

ERL 88-35(OPJ)
C-3

Energy, Mines and
Resources Canada

Énergie, Mines et
Ressources Canada

CANMET

Canada Centre
for Mineral
and Energy
Technology

Centre canadien
de la technologie
des minéraux
et de l'énergie

INFLUENCE OF FUEL PROPERTIES ON
FLUIDIZED BED COMBUSTION

I.T. Lau and F.D. Friedrich

March 1988

Presented at the 1987 AIChE Annual Meeting, New York

ENERGY RESEARCH LABORATORIES
DIVISION REPORT ERL 88-35(OPJ)

01-79900890-3

INFLUENCE OF FUEL PROPERTIES ON
FLUIDIZED BED COMBUSTION

by

Ivan T. Lau* and Frank D. Friedrich**

ABSTRACT

A recently developed experimental technique, which measures overall burning rate in terms of a novel reactivity parameter, was used to investigate the influence of fuel characteristics on fluidized bed combustion.

The experimental work was carried out in three parts. The first was devoted to comparing coal samples having the same origin but different cleaning histories. The second involved burning the same coal after it had been exposed to controlled oxidation. The third determined the overall burning rate of a petroleum coke.

Results are analyzed and discussed with respect to the effects of fuel properties on processes such as fragmentation and attrition which ultimately affect the overall performance of fluidized bed combustors.

* Research Engineer, ** Research Scientist, Combustion and Carbonization Research Laboratory, Energy Research Laboratories, CANMET, Energy, Mines and Resources Canada, 555 Booth Street, Ottawa, Ontario, K1A 0G1.

INFLUENCE DES PROPRIÉTÉS DU COMBUSTIBLE
SUR LA COMBUSTION EN LIT FLUIDISÉ

par

Ivan T. Lau* et Frank D. Friedrich**

RESUMÉ

Grâce à une technique expérimentale mise au point récemment et permettant de mesurer la vitesse globale de combustion en fonction d'un nouveau paramètre de réactivité, il a été possible d'étudier les effets des caractéristiques du combustible sur la combustion en lit fluidisé.

Ce travail expérimental a été réalisé en trois parties. La première partie était consacrée à la comparaison d'échantillons de charbon de même origine mais ayant été soumis à des techniques de lavage différentes. La deuxième partie consistait à faire brûler le charbon qui avait été exposé à une oxydation contrôlée. La troisième partie a permis de déterminer la vitesse globale de combustion du coke de pétrole.

On fait l'analyse des résultats et on discute des effets des propriétés du combustible sur des procédés tels que la fragmentation et l'attrition qui en fin de compte influent sur la performance globale de la chambre de combustion en lit fluidisé.

* Ingénieur de recherche, **Chercheur, Laboratoire de recherche sur la combustion et la carbonisation, Laboratoires de recherche sur l'énergie, CANMET, Énergie, Mines et Ressources Canada, Ottawa, K1A 0G1.

CONTENTS

	<u>Page</u>
ABSTRACT	i
RESUMÉ	ii
INTRODUCTION	1
EQUIPMENT AND PROCEDURE	2
RESEARCH PROGRAM	2
Feedstock Selection and Treatment	2
Computational Techniques	3
RESULTS AND DISCUSSION	4
Burning Rate Correlations	4
Effects of Operating Parameters	5
Elutriated Carbon Loss	5
Incomplete Combustion of Carbon Monoxide	6
CONCLUSIONS	6
REFERENCES	7

TABLES

1 Volatile content of fuels (% db).....	8
2 Ash content of fuels (% db)	9
3 Carbon content of fuels (% db)	10
4 Free swelling index of fuels	11
5 Average values of \bar{t}_c for the h-v bituminous coal F	12
6 Comparison of unburnt CO, expressed as % of the total burnt carbon, of various fuels	13

FIGURES

1 Schematic diagram of bench-scale FBC	14
2 Carbon burning rate and 1-f vs. time	15
3 Comparison of FBC reactivity of various fuels	16
4 Comparison of FBC reactivity of various coal chars	17
5 Effect of carbon content on \bar{t}_c	18
6 Effect of bed temperature on \bar{t}_c	19
7 Effect of oxygen concentration on \bar{t}_c	20
8 Comparison of carbon loss of various coals	21
9 Percentage of fixed carbon burnt during devolatilization	22
10 Temperature effect on unburnt CO %	23

INTRODUCTION

It is well known that fluidized bed boilers are capable of burning extremely low grade and variable fuels. In fact, the range of feedstocks is so wide that the body of information relating fuel properties to combustor performance is far from adequate.

Generally the most important parameter of combustor performance is combustion efficiency, which is commonly defined as the percentage of input carbon that is completely converted to CO₂. Combustion efficiency may be influenced by a number of controllable factors such as temperature, residence time, fuel particle size, oxygen concentration, and mixing. However, it also depends on a number of uncontrollable properties of the fuel which are commonly combined into an empirical parameter known as fuel reactivity.

For conventional pulverized coal firing, fuel reactivity is often expressed adequately by rank or volatile content, perhaps with some corrections for ash content or maceral count. For FBC systems attrition and elutriation are important factors which affect combustion efficiency, therefore fuel properties such as hardness, swelling and fragmentation are likely to affect reactivity. It has been suggested that the combustion efficiency of a FBC system depends on the competing processes for particle size reduction of combustion and attrition (1).

Investigations have shown that higher reactivity in FBC can be correlated to higher volatile content and lower fixed carbon (2-4), which are standard fuel properties. Also, Vleeskens (5) correlated, with exceptions, combustion efficiency in FBC to vitrinite reflectance, which is a parameter of coal rank. Other work (6,7) indicates that high ash content could impair reactivity by forming a diffusion-resistant ash layer around the unreacted carbon core. Whereas this has been shown to be true for pulverized coal combustion, an attempt to correlate carbon loss in FBC with fuel ash content was unsuccessful (8).

The potential for interactions among the aforementioned factors is great. For example, the rate of attrition is enhanced by combustion (9) and vice versa. Therefore when the fuel type is changed, the factors affecting reactivity may affect the influence on combustion efficiency of operating conditions such as bed temperature, excess air level and particle size distribution, according to the regime within which the reactions occur.

To identify the most important fuel properties and determine their effects on combustion performance, selected solid fuels were burnt batchwise in a bench-scale fluidized bed combustor, while measuring burning rate and carbon loss. Efforts were made to elucidate the influence of fuel

particle size, ash content, and particle swelling on the combustion reaction and on attrition, since both ultimately affect combustion efficiency. Effects of fuel type were also investigated. The overall objective of these studies was to develop the capability of predicting, from the properties of a given feedstock, the operating conditions which will optimize its performance.

EQUIPMENT AND PROCEDURE

The experimental apparatus used for this project is shown schematically in Figure 1. Except for a few modifications it has been described in detail previously (10,11). The fluidized bed combustor, 0.1 m ID, is heated externally by electrical elements divided into four individually controlled sections. The main section surrounds the bed zone and is capable of controlling it at a stable temperature between 650 and 900°C. One section preheats the windbox, in order to provide fluidizing gas at a selected temperature between 600 and 700°C. Two heating sections respectively control the lower and upper freeboard regions below 600°C and 400°C. The freeboard is maintained at a low temperature to minimize chemical reaction of particles elutriated from the bed.

Air or an air-nitrogen mixture was used as the fluidizing medium, at a superficial velocity of about 0.6 to 0.8 m/s. The bed material was sand with a mean particle diam of 0.5 mm. The static bed height was 0.12 m.

The fuel samples, screened to narrow size ranges, were fed into the combustor batchwise through a pneumatically purged, electrically operated double valve. The fuel sample mass was limited to 10 g per run to minimize the impact of combustion on target operating conditions, e.g., rise in bed temperature and reduction in oxygen concentration during the evolution of volatiles. This was especially important in the experiments involving small particles and reactive fuels.

Particulates elutriated from the bed were collected by a cyclone and a high temperature filter in series. A graduated 12.7 mm diam glass tube, which was joined to the lower end of the cyclone, provided a qualitative indication of the amount elutriated. Signals from the fuel valve

switch, gas analyzers, thermocouples and pressure transducers were recorded by a datalogging system, then stored and analyzed by a mini computer.

RESEARCH PROGRAM

Feedstock Selection and Treatment

The experimental work was carried out in three parts. The first involved examining samples of high volatile coal having the same origin but different cleaning histories in order to establish the effect of ash content. The second involved subjecting samples of a cleaned coal to long-term, low-temperature oxidation to destroy the caking property, and thus facilitate a study of its influence. The third involved studying a petroleum coke. In all cases the effects of particle size were studied by testing a range of size fractions.

The coal was a freshly mined, high volatile coal from Eastern Canada. Four samples were obtained: raw coal, coal washed by a deep cleaning process, coal washed by a medium cleaning process, and rejects from the deep cleaning process. Each sample was screened into five size fractions. These were subjected to proximate and ultimate analysis, i.e., volatile matter, ash and carbon contents, and determination of the free swelling index (FSI). The results are presented in Tables 1 to 4.

The proximate analysis showed little difference between the raw coal and the rejects from the deep cleaning process, which seemed illogical. Further investigation revealed that the efficiency of the cleaning process was low for this particular coal, and much of the ash was lost in the washing medium. Thus the rejects could not be considered as representative of a full-scale cleaning operation. Furthermore, they were highly variable in quality, which led to inconsistent experimental results. Therefore, although the results of the experiments using rejects are included in the data, they were not used to draw general conclusions.

The oxidation for the second part of the program was achieved by exposing samples of each sieve fraction of the deep cleaned coal for 6 to 10 days in an oven maintained at 125°C. Analytical results for the

oxidized samples are reported in Tables 1 to 4. The effect of oxidation on volatile matter and fixed carbon was small, but the effect on FSI was dramatic.

Petroleum coke was selected as an example of a relatively unreactive fuel which burns in a different reaction mode from coal. Analytical data for various size fractions are also given in Tables 1 to 4.

A total of six fuel samples each in five different size fractions were burnt in the bench-scale FBC described previously.

Computational Techniques

Because most conventional experimental methods and existing rate parameters were unsuitable for comparing burning rates of various fuels in a multiparticle FBC reactor, the present apparatus and batchwise operating system were developed (10). Burning rates are measured in terms of a novel reactivity parameter, mean carbon conversion time, \bar{t}_c , which is defined as the inbed mean residence time of all burnt carbon, or,

$$\bar{t}_c = \int_0^1 t df \quad (1)$$

where df is the fraction of total burnt carbon converted at time t .

The value of the mean carbon conversion time is readily determined and is given by:

$$\bar{t}_c = \int_0^{t_B} (1-f) dt \quad (2)$$

where t_B is the overall burnout time. The fractional burnout, f , by definition, can be estimated from the reaction rate, r , using the relationship:

$$f = \frac{\int_0^t r dt}{\int_0^{t_B} r dt} \quad (3)$$

Figure 2 shows a typical curve of reaction rate versus time, as directly calculated from experimentally measured flue gas composition and gas flowrate on combustion of large particles of bituminous coal. By integrating the area under this curve according to Equation (3), it is possible to obtain the relationship of the value $(1-f)$ with time. This curve, also shown in Figure 2, shows the approximate value of bed carbon inventory, assuming elutriated carbon loss is small. Equation (2) makes it clear that

the desired \bar{t}_c value is represented by the entire $(1-f)$ curve from time 0 to burnout time, t_B .

The turning point, t_v , shown on the burning rate curve in Figure 2, appears only in the combustion of large coal particles. It is considered to represent the completion of devolatilization, and this assumption makes it possible to decouple devolatilization and char combustion. Thus the mean carbon conversion time for char, t_{ch} , can be deduced in the same manner as \bar{t}_c .

The foregoing considers only the carbon fraction burnt, and thus distinguishes the combustion rate from the carbon loss rate due to elutriation. The latter is usually estimated from the amount of fines collected in the cyclone. However, because of the small fuel samples used, even small amounts of elutriated material adhering to the walls of the gas path could introduce significant error when measuring combustion efficiency. Instead, the carbon loss, Le , was calculated from a material balance based on flue gas composition:

$$Le = \frac{WX_c}{M} - \int_0^{t_B} r dt \quad (4)$$

where W = weight of fuel sample
 M = molecular weight of carbon
 X_c = carbon content of fuel determined by ultimate analysis

Even in the combustion of large coal particles, some overlap between devolatilization and char combustion was found (10). The mechanism probably involves ignition of small char particles formed through attrition and fragmentation which result from caking and expansion of the coal particles. The same mechanism broadens the size distribution of the fuel charge. Assuming that no volatile matter escapes unburnt, the amount of char, N_v , burnt during devolatilization can be approximated from the overall fixed carbon balance as follows:

$$N_v = \int_0^{t_v} r dt - \frac{W}{M} (X_c - X_{ch}) \quad (5)$$

where X_{ch} is the fixed carbon content of the fuel as determined by proximate analysis.

The conditions under which the proximate analysis is determined are different from those in a FBC and the actual

volatile and fixed carbon contents of fuels depend to some extent on the conditions under which they are determined. Thus the actual amount of volatiles and fixed carbon available for combustion in a FBC may be different from those determined by the proximate analysis. However, for the same type of combustion the trend in those differences is expected to be the same for all fuels. Thus Equation (5) is expected to provide results by which various fuels burnt in a FBC can be compared.

RESULTS AND DISCUSSION

Burning Rate Correlations

The overall burning rates of the selected samples were compared by calculating the reactivity parameter mean carbon conversion time, $\bar{\tau}_c$, and values for the bituminous coal samples are shown in Table 5. The $\bar{\tau}_c$ values reflect the average of results obtained over a wide range of conditions in which temperature showed no significant effect on combustion rate except for the oxidized coal. The effects of operating parameters on burning rate are discussed later. The raw, washed and reject coals show little variation in $\bar{\tau}_c$ despite a wide range in ash content. In comparison, the oxidized coal samples, which were characterized by a sharp decrease in plasticity and FSI, have much higher values for $\bar{\tau}_c$ particularly in the larger particle sizes. This indicates that they burned slower, i.e., they were less reactive. The results suggest, at least within the context of this experimental program, that ash forms no significant resistance to the reaction but coal swelling enhances the burning rate.

The importance of coal's plastic property to reaction can also be assessed by comparing the present results to those of previous studies (11) involving five other coals. The mean carbon conversion times, obtained under similar operating conditions, are given in Figure 3 as a function of fuel particle size. The $\bar{\tau}_c$ values of the bituminous coal burnt in this work (coal F) were plotted as a shaded band to indicate the range of burning rates for coals of various cleaning histories. Among the previously studied fuels is a reactive lignite, coal E. The rest are highly oxidized bituminous coals except for those fractions of coal D which are larger than 0.84 mm in size. It is interesting to note that the present fresh bituminous coal F,

along with the large size coals E and D are more reactive than the other fuels. On the other hand, the oxidized coal F samples burned much slower, like the rest of the oxidized bituminous coals. Since oxidation sharply reduces particle swelling, it is clear that swelling plays a major role in determining the combustion rate of these coals.

That there is no significant difference in burning rate between coal samples having the same origin but different cleaning histories suggests that these coals swelled in the same manner to create similar porosity and structure, and thus had similar reactivity. This means that coal cleaning processes, which normally wash out external mineral matter, do not significantly alter the properties of coal macerals. Conversely, the different amounts of inert material present affect the FSI values of these coals as shown in Table 4. Therefore, the correlation between $\bar{\tau}_c$ and FSI should be based on coals of the same ash content, or be corrected for the effect of ash content on FSI. The relationship between FSI and ash content for coal F in this study can be determined easily from the analyses of the cleaned and uncleaned samples but unfortunately these results cannot be generalized for other coals.

Figure 4 gives char burning rates in terms of the mean carbon conversion times for char, which were obtained using the turning points on the burning rate curves as time zero. Only results from the three largest size fractions are available. Figures 3 and 4 show that the ranking of FBC reactivities of char is similar to those of the parent coals. The rate of volatiles combustion is similar and very rapid for all coals and thus can have little influence on the differences in $\bar{\tau}_c$ values between coals. Thus, the observed differences in $\bar{\tau}_{ch}$ values indicate that higher char reactivity is related to parent coals with higher volatiles.

If analyses of coal are reduced to an ash and moisture free basis, then volatiles content usually varies inversely with elemental carbon content. Thus, the influence of carbon content on reaction rate can be expected to be the opposite of that of volatiles content. Since ash apparently has no effect on reaction in a FBC, comparing the burning rates of the various non-swelling fuels tested in this work should provide the correlation between

carbon content and $\bar{\tau}_c$. Figures 5a to 5e show that the reactivity parameter increases with carbon content in a similar manner for the five size fractions. Data from burning coals of FSI higher than one are excluded here. If plotted they would appear below the existing curves, and thus would represent higher combustion rates. If only results from burning volatile coals were used, the correlation curves would be closer to linear as given by the dotted lines. Because combustion of an extremely low volatile fuel such as petroleum coke provides little heat to the particle from the volatile flame, a longer time is required to ignite and burn it. This suggests that for non-swelling coals volatile content probably has no significant effect on char reactivity. Also, it would appear that for non-swelling, medium to high volatile coals, carbon content is the only important fuel property which influences burning rate. For swelling coals the FSI and the amount of volatiles are two additional factors that must be considered. However, the present work did not encompass a sufficiently wide range of volatile content to fully assess its effect on the burning rate.

Effects of Operating Parameters

The correlations between burning rate and fuel characteristics may vary with different operating conditions. Conversely, the importance of an operating parameter may alter when burning fuels of different properties. Table 5 and Figures 3 and 4 show the effect of fuel particle size on combustion rate. Despite a large variation in reactivity, for all fuels the increase in $\bar{\tau}_c$ with increasing particle size is similar.

A weak effect of temperature on $\bar{\tau}_c$ for the fresh coals is shown in Figure 6, a to e. Figure 6d indicates that only under conditions of small coal particle size and extremely low bed temperature would the burning rate be significantly affected by temperature. Conversely, these figures show the marked effect of temperature on $\bar{\tau}_c$ for the petroleum coke. This, taken along with the much lower reactivity values, suggests that the coke burns in a reaction mode different from that of the coal.

As expected and shown in Figure 7 the combustion rate increases with increased oxygen concentration in the fluidizing gas. When comparing fuels it becomes evident that, to minimize combustion time, supplying

enough oxygen to the combustor is more important when burning a low reactivity fuel than a high reactivity one.

Elutriated Carbon Loss

As stated previously, the fines collected from the cyclone cannot be measured with sufficient accuracy for efficiency calculations. They can, however, provide qualitative information for interpreting results. In particular, such data may be used to compare the entrained loss during the devolatilization period versus the char burning period, since this cannot be estimated from material balance based on flue gas composition.

Such a comparison shows some interesting results. Despite the fact that devolatilization requires a much smaller period of time than char combustion, the amounts of material elutriated during the two periods are about equal, indicating that the devolatilization process is very important for the overall combustion efficiency. The coal samples having various cleaning histories gave much smaller differences in results than might be expected from chemical analyses. During the devolatilization period, experiments with clean coal generally yielded more fly ash than those involving the uncleaned counterpart. Similarly, petroleum coke produced more elutriated fines than bituminous coals, especially at low bed temperature or low oxygen concentration.

The elutriated carbon losses as calculated from the carbon balance are given in Figure 8. The results show that, unlike pulverized coal combustion, oxidized coals burned fairly completely in the FBC, compared to their unoxidized counterparts. The raw coals, surprisingly, burned even more completely than the cleaned coals, particularly in large particle sizes. Fuel reactivity does not appear to be the dominant factor in determining combustion efficiency. Although the faster burning coals have a shorter residence time available for attrition, they nonetheless experience a carbon loss similar to that of the slower burning coals.

In the combustion of large coal particles attrition and fragmentation must be the major causes of elutriated carbon loss. These results indicate that cleaned coals burned with higher carbon loss than

raw coals, as determined both by the entrained fines collected in the cyclone during devolatilization and by carbon balance. The obvious cause of higher carbon loss is entrainment of small particles, which indicates a more vigorous attrition and fragmentation during the combustion of the cleaned coals. The generation of smaller particles and more surface area might be expected to lead to more combustion of fixed carbon during devolatilization. However, this could not be verified. The amounts of char burnt during volatiles evolution were calculated using the fixed carbon balance and Equation (5) as described previously. The results, which are given in Figure 9, show that chars from cleaned coals, although they experienced more elutriation, burned less during devolatilization than chars from raw coals. The burning rate curves resulting from combustion of various coal samples have essentially the same shape with nearly equal devolatilization times. In addition, their combustion rates showed no significant difference; these fresh coal samples all burned in the same manner with similar reaction rates and attrition rates.

If raw and cleaned coals experience approximately equal levels of fragmentation and attrition, then differences in carbon loss probably result from differences in the completeness of combustion of attrited fines. This in turn is determined by the residence time. It is well known that coal particles tend to float on the top surface of the fluidized bed during volatiles evolution. However, flame-enclosed coal particles have also been observed to be occasionally drawn into the bed by the circulation of solids when the superficial gas velocity was high enough. Raw coal particles swell less due to their higher ash content, and therefore have a higher density than particles of cleaned coal. They also evolve relatively less volatile matter. Thus raw coal particles are more easily drawn into the bed and on average the fines attrited from them have a longer residence time there. Fine particles which form by attrition inside the bed can be expected to burn more completely than those formed on the bed surface.

In the combustion of oxidized coals the lower reactivity results in longer residence times, which in turn allow more attrition. While the attrited fines are harder to burn completely, the non-swelling characteristics and lower attrition rate

seem to compensate for the low reactivity to the extent that combustion efficiency is not significantly lower.

Incomplete Combustion of Carbon Monoxide

Incomplete combustion of carbon monoxide is another source of combustion inefficiency. In full-scale applications, most carbon monoxide escaping the bed may eventually burn in the freeboard region. However, information on the reactions involving CO in the bed and freeboard may still be important for in-bed heat exchanger design.

In the present study it is assumed that all the combustion of carbon monoxide occurred in the bed and that the low temperature of the freeboard quenched any further gas phase reactions. Figure 9 shows, for the deep-cleaned coal samples, CO as a percentage of total reacted carbon plotted against bed temperature. In the combustion of large particles, the reaction was slow and no CO was found except at a very low bed temperature condition which restricted the gas phase reaction. On the other hand, in the combustion of small particles oxygen starvation occurred due to the high reaction rate and significant amounts of CO were produced. The curve for medium particle sizes in Figure 9 shows a minimum. At high temperatures, CO formed during devolatilization due to oxygen depletion whereas at low temperatures CO appeared during the whole combustion period.

Table 6 shows amounts of carbon monoxide produced while burning the various fuel samples. At bed temperatures above 770°C the cleaned coals produced more CO than the raw coals. This may be due to partial combustion of elutriated fines in the freeboard, since it has already been shown that the cleaned coals ejected more unburnt combustibles into the freeboard than the raw coals during devolatilization.

CONCLUSIONS

When burning bituminous coal under the operating conditions employed in this study, ash was found to offer no significant resistance to the combustion reaction. It appears that the resistance imposed by an ash layer would only become important for coals of low sintering temperature or under extreme conditions. This verifies what has already been observed in practice; that raw

coals may be burnt directly in a FBC without expensive cleaning.

Of the fuel properties measured by standard analysis, carbon content and FSI are the most important for determining overall burning rate in a FBC. The reactivity parameter \bar{r}_c , which varies inversely with reactivity, decreases with decreasing carbon content and increasing FSI. However, standard FSI values should be corrected for ash content to obtain burning rate correlations.

The generation of fines by attrition during devolatilization plays an important role for determining the combustion efficiency of a FBC. For caking coals it appears that raw coals burn more completely than cleaned coals because the particles have greater density, due to reduced swelling, and thus are more likely to be drawn into the bed, thereby providing greater residence time for the attrited fines.

When burning unreactive fuels in FBC, fuel reactivity and operating parameters that influence the combustion rate are very important to the overall performance. However, these factors have little effect on the combustion efficiency using fuels of high reactivity.

REFERENCES

1. Beer, J.M., Massimilla, L. and Sarofim, A.F. "Fluidized coal combustion: the effect of coal type on carbon load and carbon elutriation," presented at the Int Conf on Fluidized Combustion: Systems and Applications, in Inst Energy Symp Ser 4; IV:5:1, London (1980).
2. Ikeda, S., Tatebayashi, J., Yano, K. and Yutani, S. "Fluidized bed combustion of coal: effects of various parameters on combustion efficiency," Fluidization IV, Kunii, D. and R. Toei (Ed.), Eng. Foundation, New York (1983).
3. Oka, S., Dakic, D. and Arsic, B. "Low pollution and efficient combustion of low-grade coals," in Joint Yugoslav-German-Colloquium, Sarajevo (1986).
4. Hampartsonmian, E. and Gibbs, B.M. "The influence of fuel burning characteristics on the performance of a fluidized bed combustor," in 19th Symp (Int) on Combustion, 1253 (1983).
5. Vleeskens, J.M., Powder Technol, 40,323 (1984).
6. Yates, J.G. and Walker, P.R. "Particle temperatures in a fluidized bed combustor," in Fluidization, Grace, J.R. and J.M. Matsen (Ed.), p.241, Plenum Press, New York (1980).
7. Atintay, A.T. "Combustion of high ash containing coals in fluidized beds," Fluidization IV, Kunii, D. and R. Toei (Ed.), Eng. Foundation, New York (1983).
8. Vleeskens, J.M. and Nandi, B.N., Fuel, 65,797 (1986).
9. Chirone, R., D'Amore, M., Massimilla, L. and Mazza, A., AIChE J, 31,5,812 (1985).
10. Lau, I.T. "Development of a bench-scale fluidized bed combustor for coal reactivity studies," Division Report 84-31(TR), CANMET, Energy, Mines and Resources Canada (1984).
11. Lau, I.T. "Development of reactivity parameters for characterization of coal in fluidized bed combustion," in New Developments in Fluidization and Fluid-Particle Systems, Yang, Wen-ching (Ed.), published by AIChE, New York (1987).

FUEL	PARTICLE SIZE RANGE(mm)				
	12.7-25.4	4.76-12.7	3.36-4.76	0.84-3.36	0.60-0.84
WASHED REJECT	29.74	31.28	33.09	33.06	32.07
RAW COAL	29.09	30.28	29.23	28.3	27.86
DEEP CLEANED	38.36	38.42	38.69	37.84	36.89
MEDIUM CLEANED	36.17	36.58	36.9	36.42	35.98
OXIDIZED COAL	36.86	35.66	35.62	34.74	34.3
PETROLEUM COKE	6.1	6.24	6.22	6.36	6.88

TABLE 1: VOLATILE CONTENT OF FUELS(%db)

FUEL	PARTICLE SIZE RANGE(mm)				
	12.7-25.4	4.76-12.7	3.36-4.76	0.84-3.36	0.60-0.84
WASHED REJECT	30.95	25.69	20.07	18.64	21.48
RAW COAL	28.73	24.83	28.29	30.03	30.68
DEEP CLEANED	3.71	3.27	2.10	1.93	2.61
MEDIUM CLEANED	13.25	8.16	6.54	5.74	6.22
OXIDIZED COAL	2.38	3.18	1.83	1.95	2.23
PETROLEUM COKE	6.27	7.80	8.44	12.67	9.25

TABLE 2: ASH CONTENT OF FUELS(%db)

FUEL	PARTICLE SIZE RANGE(mm)				
	12.7-25.4	4.76-12.7	3.36-4.76	0.84-3.36	0.60-0.84
WASHED REJECT	51.63	56.83	62.98	63.90	61.40
RAW COAL	55.85	57.94	55.15	52.19	52.51
DEEP CLEANED	79.78	80.27	81.35	81.22	80.07
MEDIUM CLEANED	69.67	74.58	75.82	76.50	76.02
OXIDIZED COAL	77.94	76.50	76.33	76.85	77.38
PETROLEUM COKE	81.14	80.32	79.89	76.03	78.24

TABLE 3: CARBON CONTENT OF FUELS(%db)

FUEL	PARTICLE SIZE RANGE(mm)				
	12.7-25.4	4.76-12.7	3.36-4.76	0.84-3.36	0.60-0.84
WASHED REJECT	1	4	4.5	3	2.5
RAW COAL	1	4.5	2.5	1	0.5
DEEP CLEANED	7	4	7	6.5	6.5
MEDIUM CLEANED	2.5	2.5	3.5	3	2
OXIDIZED COAL	1	1	1	0.5	0
PETROLEUM COKE	—	—	—	—	—

TABLE 4: FREE SWELLING INDEX OF FUELS

FUEL	$\bar{t}_c(\text{min.})$				
	13	7.2	3.36-4.76	0.84-3.36	0.60-0.84
WASHED REJECT	3.15	2.50	1.19	0.55	0.40
RAW COAL	3.39	2.53	1.05	0.51	0.37
DEEP CLEANED	3.11	2.48	1.03	0.54	0.42
MEDIUM CLEANED	3.64	2.74	1.15	0.54	0.40
OXIDIZED COAL	5.20	4.66	1.68	0.71	0.47

TABLE 5: AVERAGE VALUES OF MEAN CARBON CONVERSION TIME FOR HIGH-VOLATILE BITUMINOUS COAL F

FUEL	TEMPERATURE (Degrees C)					
	620	650	770	800	850	900
WASHED REJECT	—	—	0.8	0.0	0.76	2.58
RAW COAL	23.64	3.3	0	1.13	1.15	2.0
DEEP CLEANED	18.8	2.17	3.55	4.0	3.98	4.39
MEDIUM CLEANED	—	—	3.24	3.55	3.88	4.39
OXIDIZED COAL	—	—	—	2.45	—	—
PETROLEUM COKE	0	0	0	0	—	—

Size Range :3.36–4.76mm

TABLE 6: COMPARISON OF UNBURNT CO , EXPRESSED AS A PERCENT OF THE TOTAL BURNT CARBON OF VARIOUS FUELS

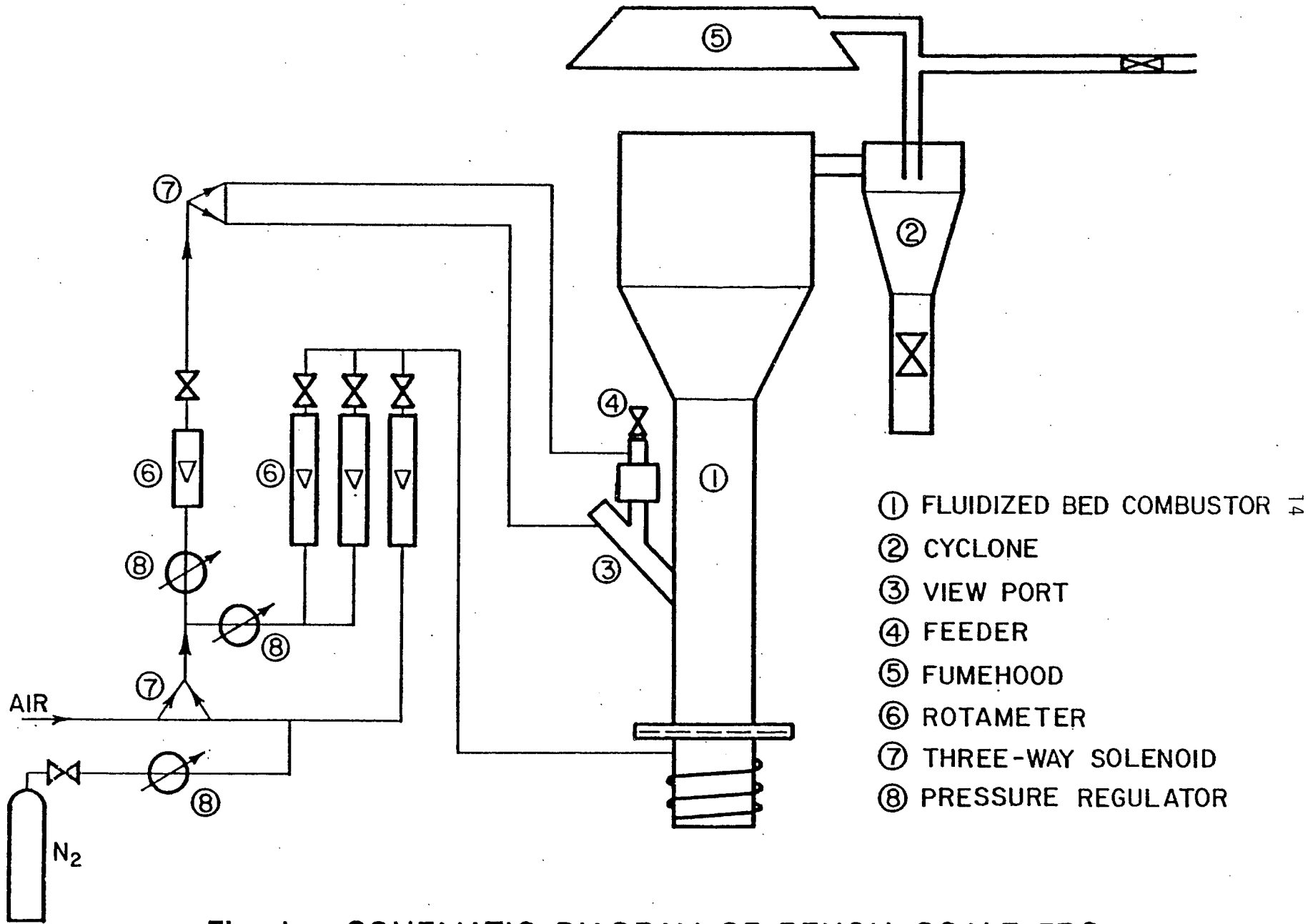


Fig. 1 - SCHEMATIC DIAGRAM OF BENCH-SCALE FBC

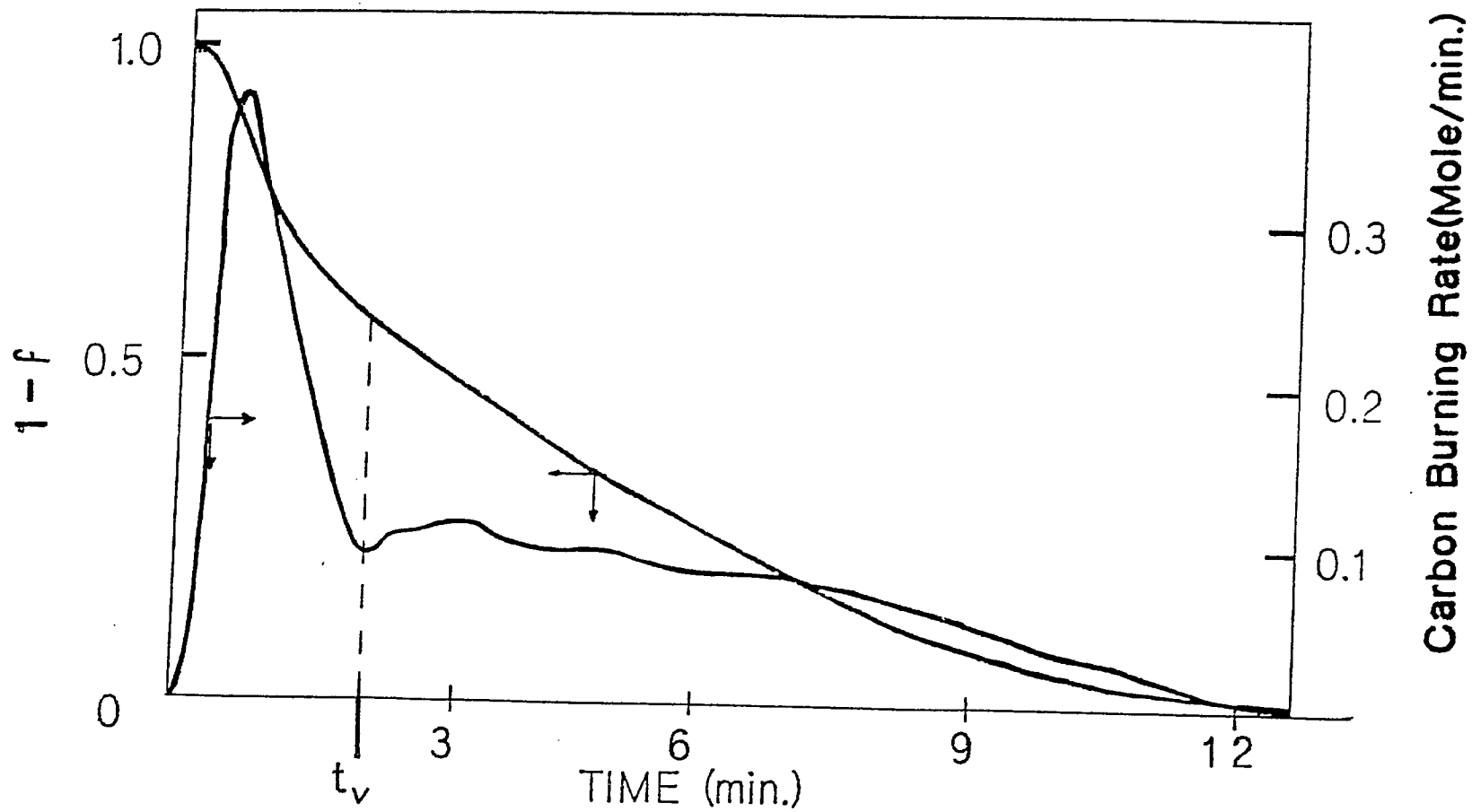


FIG. 2: Carbon Burning Rate and $1-f$ vs. Time

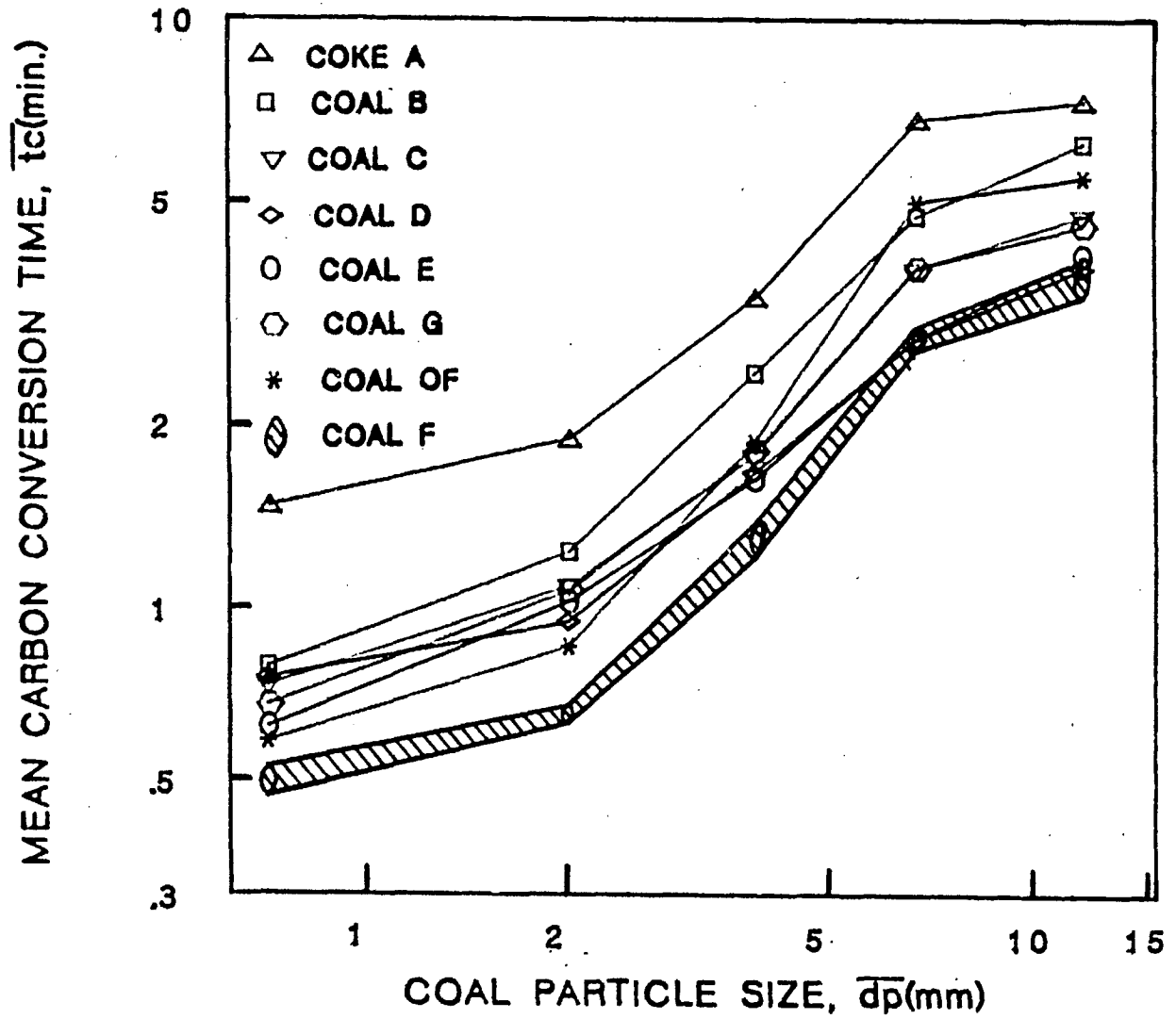


FIG. 3: Comparison of FBC reactivity of various fuels

MEAN FIXED CARBON CONVERSION TIME, $\overline{t_{ch}}$ (min.)

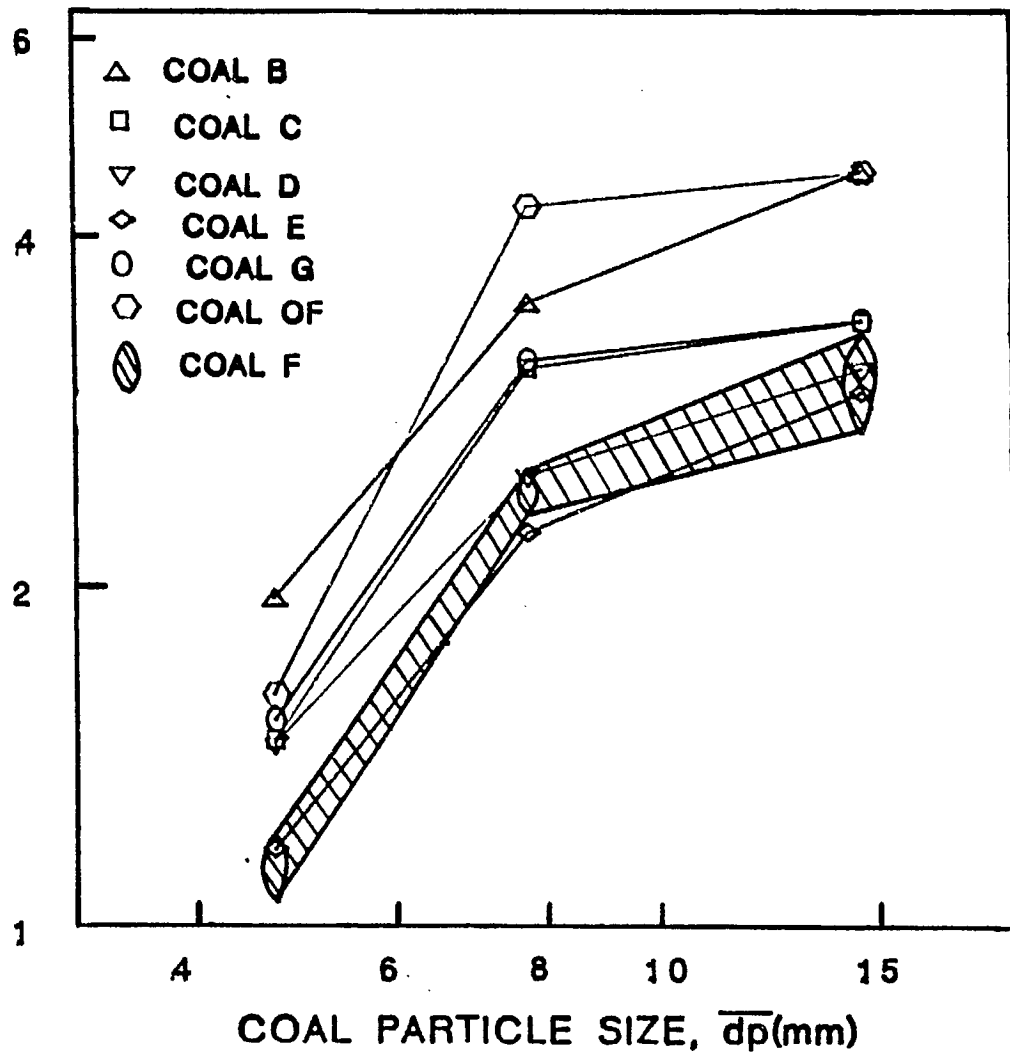


FIG. 4: Comparison of FBC reactivity of coal chars

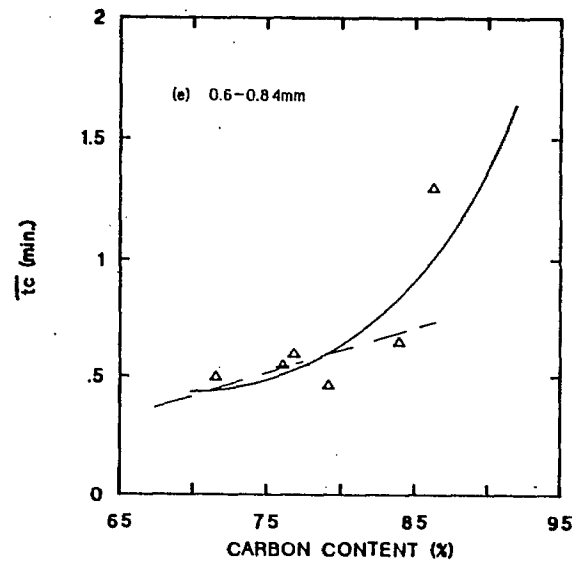
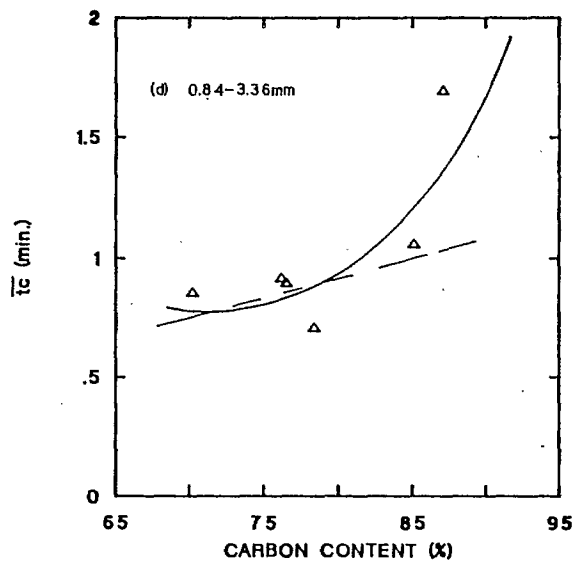
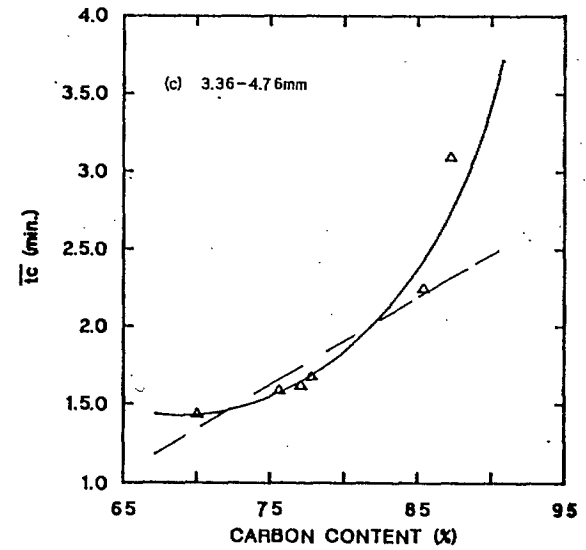
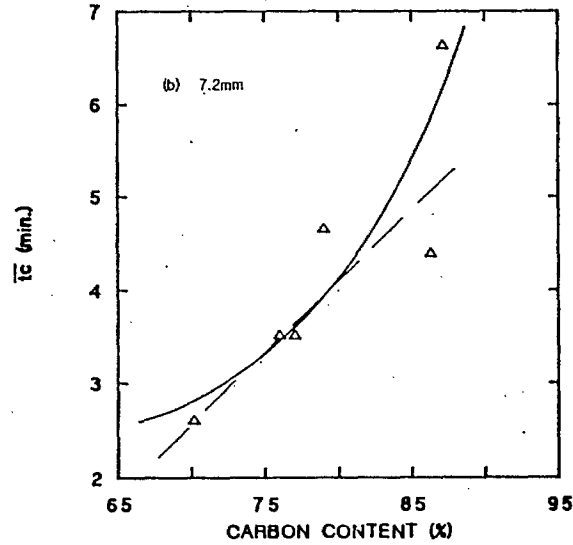
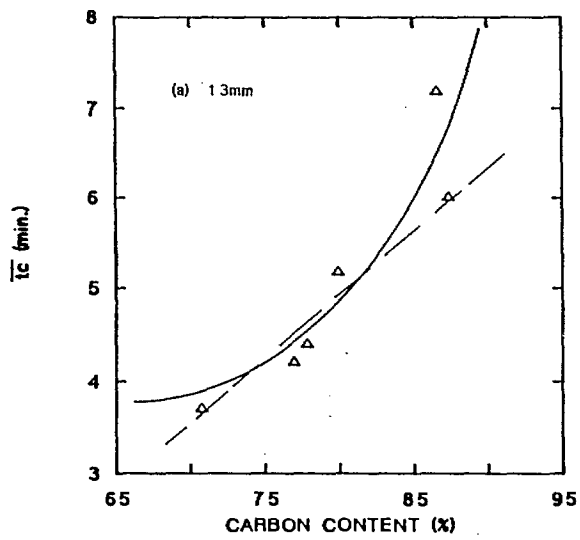


FIG. 5: Effect of carbon content on \bar{t}_c

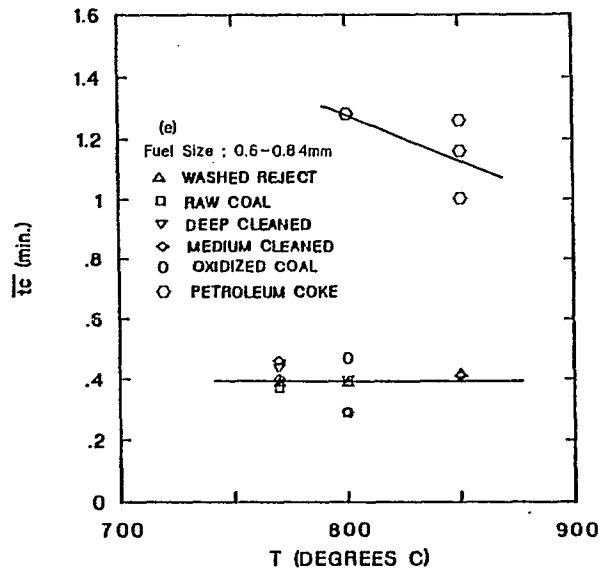
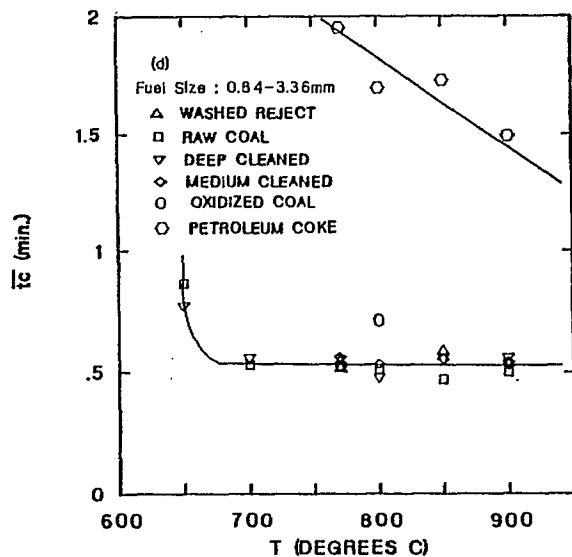
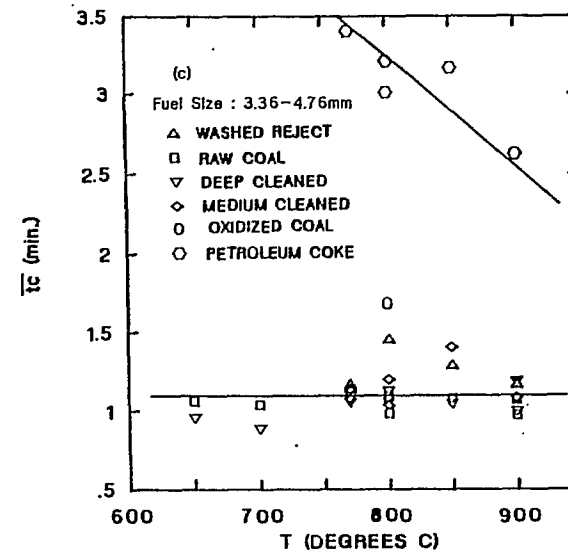
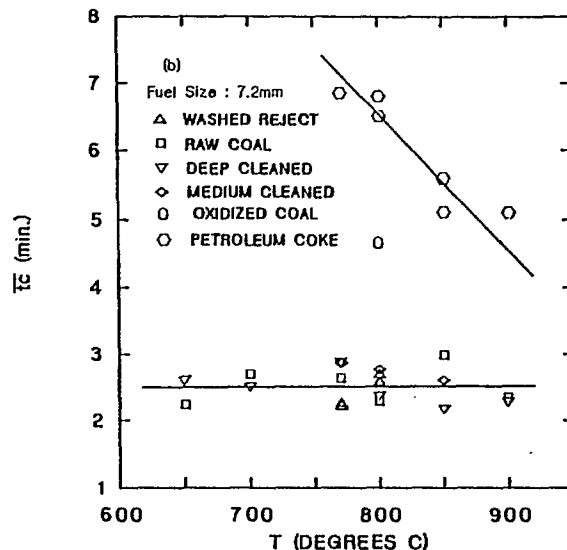
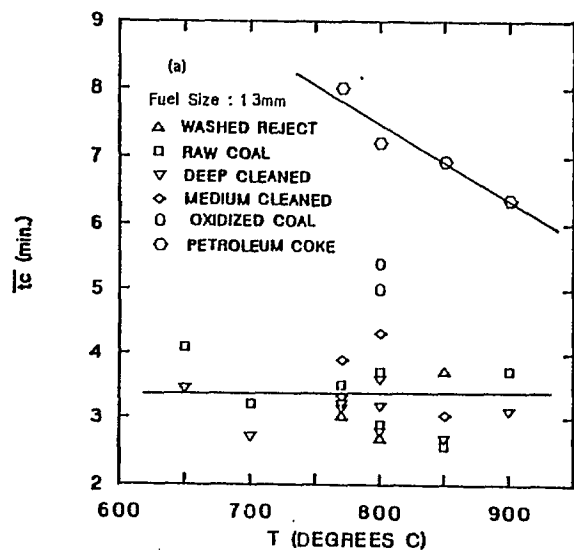


FIG. 6: Effect of bed temperature on \bar{t}_c

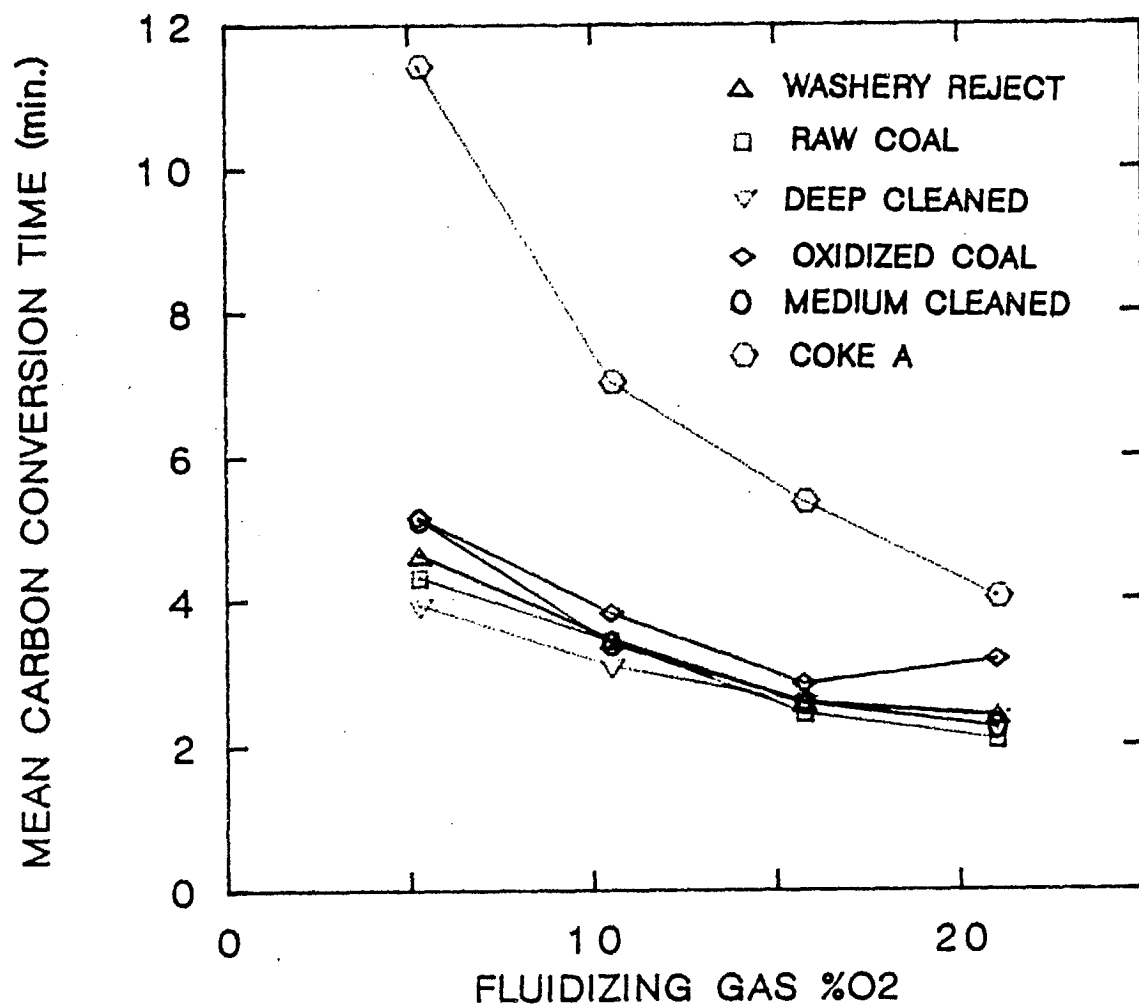


FIG. 7: Effect of Oxygen concentration

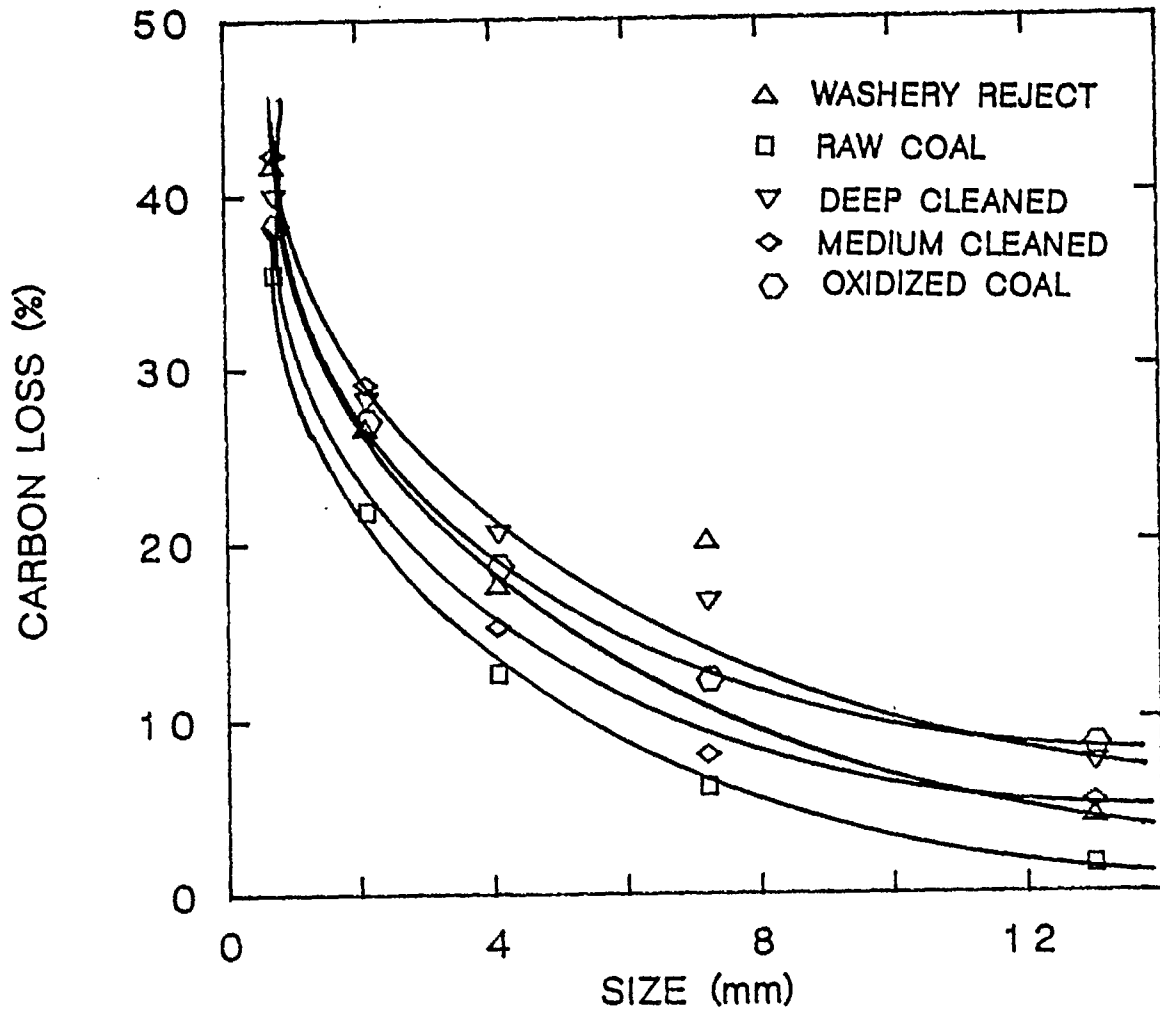


FIG. 8: Comparison of carbon loss of various fuels

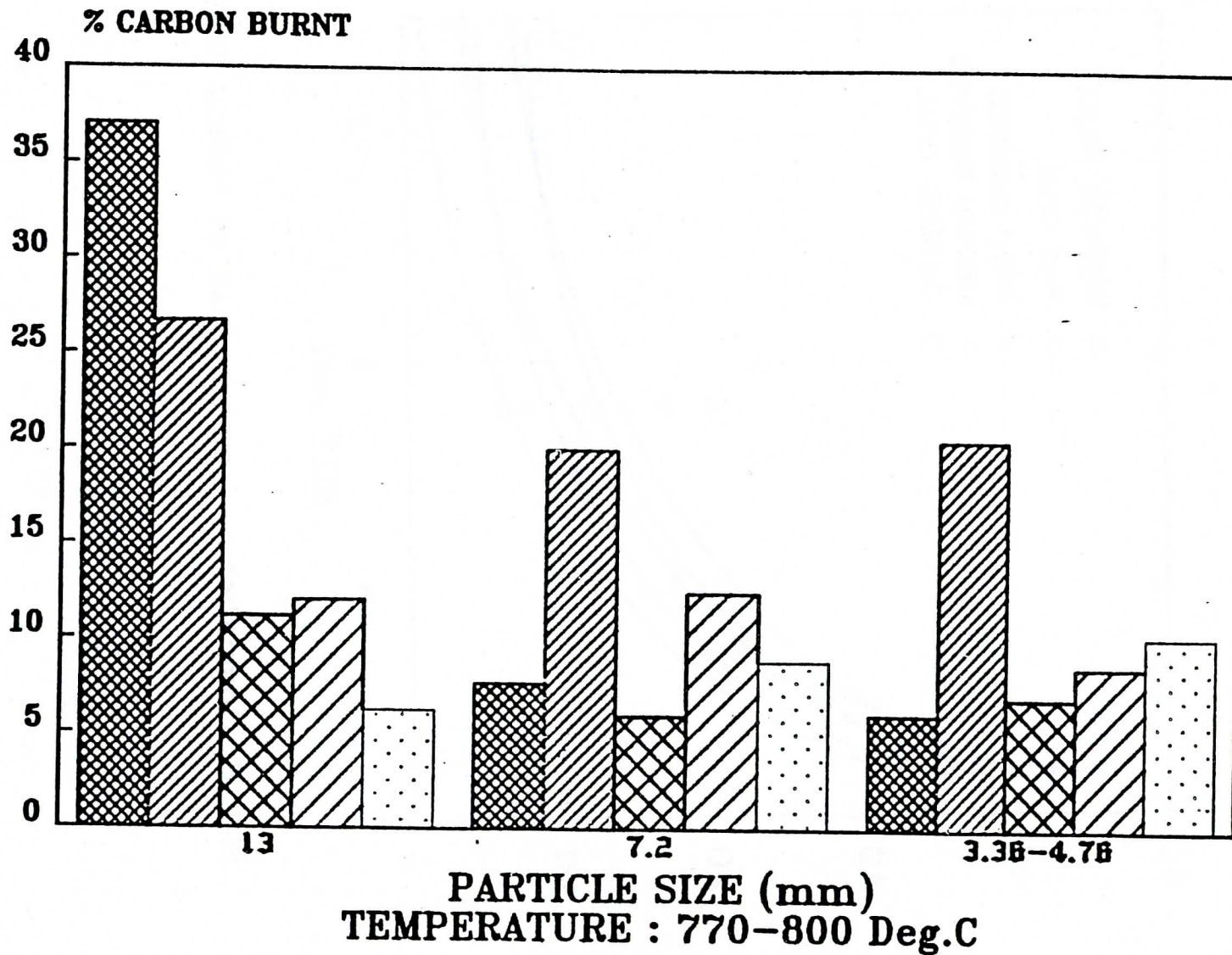


FIG. 9: % FIXED CARBON BURNT IN THE DEVOLATILIZATION PERIOD

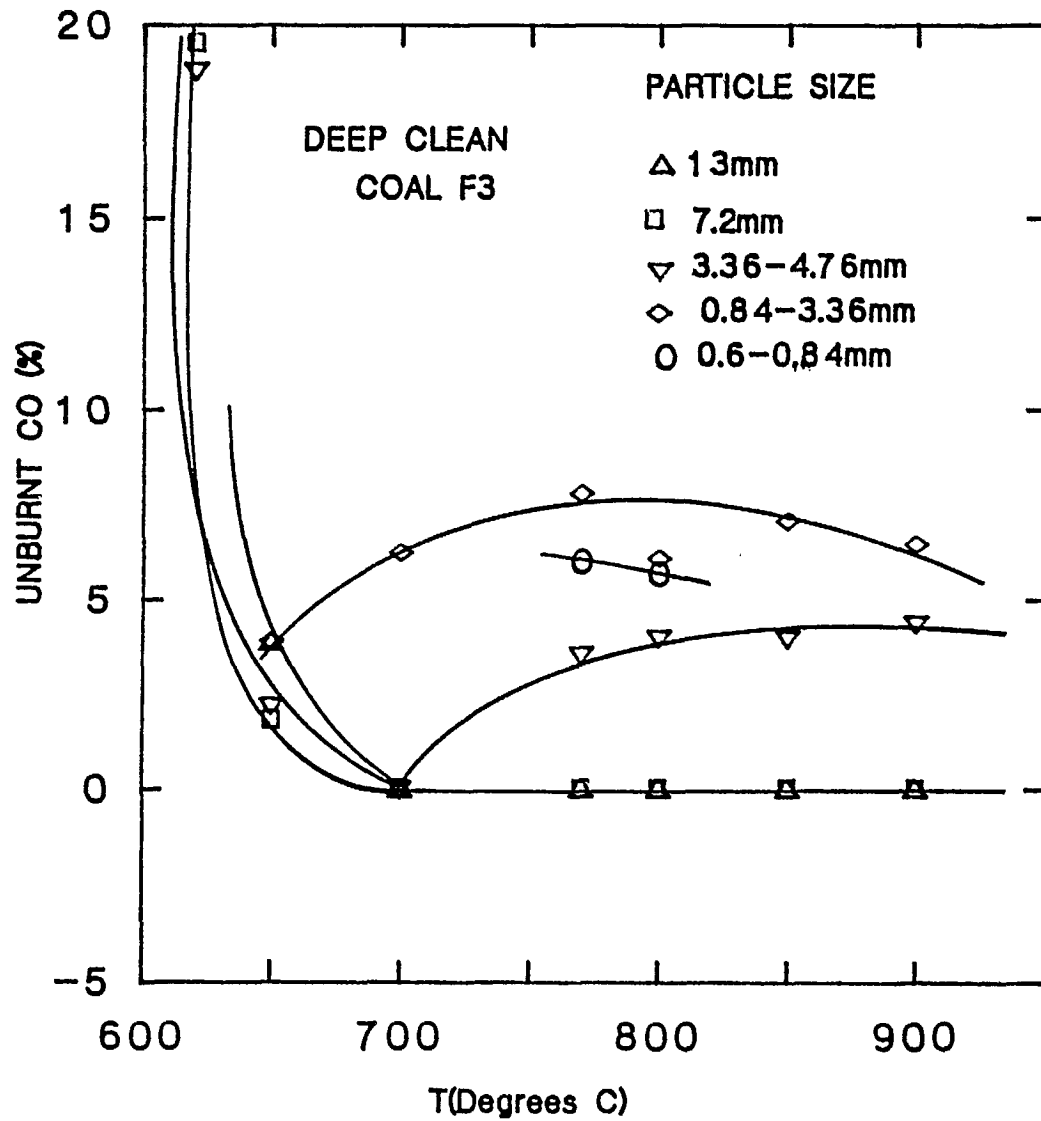


FIG. 10: Temperature effect on unburnt CO