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

FLUIDIZED BED COMBUSTION OF HIGH-SULPHUR MARITIME COAL

V.V. Razbin, E.J. Anthony, D.L. Desai and F.D. Friedrich

December 1984

DISPLAY COPY

ENERGY RESEARCH PROGRAM
ENERGY RESEARCH LABORATORIES
DIVISION REPORT 85-44 (OPJ)

FLUIDIZED BED COMBUSTION OF HIGH-SULPHUR MARITIME COAL

by

V.V. Razbin*, E.J. Anthony**, D.L. Desai* and F.D. Friedrich**

ABSTRACT

A high-sulphur bituminous coal from Eastern Canada, Devco Prince, containing up to 6% sulphur has been successfully burnt in a program of 36 tests using a pilot-scale atmospheric fluidized bed combustor. Three different size ranges of high calcium limestone, also from Eastern Canada, were employed to study the effects of limestone size on sulphur capture.

The tests were conducted at three fluidizing velocities: 1.2, 2.1 and 3 m/s, all at a bed temperature of 850°C and 20% excess air. Combustion efficiencies of up to 98% without fly ash recycle and up to 99.7% with fly ash recycle were obtained. When recycle was employed, the applicable SO_2 emission guideline of 705 ng/J was achieved with a Ca/S ratio of about 2.1 when limestone sized at 6.3 mm x 0 and 6.3 x 0.84 mm was used, whereas a Ca/S ratio of about 3.3 was required when using limestone sized at 2.38 x 0.84 mm.

Two tests were carried out for 24 h each to study the effect of longer operation on bed inventory, fluidization, sulphur capture and combustion performance.

*Research Engineers, and **Research Scientists, Combustion and Carbonization Research Laboratory, Energy Research Laboratories, CANMET, Energy, Mines and Resources Canada, Ottawa, K1A 0G1.

CONTENTS

TABLES

TABLES (Cont'd)

FIGURES

INTRODUCTION

Fluidized bed combustion (FBC) is suitable for burning coals containing any combination of high sulphur, high ash or high moisture. By using limestone as a sulphur sorbent, a reduction of 90% or more in SO_2 emissions can be achieved. Since fluidized bed combustors typically operate at temperatures from 750°C to 950°C they avoid slagging problems frequently encountered with conventional combustion technology (1,2). In addition, high heat transfer coefficients in the fluidized bed (200-510 $W/m^2/°C$) allow for more compact boiler designs (3).

Energy, Mines and Resources Canada is encouraging the development and application of FBC by sponsoring a wide range of research and demonstration projects (4). The first full-scale demonstration is a heating plant at Canadian Forces Base Summerside, Prince Edward Island, which consists of two boilers each rated at 18 t/h of steam (5,6). The project is supported by parametric studies of various fuels and sorbents, both in-house at the Combustion and Carbonization Research Laboratory (CCRL) and at Queen's University (7). This paper describes pilot-scale research on a high-sulphur bituminous coal, Devco Prince, from Eastern Canada which has been utilized at CFB Summerside. The major objectives were:

1. To evaluate the combustion performance of this coal, in terms of carbon carryover and pollutant emissions with and without fly ash recycle.
2. To evaluate the sulphur capture performance of a local limestone (Havelock, from New Brunswick) with this fuel as a function of the limestone size, to determine the Ca/S ratio necessary to maintain the SO_2 concentration at 705 ng/J (1.64 lbs/million BTU) heat input.
3. To briefly examine the effect of sodium carbonate as an additive to enhance the sulphur capture performance of the limestone.

PILOT-SCALE COMBUSTOR

The major components of CCRL's pilot-scale combustor are shown in Fig. 1. It consists of a combustor and freeboard assembly, systems for feeding fuel and sorbent, a multi-cyclone for flue gas clean-up with provisions for recycle of fly ash to the combustor, and appropriate instrumentation.

The combustor stands about 4.8 m high with external dimensions of 0.94 x 0.97 m and internal dimensions of 380 x 406 mm, giving a bed area of 0.155 m^2. The bed, which is lined with firebricks and insulating refractory bricks, is instrumented with thermocouples and pressure probes. In addition, there are inserts on two opposite faces of the bed to allow water-cooled tubes to pass through it. Although there is facility for up to 48 in-bed cooling tubes, in this study the number of tubes was kept constant at 16 to ensure the same hydrodynamic environment in the bed. Depending on the heating load, only some of the tubes were cooled.

The air distributor consists of a 9.5-mm thick mild steel plate fitted with 100 bubble caps to provide even distribution of the fluidizing air. The bubble caps, which are made from 32 x 13 mm diam stainless steel bolts, are arranged in a 35 x 38 mm rectangular pitch. These bolts are drilled with a 6-mm hole through their central axis and four 3-mm holes just below the head of the bolt. This arrangement prevents "weeping" and causes the air to egress horizontally. A 20-mm gap between the distributor plate and the bolt heads allows the plate to be covered with a dead layer of sand.

The fuel feed system consists of a coal hopper connected to a double screw-feed system. Each screw is variable speed. The screw in the bottom of the coal hopper is connected via a flexible fiberglass hose to the second water-cooled conveying screw which delivers the coal directly into the bed, 114 mm above the distributor plate. The hopper sits on an electronic weigh scale which permits feed rates to be calculated from the change of weight per unit time.

The multicyclone is connected in series to the freeboard by means of a "flexible" stainless steel duct. The cyclone products are either collected in a drum for non-recycle tests, or pneumatically reinjected into the bed during tests with cyclone ash recycle.

The instrumentation consists of NDIR recorders to continuously measure CO, CO_2 and SO_2 concentrations, a paramagnetic oxygen analyzer and a chemiluminescent NO_x analyzer. The temperatures in the bed, freeboard and cooling circuits are measured by "K type" thermocouples and the pressure drop across the bed by means of a manometer. With the exception of pressures, all data are logged every 2 min using an electronic data-logger.

A more detailed description of the apparatus has been published separately (8).

TEST FUEL AND LIMESTONE

The coal used in this study is a bituminous thermal coal from Sydney, Nova Scotia known as Devco Prince. It has a high sulphur content, normally 5%, although in these tests sulphur content varied from 3 to 6%. The ash composition with its high iron content is typical of Eastern Canadian coal. It is a reactive fuel, performing well in conventional pulverized-fired systems. Analytical data are given in Table 1.

For these studies the coal was fired "as received" with a size consist of 32 mm x 0. The size distribution of a representative sample is shown in Fig. 2.

Limestone from Havelock, New Brunswick was chosen as the sulphur sorbent for this research program both because other work (9,10) has indicated that it is a fairly good sulphur sorbent and because it is the main source of limestone for the FBC boiler demonstration at CFB Summerside (4). The analytical data for Havelock limestone are given in Table 2.

Three different size consists of limestone were used for these trials; 6.3 mm x 0 (or 1/4 in. x 0), 2.38 mm x 0.84 mm (or 8 x 20 mesh) and 6.3 mm x 0.84 mm (or 1/4 in. x 20 mesh). The first two of these are available commercially at a cost of about \$6/t for the 6.3 mm x 0 material, and about \$20/t for the 2.38 mm x 0.84 mm material, excluding transportation. The third limestone size consist was produced by sieving the 6.3 mm x 0 material. The main purpose in testing the different size consists was to explore the feasibility of utilizing the low-cost, single-screened material at CFB Summerside.

For these tests a starter bed of "brown sand" (silica sand) was used. This material had a mean size of 1 mm, a particle density of 2580 kg/m^3 and a bulk density of 1570 kg/m^3. A fresh charge of 100 kg of sand was used for each experiment. No attempt was made to achieve a limestone bed, since the turnover time varied from 4 to 14 h, and it has been suggested that three bed turnovers would be required, i.e., from 12 to 32 h of operation, depending on limestone feed rate, to ensure that over 95% of the bed material was limestone products (7). Instead, once the bed was up to temperature, coal and limestone were fed simultaneously, and when bed temperature, feed rates and SO_2 concentration in the flue gas had stabilized, data were collected over a period of 3 to 6 h. In addition, two 24-h runs demonstrated combustion efficiencies and sulphur capture similar to those from the shorter runs under comparable conditions, and thus indicated that the shorter runs had achieved an effective equilibrium.

TEST PROGRAM AND PROCEDURE

The test program was divided into five sections. Common operating conditions for all tests were:

- bed temperature, which was maintained as nearly as possible to 850°C;
- bed height, which was maintained between 610 and 710 mm (24 and 28 in.);
- excess air, which was maintained at about 20%, or 3.6 % O_2 in the flue gas.

Test duration was typically 3 to 6 h (except for two 24-h runs) after establishment of steady-state conditions, that is, after bed temperature, feed rates and SO_2 emissions had become relatively constant.

In the first section, which was intended to establish baseline emission levels, the coal was burnt in a sand bed, without limestone addition, with and without cyclone ash recycle, at three different fluidizing velocities. Results of these tests (BDC-1 through BDC-5) are given in Table 3. Results for BDC-6 (fluidizing velocity 1.2 m/s, with recycle) are not reported cause an analyzer malfunction, not detected at the time, rendered the data unreliable.

The second series of tests, labelled DC-1 through DC-18, was intended to evaluate the effect of limestone size consist on SO_2 capture. Therefore the coal was burnt in the presence of three different sizes of limestone, at three different fluidizing velocities, with and without cyclone ash recycle. These results are presented in Tables 4, 5 and 6. Unfortunately, sulphur content of the coal varied considerably, and because analysis of the coal fired during each test was not available until well after the tests were completed, Ca/S ratios varied from the target of 3:1. Again, because of an analyzer malfunction, no data are reported for DC-13 (6.3 x 0.84 mm limestone, fluidizing velocity of 3.0 m/s, without recycle).

In the third series of tests, the objective was to establish, for each limestone size consist, the lowest possible Ca/S ratio which would achieve the Environment Canada emission guideline of 705 ng SO_2/J of heat input. Thus tests DC-20 through DC-24 were conducted at a constant coal feed rate while limestone feed rate was varied to obtain a constant level of SO_2 in the limestone gas. Tests were performed with and without cyclone ash recycle and the results are given in Table 7.

The fourth section aimed to determine the effect on sulphur capture of adding Na_2CO_3 to the limestone. Four tests were run (DC-25 through DC-28) using 2.38 x 0.84 mm limestone, with and without cyclone ash recycle, with additions of 0.1 and 4.0 mol % Na_2CO_3 to the limestone. Fuel feed rate and fluidizing velocity were held constant, while limestone feed rate, and hence Ca/S ratio, was varied to maintain SO_2 emissions at or below a target of 705 ng/J of feed input. The results are presented in Table 8.

Finally, in the fifth section, two 24-h runs were carried out (EDC-1 and EDC-2) to determine whether results would be comparable to those from shorter runs, and whether buildup of oversize particles in the bed would present a risk of defluidization. Two sizes of limestone were used, cyclone ash recycle was employed, and fluidizing velocity was periodically reduced from 2.1 m/s to 1.2 m/s, to check for potential defluidization. The results are presented in Table 9.

With respect to cyclone ash recycle, it must be explained that the pilot plant is not equipped for continuous measurement of recycle rate. It can be determined approximately by directing the recycle stream from the multicyclone into a drum for a given period of time, and weighing the quantity thus collected, but this procedure upsets the bed inventory and thus changes the rate one is attempting to measure. Therefore recycle rate was measured by this means for only a few tests, which determined it to be about 1.6 times the coal feed rate. On this basis, recycle rate is assumed to be 1.6 for all tests involving cyclone ash recycle.

DISCUSSION

24-h TESTS

The primary objective of the two 24-h runs was to study the effects of continuous operation on bed inventory and hence fluidization. A secondary objective was to compare the combustion performance and SO_2 reduction with tests of shorter duration.

In the test employing 6.3 mm x 0 limestone as sulphur sorbent, after 12-h operation the fluidizing velocity was reduced from 2.1 m/s to 1.2 m/s. In about 1.5 h the temperature at 50 and 125 mm bed levels started to drop, indicating onset of defluidization due to accumulation of larger particles in this region. After approximately 5.5 h at the lower velocity, the temperature difference between the 200 mm level and the 306 mm level began to increase, indicating incipient defluidization at the 200 mm level. The fluidizing velocity was then increased to 2.1 m/s, whereupon the temperature in the lower levels of the bed rose to near the mean bed temperature, indicating that good fluidization had been re-established.

In the other test, which employed 2.38 mm x 0.84 mm limestone, again the fluidizing velocity was reduced to 1.2 m/s after about 12-h operation at 2.1 m/s velocity. Approximately 8 h later, the temperature at the 50 mm bed level began to drop, indicating onset of defluidization. Subsequently the temperature difference between the 125 mm bed level and the 306 mm bed level increased by more than 20°C. The fluidizing velocity was then increased to 1.5 m/s, whereupon fluidization was restored in the lower section of the bed and the temperature there rose close to the mean bed temperature.

These observations indicate that at a fluidizing velocity of 1.2 m/s defluidization can be a problem, but less so with 2.38 mm x 0.84 mm limestone than with 6 mm x 0 limestone. Also, a partially defluidized bed can be restored to satisfactory operation by increasing the fluidizing velocity.

The longer-term tests showed no differences in sulphur neutralization, combustion efficiency and flue gas concentrations when compared with tests of shorter duration at similar conditions. Thus, it is concluded that reliable test data on sulphur neutralization and combustion efficiency can be obtained from short-term tests once steady-state operation has been achieved.

SULPHUR RETENTION WITH AND WITHOUT LIMESTONE ADDITION

The Devco Prince coal for these tests was received in three batches, which varied in sulphur content from 2.8% to 6%. In the tests without limestone the average SO_2 concentrations in the flue gas would be about 5190 ppm if all sulphur were converted to SO_2, but it was observed that the average SO_2 concentration during the tests was 4630 ppm. This indicates that the ash constituents of the coal captured about 11% of the total sulphur.

Twenty-four tests were conducted with this coal, adding limestone of three different sizes as mentioned earlier. The Ca/S molar ratio varied between 2.03 and 4.86 except in one test where it was 5.7. It was observed that with all three sizes of Havelock limestone, the sulphur capture was significantly higher in the tests with cyclone ash recycle compared with those without cyclone ash recycle. Also, the 6.3 mm x 0 limestone, which incidentally is the cheapest, provided better sulphur capture than the other two. This is due to the presence of a large proportion of fine particles, providing greater surface area for reaction. Also, the 6.3 x 0.84 mm limestone performed better than the 2.38 x 0.84 mm limestone. It is believed that this is because when the 6.3 x 0.84 mm limestone was produced by sieving the 6.3 mm x 0 limestone, some fine particles adhered to the larger particles.

A sulphur capture ranging from 51.1% to 79.6% was achieved with Ca/S ratios of 3.0 to 4.1 in the tests without recycle. In the tests with recycle, Ca/S ratios of 3.2 to 4.9 resulted in sulphur capture ranging from 73.0% to 94.2%. As stated earlier, spot measurements indicated that the recycle rate was about 1.6 times the coal feed rate.

In tests DC-19 to DC-24, in which limestone feed rate was adjusted to meet the SO_2 emission guideline of 705 ng/J of heat input, limestone size and cyclone ash recycle were found to have the following effects on Ca/S ratio:

Limestone size	Ca/S ratio without recycle	Ca/S ratio with recycle
6.3 mm x 0	4.11	2.02
6.3 x 0.84 mm	4.10	2.10
2.38 x 0.84 mm	4.06	3.30

As stated earlier, the 24 h runs produced similar results. Clearly it is important to include cyclone ash recycle in the design of commercial FBC units.

The following equations correlating sulphur retention and Ca/S ratio were obtained:

$$\% \text{ S retention} = 100 [1-\exp[-(0.054 \text{ Ca/S} - 0.337)\text{Ca/S}]] \text{ (with recycle)} \quad (1)$$

$$\% \text{ S retention} = 100 [1-\exp[(0.033 \text{ Ca/S} - 0.447)\text{Ca/S}]] \text{ without recycle)} \quad (2)$$

With an increase in the fluidizing velocity the sulphur capture decreased slightly in all tests.

In the fourth section of tests with Devco Prince coal, 2.38 x 0.84 mm limestone was sprayed with Na_2CO_3 solution, 0.1% and 4% per mole of limestone, to study the effect of Na_2CO_3 addition on sulphur capture. Table 8 shows that the addition of Na_2CO_3 produced some improvement in sulphur capture when there is no recycle of cyclone ash but has no significant effect when recycle is employed.

COMBUSTION EFFICIENCY OF CARBON

The carbon losses at the various test conditions, calculated as a percentage of carbon fired, are given in Tables 3 to 9. With recycle, carbon loss varied from 0.3% to 3.8% whereas without recycle it varied from 1.8% to 7.4%, except for one test, in which it was 0.6%, and three tests, involving Na_2CO_3 addition or baseline tests, in which it was over 9%. The recycle clearly improves the combustion efficiency of carbon.

Most of the unburnt carbon was found in the cyclone ash and the fly ash which escaped the cyclone. The carbon loss in the bed material was negligible. In all tests, the combustion efficiency decreased slightly as the fluidizing velocity increased. Different sizes of limestone did not have any significant effect on the combustion efficiency. There is considerable scatter in the data and no attempt has been made to obtain a correlation.

NO_x EMISSIONS

The NO_x concentrations in the flue gas varied from 234 to 622 ppm, but in most of the tests were less than 480 ppm. The data are scattered and there is no apparent correlation between NO_x concentration and the fluidizing velocity or limestone size consist. In tests with addition of limestone, NO_x concentrations were slightly lower than in the baseline tests. Also, the NO_x concentrations in the tests with recycle were lower than in the tests without recycle, with only one exception.

CO EMISSIONS

CO concentration in the flue gas varied widely; from 247 ppm to 1670 ppm in the tests without Na_2CO_3 addition, and from 1342 ppm to 2814 ppm in the tests with Na_2CO_3 addition. The data reveal no correlation between CO concentration and limestone size consist, fluidizing velocity, or cyclone ash recycle.

SUMMARY AND CONCLUSIONS

1. Devco Prince coal containing up to 6% sulphur was burnt successfully in a pilot-scale atmospheric fluidized bed combustor. Combustion efficiencies ranged from 96.2% to 99.7% with cyclone ash recycle and from 92.6% to 98.2% without cyclone ash recycle.

2. In the tests without limestone approximately 11% of SO_2 was captured by the coal ash constituents. A total sulphur capture of 51.1% to 79.6% was achieved with Ca/S ratios of 3.0 to 4.06 respectively without cyclone ash recycle. With recycle, the total sulphur capture ranged from 73.0% to 94.2% with Ca/S ratios of 3.2 to 4.9 respectively.

3. With cyclone ash recycle, the SO_2 emission guideline of 705 ng/J of heat input was met with Ca/S ratios of 2.02, 2.1 and 3.3 with 6.3 mm x 0, 6.3 x 0.84 mm and 2.38 x 0.84 mm limestone respectively. For sulphur capture, 6.3 mm x 0 appears to be the most effective limestone size.

4. With the addition of Na_2CO_3 to the limestone, sulphur capture improved slightly.

5. In industrial applications the cyclone ash should be recycled to the bed to improve significantly the combustion efficiency and sulphur capture.

6. In 24-h tests defluidization in the lower section of the bed was observed at 1.2 m/s fluidizing velocity after 12-h operation at 2.1 m/s velocity. But by increasing the velocity to 1.5 to 2.1 m/s, good fluidization was restored.

7. NO_x emission in the flue gas varied from 234 to 622 ppm at a bed temperature of about 850°C.

REFERENCES

1. Makansi, J. and Schwieger, B. "Fluidized-bed boilers"; Power S1-S16; 1982.

2. Haque, R., Dutta, M.L. and Chakrabarti, R.K. "Fluidized bed combustion of high sulphur coal"; Journal of the Institute of Energy 413:173-177; Vol. L11; 1979.

3. Botterill, J.S.M. "Fluid bed heat transfer"; Academic Press 229-277; London; 1975.

4. Friedrich, F.D. "A review of major Canadian activities in fluidized bed combustion"; The Seventh International Conference on Fluidized Bed Combustion 644-658; Philadelphia, Pennsylvania; 1982.

5. Taylor, M.E.D. and Friedrich, F.D. "The CFB Summerside Project: Canadian state of the art in AFBC boilers"; Division Report ERP/ERL 82-10(TR); CANMET, Energy, Mines and Resources Canada; 1982.

6. Razbin, V.V. and Friedrich, F.D. "The CFB Summerside Project: Initial operating experience with 18 tph AFBC heating boilers"; Division Report ERP/ERL 83-40(OP)(TR); Energy, Mines and Resources Canada; 1983.

7. Becker, H.A. and Code, R.K. "Pilot scale trials on atmospheric fluidized bed combustion of high-sulphur eastern Canadian coals (Minto and Devco) with limestone addition for sulphur capture"; Technical Report QFBC TR 83-1; Queen's Fluidized Bed Combustion Laboratory; Prepared for Energy, Mines and Resources Canada; 1983.

8. Hector, D.R., Desai, D.L., Friedrich, F.D. and Anthony, E.J. "Description of the Mark II atmospheric fluidized bed combustor at the Canadian Combustion Research Laboratory"; Division Report ERP/ERL 81-55(TR), Energy, Mines and Resources Canada, Ottawa; 1981.

9. Friedrich, F.D. "The CFB Summerside Project: An AFBC boiler for high sulphur coal and wood chips"; Fluidized Combustion Systems and Applications; Institute of Energy Symposium Series No. 4; Session I(6), IB-2-1-IB-2-9; 1980.

10. Stover, N.S.H., Anthony, E.J., Desai, D.L. and Friedrich, F.D. "Combustion performance and sulphur capture of a Western sub-bituminous coal and an Eastern bituminous coal"; American Society of Mechanical Engineers; Winter Annual Meeting; Washington, D.C.; 1981.

Table 1 - Analytical data for the test coal

Ultimate and proximate analysis of Devco Prince coal		Ash analysis for Devco Prince coal	
Proximate Analysis	wt % dry	Major element	wt %
Ash	17.8	SiO_2	37.3
Volatile	33.1	Al_2O_3	23.6
Fixed carbon	49.1	Fe_2O_3	30.1
		TiO_2	0.7
Ultimate Analysis,	wt % dry	P_2O_5	0.1
		CaO	1.5
Carbon	66.8	MgO	1.3
Hydrogen	4.3	SO_3	1.5
Sulphur	avg. 5.2*	Na_2O	0.5
Nitrogen	1.4	K_2O	2.2
Ash	17.8		
Oxygen (by difference)	4.5		
Gross calorific value, MJ/kg	27.1		
Equilibrium moisture wt %	4.0		

*range: 2.8 to 6%.

Table 2 - Analytical data for Havelock limestone

Component	wt %
$CaCO_3$	94.6
$MgCO_3$	1.83
Fe_2O_3	0.37
Al_2O_3	1.37
SiO_2	3.08
Na_2O	0.03
K_2O	0.15
S	0.02

Table 3 - Operating conditions for Devco Prince coal without limestone

Baseline Tests

Test No.	BDC1	BDC2	BDC3	BDC4	BDC5
Limestone size mm			N/A		
Coal kg/h	58.7	57.4	43.3	40.5	26.2
Limestone kg/h			N/A		
Ca/S ratio			N/A		
Bed temp °C	860	860	855	858	853
Fluidizing vel. m/s	3.0	3.0	2.1	2.1	1.2
Recycle	No	Yes	No	Yes	No
O_2 %	4.3	4.2	3.5	3.5	3.3
CO_2 %	14.4	14.1	14.3	13.2	14.7
SO_2 ppm	4408	4450	4569	3816	5081
CO ppm	1600	1300	1580	1631	777
NO ppm	475	468	416	439	506
Carbon loss %	9.4	-	9.9	-	7.4
SO_2 reduction %	12.1	9.1	13.4	8.3	9.0

Table 4 - Operating conditions for Devco Prince coal and Havelock limestone sized 6.3 x 0 mm. Target Ca/S ratio 3:1

Test No.	DC1	DC2	DC3	DC4	DC5	DC6
Limestone size mm	<---------------- 6.3 x 0 ------------------------>					
Coal kg/h	47.5	49.2	37.5	36.6	23.2	21.9
Limestone kg/h	24.0	22.2	17.8	15.9	12.4	11.5
Ca/S ratio	4.49	4.04	4.11	3.77	5.71	4.86
Bed temp °C	852	856	849	850	849	847
Fluidizing vel. m/s	3.0	3.0	2.1	2.1	1.2	1.2
Recycle	No	Yes	No	Yes	No	Yes
O_2 %	3.7	3.5	3.4	3.3	3.3	3.6
CO_2 %	12.7	12.6	13.4	14.4	14.4	16.0
SO_2 ppm	736	315	650	197	534	141
CO ppm	1160	411	1623	1277	1007	1397
NO ppm	314	318	349	338	288	268
Carbon loss %	6.8	1.6	5.9	1.3	3.4	0.3
SO_2 reduction %	71.4	87.6	76.2	92.8	75.8	94.2

Table 5 - Operating conditions for Devco Prince coal and Havelock limestone sized 2.38 x 0.84 mm. Target Ca/S ratio 3:1

Test No.	DC7	DC8	DC9	DC10	DC11	DC12
Limestone size mm	<----------------		2.38 x 0.84			---------------->
Coal kg/h	58.2	52.2	39.3	40.2	24.4	22.9
Limestone kg/h	24.3	24.1	20.0	18.6	11.8	12.3
Ca/S ratio	2.57	3.15	3.29	2.84	3.04	3.33
Bed temp °C	852	854	850	851	854	860
Fluidizing vel. m/s	3.0	3.0	2.1	2.1	1.2	1.2
Recycle	No	Yes	No	Yes	No	Yes
O_2 %	3.3	3.5	3.3	3.3	3.6	3.5
CO_2 %	14.5	15.0	14.2	15.2	13.4	15.2
SO_2 ppm	1478	952	992	819	1859	782
CO ppm	1081	1075	672	1199	367	247
NO ppm	368	319	493	339	622	543
Carbon loss %	7.4	1.0	7.2	1.1	5.7	0.5
SO_2 reduction %	62.9	73.0	73.2	78.4	51.1	79.3

Table 6 - Operating conditions for Devco Prince coal and Havelock limestone sized 6.3 x 0.84 mm. Target Ca/S ratio 3:1

Test No.	DC14	DC15	DC16	DC17	DC18
Limestone size mm	<----------------		6.3x0.84		---------------->
Coal kg/h	48.1	39.2	36.0	23.2	22.1
Limestone kg/h	24.3	17.7	16.5	11.1	9.9
Ca/S ratio	4.43	3.42	3.90	4.64	3.77
Bed temp °C	849	852	849	850	849
Fluidizing vel. m/s	3.0	2.1	2.1	1.2	1.2
Recycle	Yes	No	Yes	No	Yes
O_2 %	3.0	3.7	3.4	3.0	3.5
CO_2 %	13.0	13.1	14.1	15.1	13.6
SO_2 ppm	251	1235	309	554	283
CO ppm	504	910	1430	573	1098
NO ppm	366	332	291	395	284
Carbon loss %	3.8	3.6	0.9	0.6	0.4
SO_2 reduction %	90.9	58.6	88.2	76.9	89.3

Table 7 - Operating conditions for Devco Prince coal and Havelock limestone. Ca/S ratio varied to obtain constant SO_2 emissions

Test No.	DC20	DC21	DC22	DC23	DC24
Limestone size mm	6.3-0	<2.38x0.84>		<6.3x0.84>	
Coal kg/h	35.6	38.9	37.3	36.2	38.3
Limestone kg/h	8.1	19.5	12.9	18.5	12.0
Ca/S ratio	2.02	4.06	3.30	4.10	2.10
Bed temp °C	851	850	849	850	847
Fluidizing vel. m/s	<-------------------- 2.1 -------------------->				
Recycle	Yes	No	Yes	No	Yes
O_2 %	3.6	3.4	3.7	3.6	3.5
CO_2 %	13.0	15.4	13.8	14.4	13.5
SO_2 ppm	599	591	582	650	660
CO ppm	1670	842	1530	1088	1328
NO ppm	419	404	335	359	412
Carbon loss %	0.6	5.5	1.2	1.8	1.1
SO_2 reduction %	76.8	79.6	75.8	75.9	82.2

Table 8 - Operating conditions for Devco Prince coal and Havelock limestone sized at 2.38 x 0.84 mm with addition of Na_2CO_3

Test No.	DC25	DC26	DC27	DC28
Na_2CO_3 mol %	<-- 0.1 -->		<----- 4.0 ---->	
Coal kg/h	36.8	31.6	35.0	32.6
Limestone kg/h	13.9	8.0	8.3	7.2
Ca/S ratio	3.43	2.20	2.38	2.14
Bed temp °C	849	846	848	850
Fluidizing vel. m/s	<--------------- 2.1 --------------->			
Recycle	No	Yes	No	Yes
O_2 %	3.4	3.3	3.4	3.3
CO_2 %	12.3	12.6	12.0	12.6
SO_2 ppm	590	664	630	687
CO ppm	1342	1655	2008	2814
NO ppm	397	372	266	213
Carbon loss %	5.8	1.4	9.4	0.9
SO_2 reduction %	80.0	75.2	75.0	72.3

Table 9 - Operating conditions for Devco Prince coal and Havelock limestone during 24-h runs

Test No.	EDC1	EDC1	EDC1	EDC2	EDC2
Limestone size mm	<------- 6.3x0		--------->	<2.38x0.84>	
Coal kg/h	35.3	21.1	28.7	33.2	21.9
Limestone kg/h	11.3	7.4	10.4	11.7	8.2
Ca/S ratio	2.03	2.22	2.29	2.23	2.37
Bed temp °C	840	843	847	842	850
Fluidizing vel. m/s	2.1	1.2	2.1	2.1	1.2
Recycle	<------------------		Yes		------------------>
O_2 %	3.3	3.4	3.3	3.5	3.6
CO_2 %	15.3	15.0	13.7	14.5	15.2
SO2 ppm	122	147	166	634	620
CO ppm	1327	469	310	1097	556
NO ppm	255	234	296	361	464
Carbon loss %	1.4	-	-	2.4	1.4
SO_2 reduction %	93.2	92.2	92.0	74.1	68.6

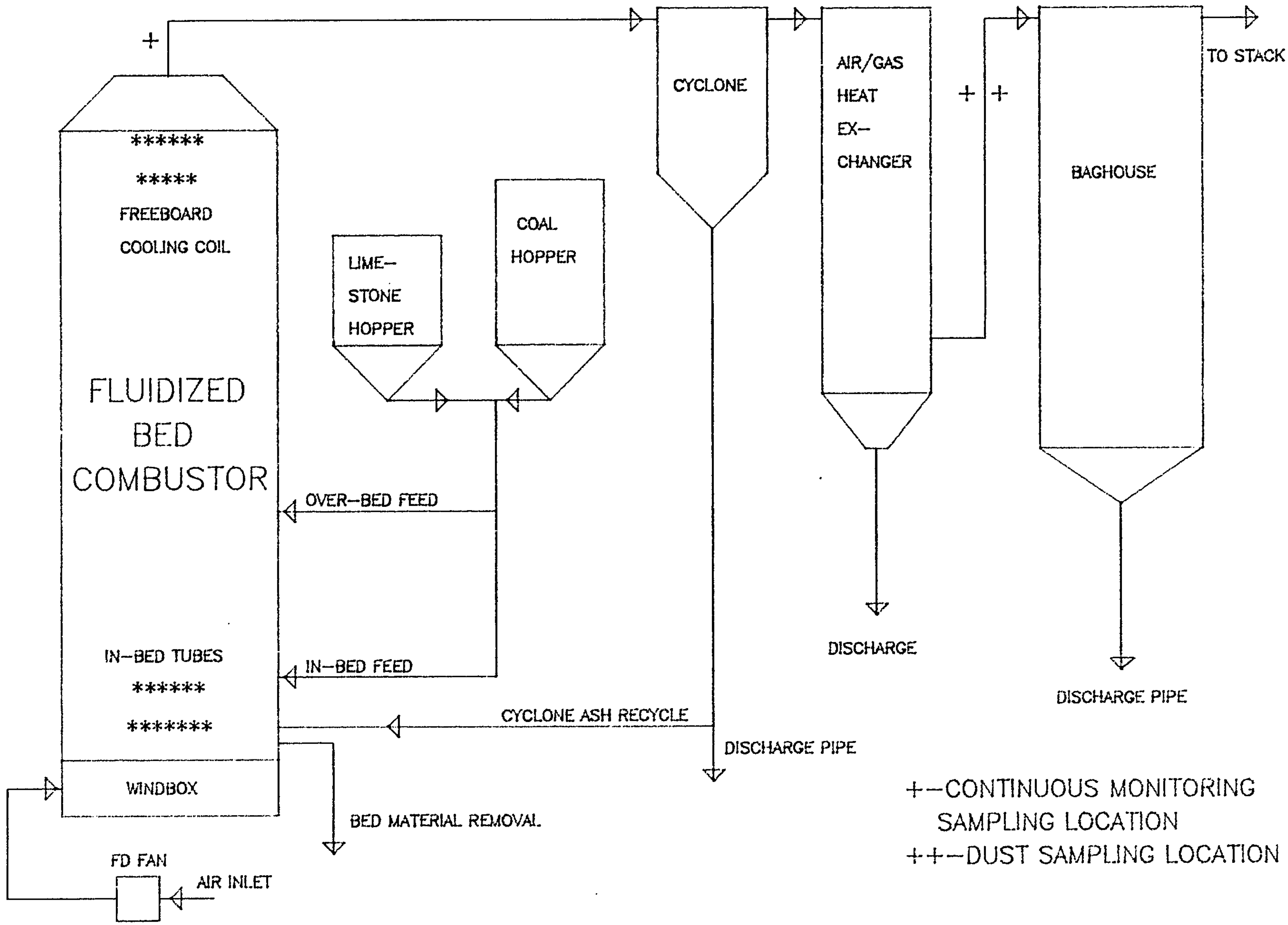

Figure 1 - Schematic of the major components of the pilot-scale FBC

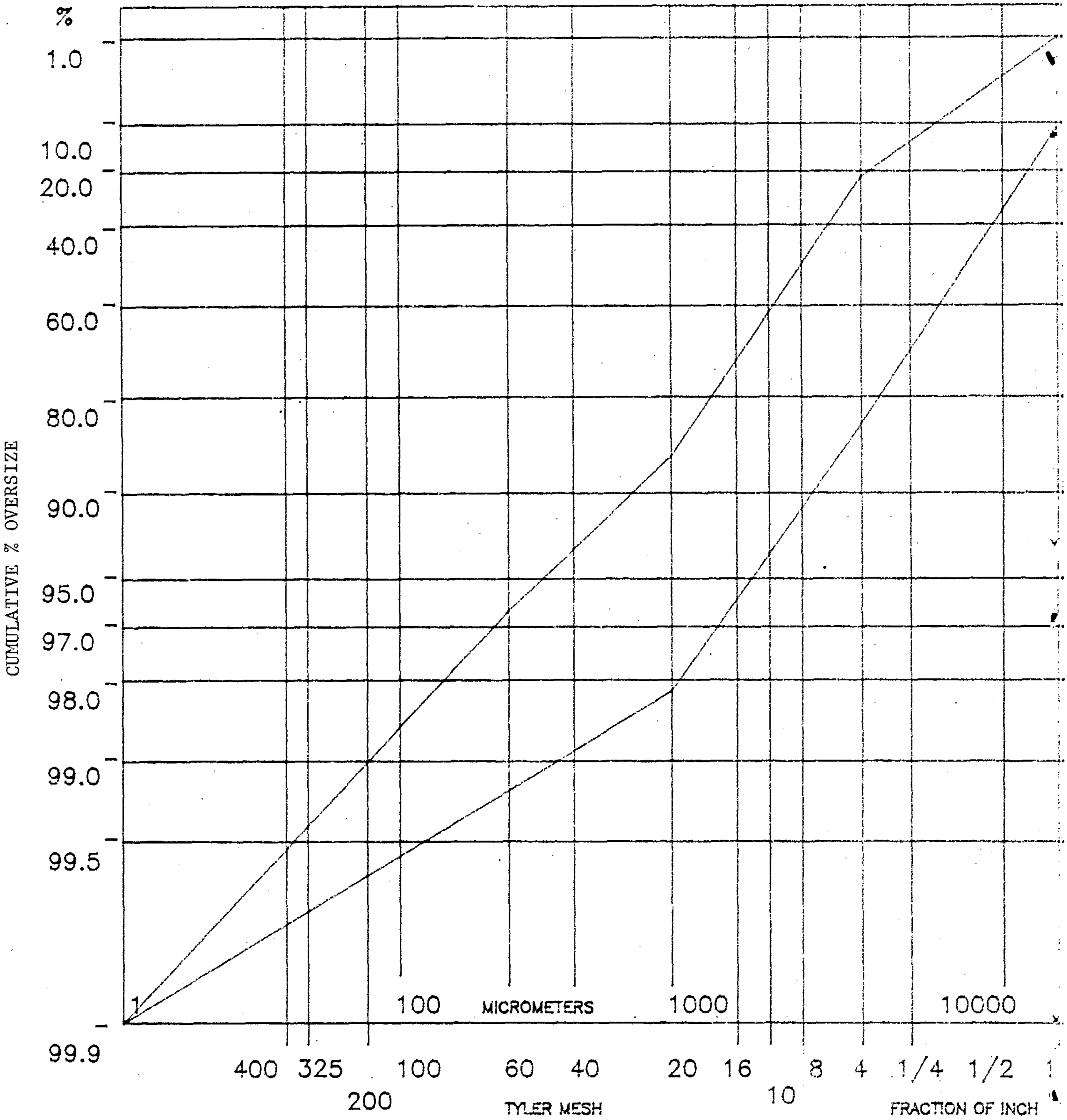

Figure 2 - Size distribution of the test coal.