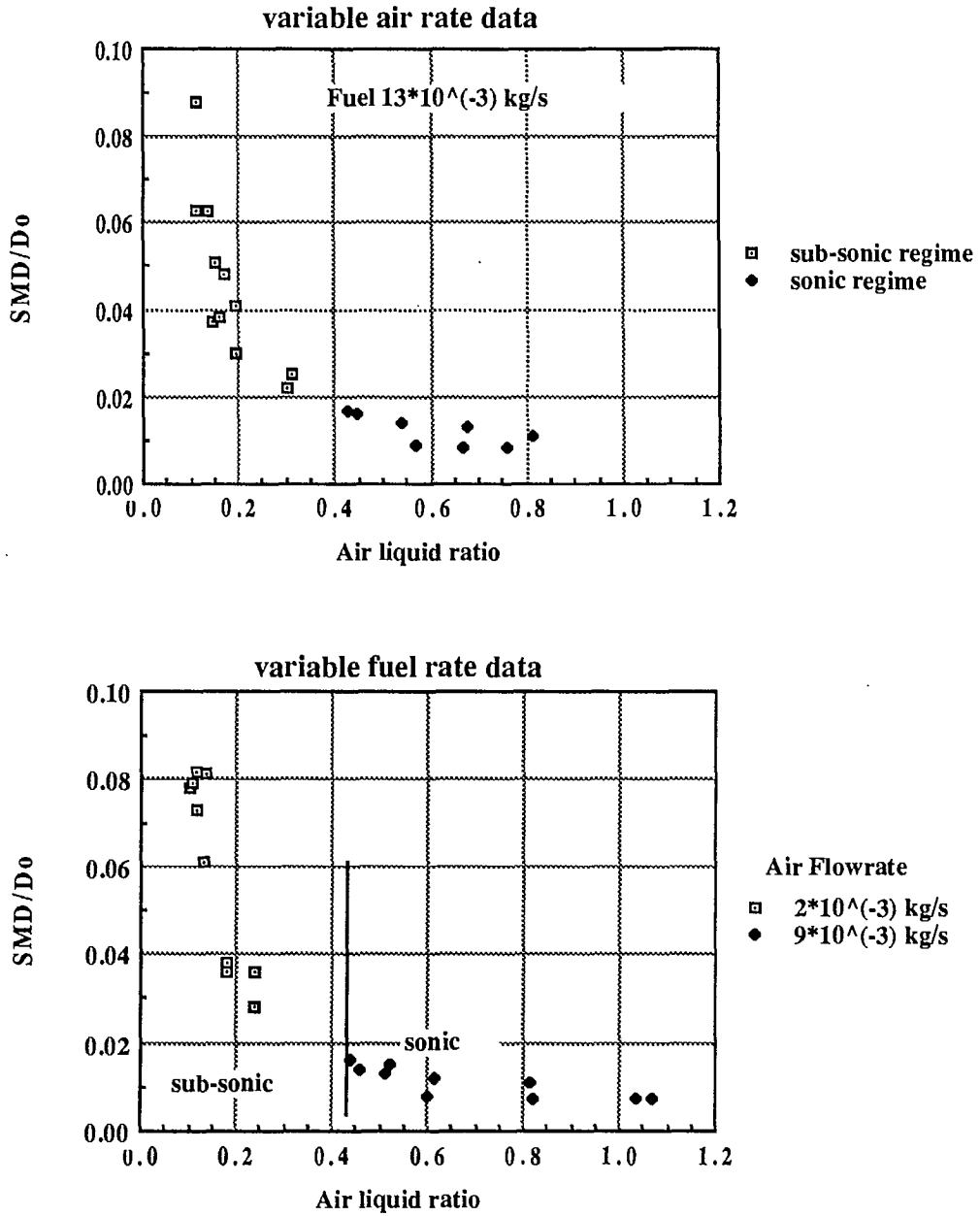
Fig. 12 - Spray data, variable air and fuel rate correlations, slurry A

variable air rate data

Fuel 1.3*10^(-3) kg/s

SMD/Do

□ sub-sonic regime
◆ sonic regime

Air liquid ratio

variable fuel rate data

SMD/Do

sonic

sub-sonic

Air Flowrate
□ 2*10^(-3) kg/s
◆ 9*10^(-3) kg/s

Air liquid ratio
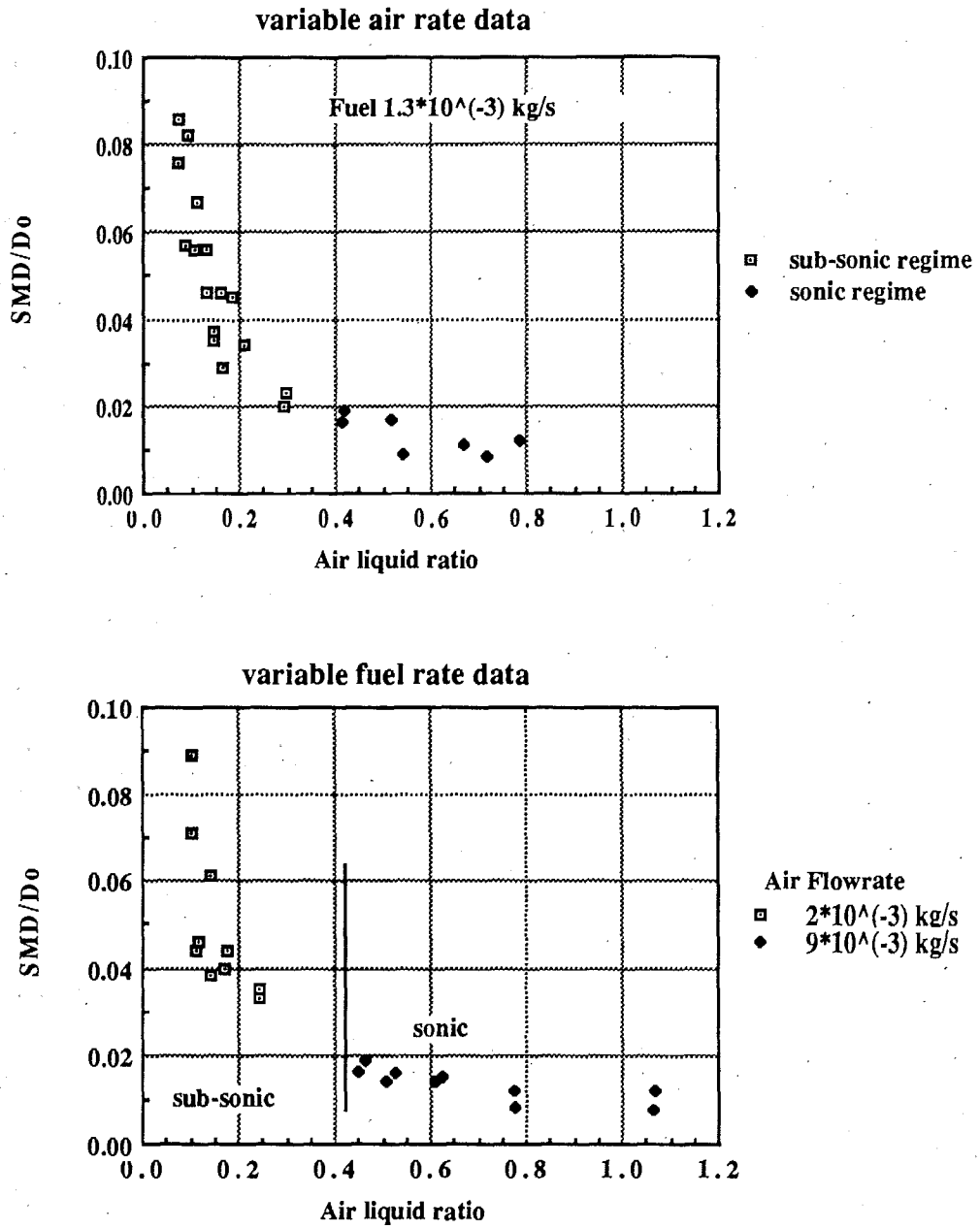
Fig. 13 - Spray data, variable air and fuel rate correlations, slurry B

superheater

CLF storage tank

U

J

I

CLF PUMP

ELECTROSTATIC
PRECIPITATOR

HEAT
EXCHANGER

AIR
HEATER

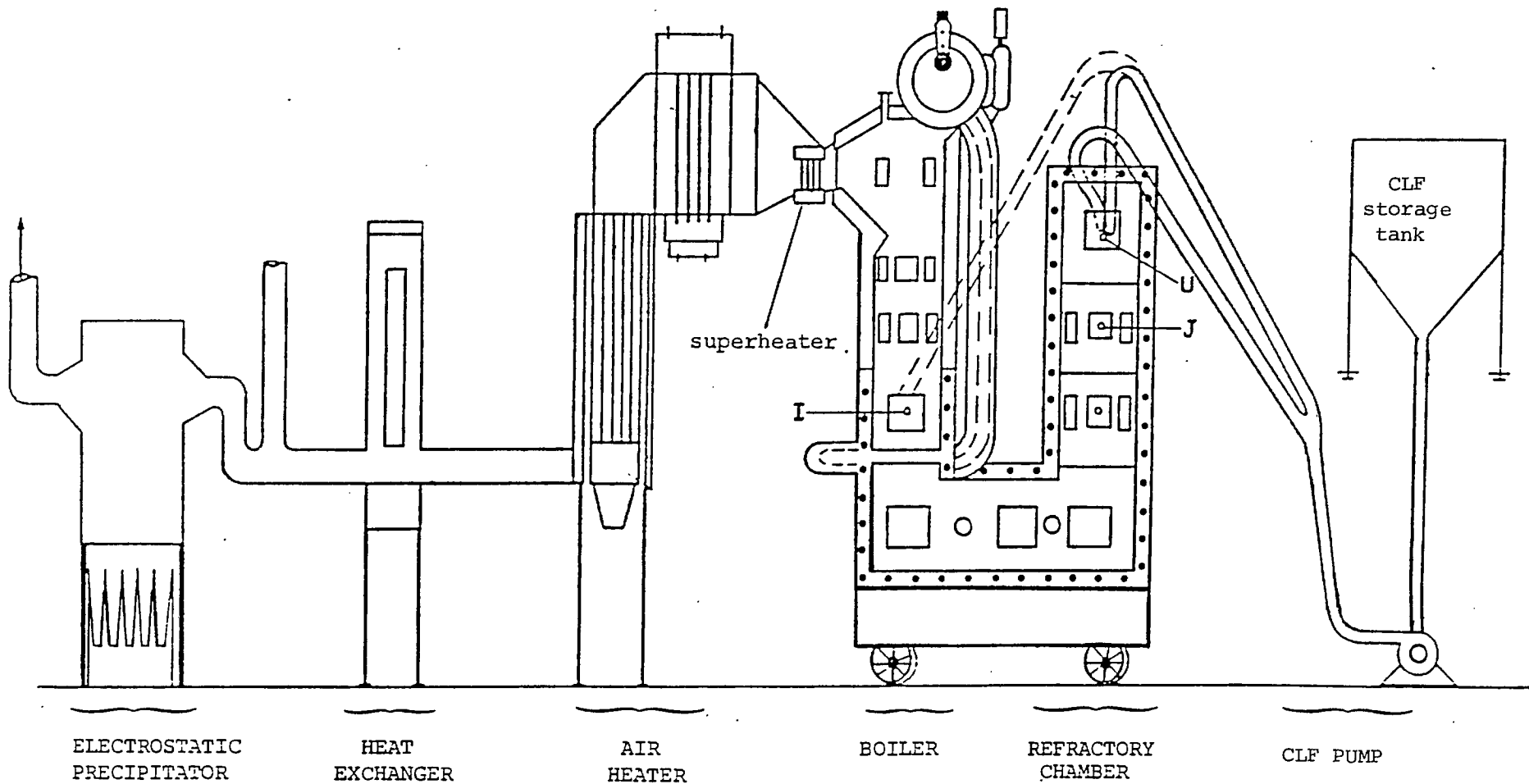BOILER

REFRACTORY
CHAMBER

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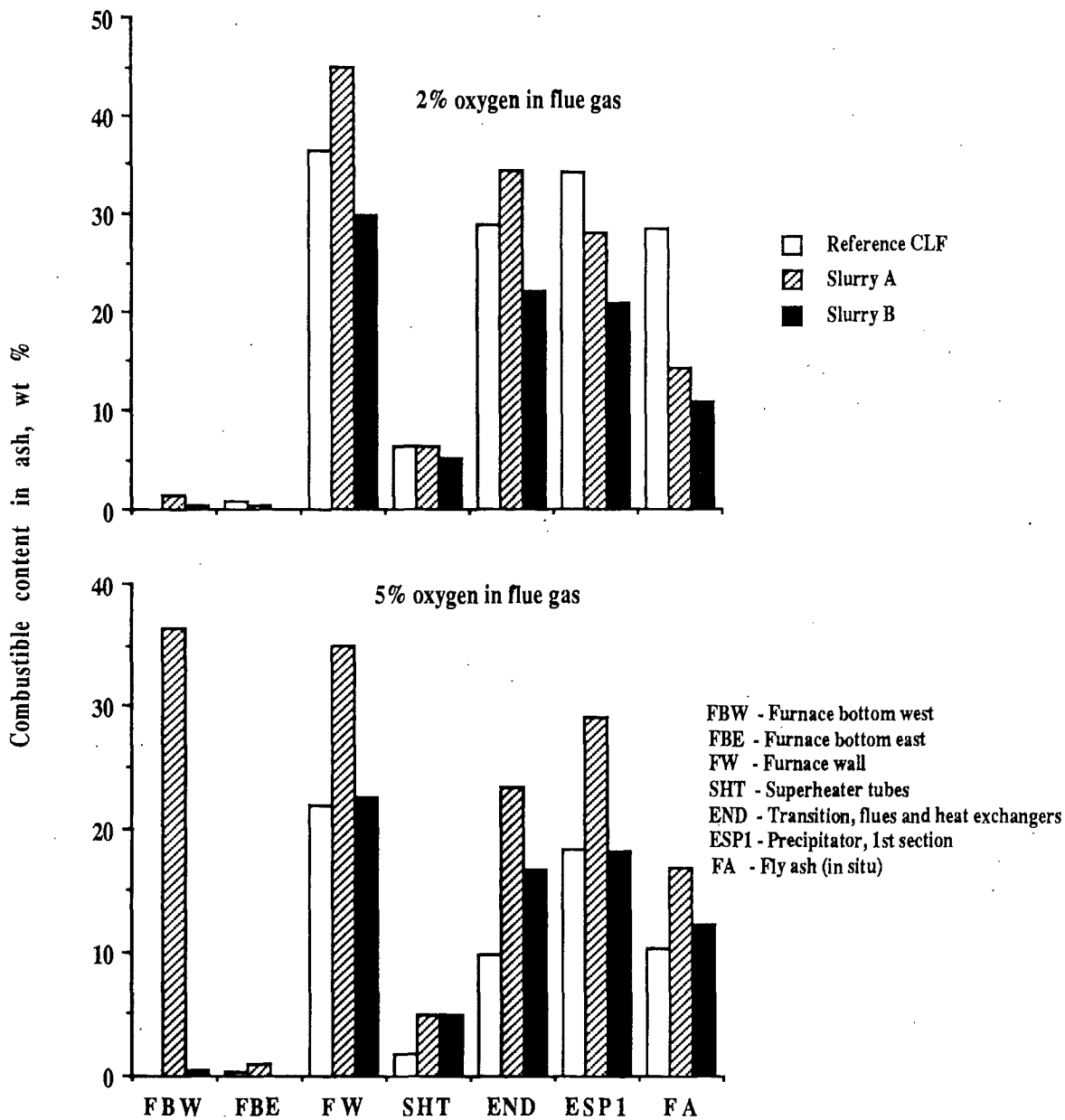Fig. 14 - Schematic of CCRL pilot-scale boiler with CLF handling system

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Fig. 15 - Combustible content in ash samples at various locations
in pilot-scale boiler