EMERGING CLEAN COAL TECHNOLOGIES IN CANADA

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EMR/CANMET/Energy Research Laboratories
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ABSTRACT

Canada generates over 17% of its electricity from pulverized coal-fired stations.. Most stations are mine mouth plants using indigenous coal; the others are supplied from readily accessible domestic or import sources. A variety of coals from lignite to low-volatile bituminous are burned cleanly, reliably and efficiently in units ranging in size from approximately 100 to 500 MWe. Over the next 20 years coal-fired capacity is forecast to grow by about 25% from 17.6 to 21.7 GW using both conventional and emerging technologies.

A number of clean coal initiatives have been demonstrated or will soon be in commercial service. These include utility applications of circulating fluidized bed combustion, low-NO_x flames, furnace sorbent injection, de-NO_x treatment and slagging combustion. A detailed design of an integrated gasification combined cycle (IGCC) generating station has also been completed. Two central heating boilers incorporating a bubbling fluidized bed and a low NO_x/SO_x burner have been successfully commissioned.

The full-scale demonstration projects have been extensively supported by pilot-scale combustion facilities for pulverized coal, circulating and bubbling fluidized beds and flame diagnostics in conjunction with process and furnace modelling and emissions characterization.

INTRODUCTION

Canadian thermal coals ranging from lignite to low-volatile bituminous are being burned successfully for heat and electricity by both domestic and foreign utilities. Development of technology to reduce operating costs, improve equipment availability, increase fuel flexibility and control emissions is on-going and several novel installations are being commissioned or are being seriously considered.

This paper describes the properties of Canadian thermal coals currently being marketed and highlights recent initiatives by the Canadian utility industry to burn coal cleanly, efficiently and economically. It also gives an overview of the research capabilities available to support the development and commercialization of new technologies for generating energy from coal.

THERMAL COAL SUPPLIES

Canada's easily and economically recoverable coal reserves are conservatively estimated at 7Gt or 2.5% of the total coal resources. At current rates of production these reserves, which range from lignite to low-volatile bituminous, are predicted to last more than 100 years. Between 1981 and 1991 domestic thermal coal production increased from 25 to 41 Mt/a while imports mostly from the United States declined slightly from 9.5 to 7.7 Mt/a. Exports primarily to South Korea, Denmark and Japan increased steadily from 1.9 to 5.4 Mt during the same period. Forecasts indicate that by the year 2020 thermal coal production will reach 110 Mt/a and that imports at 18 Mt will marginally exceed exports of 17 Mt (1).

Table 1 shows the average properties of the coals currently being burned by electrical utilities in Canada and overseas. Generally the sulphur content of the lower rank and low-volatile bituminous coals varies from 0.2 to 0.8% whereas that of the high-volatile bituminous coals varies from 1 to 3% with one mine running as high as 8%. All of these coals have nitrogen contents ranging from 0.5 to 2.0% with 1.0% being an average value.

ELECTRICITY GENERATION

Most of the thermal coal mined in Canada is used for electricity generation. Between 1989 and 2000 Canada's coal-fired generating capacity is projected to increase by 23.3% from 17.6 to 21.7 GW. These facilities which now provide about 18% of the nation's electricity demand will be sufficient to meet the expected future increase in coal consumption over the same period. It is anticipated that the annual demand for electricity from coal will grow from 91.7 TWh in 1988 to 111.1 TWh in 2000.

Table 1 - Average properties of Canadian thermal coals

Province	Rank	CV MJ/kg		Proximate analysis, wt %									
				M		A		VM		FC		S	
		R	C	R	C	R	C	R	C	R	C	R	C
Nova Scotia	hvb	25	30	7	5	15	7	28	34	44	53	3.0	3.0
New Brunswick	hvb	27	--	3	--	20	--	31	--	46	--	8.0	--
Saskatchewan	lig	15	--	36	--	10	--	26	--	28	--	0.5	--
Alberta	sub	18	--	22	--	12	--	28	--	36	--	0.3	--
	hvb	19	25	13	8	30	11	25	34	31	44	0.3	0.4
	mvb	28	31	5	7	20	10	20	22	59	60	0.3	0.3
	lvb	29	33	6	6	15	7	16	20	61	68	0.4	0.4
British Columbia	hvb	27	--	7	--	11	--	35	--	47	--	0.5	--
	mvb, lvb	25	26	7	7	24	16	22	22	60	56	0.5	0.5

Abbreviations used for rank:
lig = lignitic
sub = subbituminous
hvb = high-volatile bituminous
mvb = medium-volatile bituminous
lvb = low-volatile bituminous

Abbreviations used for proximate analysis:
M = moisture
A = ash
VM = volatile matter
FC = fixed carbon

Other abbreviations:
CV = higher heating value on moist basis
S = sulphur
C = cleaned coal
R = run-of-mine coal

All coal-fired utility boilers in Canada are pulverized-fired with wall or tangential burner arrays mounted in dry bottom furnaces. Unit sizes range from 25 to 500 MW and plant generating capacities range from 50 to 4300 MW. Ash slagging and fouling of fireside surfaces are rarely a problem because the furnaces are designed to accommodate the fluid temperatures of the ash which range from 1100 to 1482°C in a reducing atmosphere. Emissions from existing units are monitored by provincial authorities whereas new sources are designed to comply with federal guidelines that currently specify 258 ng/J for SO_2, 258 ng/J for NO_x and 43 ng/J for particulate matter. As a signatory to the Convention on Global Warming, Canada is committed to limiting national CO_2 emissions to 1990 levels. Consequently reliable cost-effective technology that maximizes the conversion of coal to electricity is a priority consideration in the selection of all new coal-fired generators.

PULVERIZED COAL TECHNOLOGY

Utility Initiatives

A number of innovative clean coal technologies are being implemented or are planned for future installation by Canadian utilities. These include a variety of systems for retrofitting to existing units and emerging processes for new units. Some are described below.

Retrofit Projects

To meet provincial targets for acid gas emissions several operational units have been modified or are being studied for retrofitting of selected abatement technologies.

In Western Canada, NO_x targets for existing units burning low-sulphur lignites and subbituminous coals are being met by reducing and biasing the combustion air. At Poplar River Generating Station, low cost changes to a 300 MWe lignite-fired boiler with tangential burners resulted in NO_x reductions of 20% from about 260 ng/J to 195 ng/J at full load; urea injection decreased NO_x levels to about 150 ng/J with little or no N_2O production. Additional trials on this unit with a system that combines in-furnace limestone injection with post-furnace humidification successfully reduced SO_2 emissions from a 150 MWe slipstream by 50% to meet federal guidelines. The solid residue containing fly ash, lime and reacted sorbent improves the natural pozzolanic properties of the fly ash component and can be used to produce low strength concrete for mine backfilling. A mixture with 80% of the cement in normal concrete replaced by the ash residue has an ultimate compressive strength of about 12 MPa after 40 d (2).

A recent project aimed at suppressing NO_x emissions in subbituminous coal-fired boilers with tangential burners has demonstrated that federal guidelines can be met with very inexpensive hardware changes. The key to consistent performance was the development of an expert system that monitors critical operating parameters including boiler load, burner tilt and combustion air distribution in conjunction with O_2, CO and

NO_x levels in flue gas. A maximum CO limit of 40 ppm places a priority on increasing excess air. During field trials in a 400 MWe unit at Sundance Generating Station, NO_x reductions of 17% and a boiler efficiency improvement of 0.25% were obtained at high load. Table 2 shows the averaged data for both the high and low load trials before and after installation of the smart system.

Table 2 - Smart system NO_x reductions

Trial	Boiler load, MWe			
	>350		>200	
	NO_x ppm	0_2%	NO_x ppm	0_2%
Baseline	196	2.7	203	2.8
Smart System	161	2.2	184	2.3

These trials indicated that the NO_x avoidance cost with this system, at approximately \$50/t, is substantially lower than alternative retrofit technologies such as selective catalytic reduction or low NO_x burners. The cost of retrofitting this expert system is estimated at \$0.5 million or \$1.25/kW.

Four 150 MWe boilers, two with wall and two with tangential burners, were evaluated by Nova Scotia Power Incorporated to determine their suitability for retrofitting SO_2 and NO_x removal processes upstream of the airheater. Three units burn high-sulphur, high-volatile bituminous coal and one unit burns heavy fuel oil. A two-dimensional modelling code was used to compute the gas temperature profiles within each furnace. These profiles were then upgraded by field measurements which indicated that this simplified model slightly underestimated the actual gas temperatures. As a result of this evaluation, a tangentially-fired boiler at Point Tupper Generating Station was selected to demonstrate a proprietary SO_2/NO_x removal process that involves co-injection of a limestone slurry and a urea solution in the 1050°C-1260°C temperature region of the upper furnace. A demonstration is scheduled to start in 1993, subject to funding approval. Capital equipment and installation costs for the SO_2/NO_x removal process are estimated at \$9.9 million or \$66/kW and operating and maintenance costs for limestone slurry injection only are estimated at \$4 million/a. Operating and maintenance costs for urea injection are significantly higher per tonne of acid gas than competing technologies.

Acid rain emissions at Lambton Generating Station are being substantially reduced through a program to retrofit four 500 MWe tangentially-fired boilers with NO_x and SO_2 abatement processes. All units burn imported coal containing about 3% sulphur. Low NO_x burner systems will be installed in 1993. Wet scrubbers for SO_2 control will be in service on two units in 1994 and on the other two in 1996.

New Units

Two new units, one rated at 300 MWe on lignite with opposed wall firing and one rated at 450 MWe on high-volatile bituminous coal with tangential firing, are now being commissioned. Both units incorporate low NO_x combustion and sulphur capture systems. The Shand Generating Station unit which burns low-sulphur lignite was originally designed for in-furnace sorbent injection only. This was changed to include post-furnace humidification because the federal limit of 258 ng/J can be met with a lifetime cost advantage of $10 million. The capital cost of the combined limestone/humidification SO_2 removal system was $75/kW compared with $15/kW for in-furnace sorbent injection only and $256/kW for a wet scrubber.

The high-volatile bituminous coal unit at Belledune Generating Station is capable of burning offshore as well as domestic coals and is equipped with a wet limestone scrubber to provide SO_2 emissions below 258 ng/J on a 3.9% sulphur coal. If required the scrubber can reduce SO_2 emissions on this coal to 130 ng/J. At a stoichiometric ratio of 1.02 mol of calcium carbonate per mole of reacted SO_2, the scrubber operates at 95% removal efficiency. The capital cost of this system is about $330/kW. The solid waste from the scrubber will be deposited at an on-site landfill lined with a membrane to prevent the escape of leachates.

Industrial Boilers

A central heating boiler rated at 74G J/h of hot water has been operating routinely since 1988 with a limestone injection multi-staged burner [LIMB] system. The unit has two front wall, variable swirl burners with four circumferential ports for the injection of staging air and powdered limestone. Flame pulsations, rear water wall erosion due to coal impingement, unsteady limestone metering and high carbon in ash were resolved by using detailed three-dimensional furnace modelling studies to determine flame temperature, O_2 depletion, heat transfer and carbon conversion patterns as the flow rates of air and coal were varied (3). The selected hardware changes produced excellent control of both flame shape and flame stability with high-volatile bituminous coals. As shown in Fig. 1 and 2, relative to the modified burners, NO_x levels decreased by 50% and SO_2 levels decreased by 50% and 25% respectively with 3% and 1% sulphur coals while using a calcium mole ratio of 3.0.

A full scale demonstration of a slagging burner prototype in a 52 GJ/h steam generator for heavy oil recovery has been completed. In this system a pulverized mixture of coal and limestone is injected into an entrained flow reactor where partial gasification of the coal occurs. Combustion air staging is used to enhance a) char burnout in the combustor, b) sulphur capture by calcium species in the slag,

c) conversion of fuel nitrogen to N_2, and d) flowability of slag at the burner exit. During field trials with a 0.3 sulphur subbituminous coal having an ASTM ash fluid temperature of 1431 °C in a reducing atmosphere, NO_x and SO_2 emissions respectively were below 86 ng/J and 128 ng/J. Carbon burnout consistently exceeded 99% and ash removed as slag varied from 50 to 65%. In addition a number of component designs were verified or improved. These included coal splitter and injector, slag tap, burner refractory, and burner management system. Commercialization of the technology is open to interested parties with boiler manufacturing and marketing capabilities.

PULVERIZED COAL RESEARCH AND DEVELOPMENT

Following is a summary of major Canadian activities in pulverized coal combustion being performed at CANMET and other laboratories.

In-house Research

1. *Mathematical modelling*
   Two-/and three-dimensional codes for modelling burner air/fuel mixing, furnace heat transfer, and specie reactions are being applied to improve equipment availability, reduce stack emissions and optimize costs. Model verification by field measurements is an important element of these studies.

2. *Simulation and Process Control*
   Energy and combustion efficiencies are being optimized by developing neural networks to simulate and control conventional and chaotic systems. Trade-offs between process and environmental concerns can be examined and sensor strategies optimized.

3. *Coal reactivity*
   A 50 mm diameter by 2 m long entrained flow reactor provides time/temperature histories of coal devolatilization and char burnout. These data are used in mathematical models and evaluations of combustion and gasification processes.

4. *Ash sintering potential*
   A high temperature apparatus has been developed for measuring electrical conductivity and dilatation of ash. It provides an inexpensive method for predicting the on-set and severity of ash deposition on boiler surfaces.

5. *Laser optical measurements*
   A portable Coherent Anti-Raman Stokes (CARS) spectroscopy system has been developed for non-invasive measurements of temperature and specie concentrations in flames. This system is complemented by laser sheet illumination (LSI) and laser doeppler anemometry (LDA) to measure velocity and turbulence fields.

6. *Combustion evaluations*
Most thermal coals that are marketed in Canada have been characterized in a pilot-scale research boiler for combustion performance, ash fouling and slagging tendency, ash precipitation, and stack emissions. This facility, rated at 0.7 MWt, is direct fired and can be easily altered to provide variable furnace residence times.

7. *Flame studies*
These are carried out in a 0.7 MWt calorimetric tunnel furnace designed for detailed probing of flames by optical or intrusive means. It is ideal for studying near burner field mixing, flame ignition and stability, and pollutant kinetics.

8. *Gasification*
A small scale slagging gasifier provides data to quantify feedstock reactivity, gasification products and effluent streams while using CO_2, O_2 or steam mixtures. The data are being used to predict the performance of coals in various gasification processes.

9. *Analytical standards*
Extensive analytical work is being performed as part of CANMET's contribution to standards development by ISO, ASTM and IUAPC. This work covers protocols for analyses of coal and ash, solid combustion products, trace elements and leachates.

External Agencies

1. *Ontario Hydro*
This utility has a facility with a 0.25 m^2 shaft that simulates utility furnace chill rates. Research is being conducted on air and fuel staged flames, in-furnace sorbent injection, post furnace reduction of SO_2 and NO_x, trace element emissions and ash precipitation.

2. *Alberta Environment Centre*
This centre specializes in sampling and analyzing trace elements, trace organics and air toxics as well as the toxicology of combustion residues. Other programs focus on solid waste management, hazardous waste destruction and land rehabilitation.

FLUIDIZED BED TECHNOLOGY

Incentives for Development

Canadian interest in fluidized bed combustion has been driven primarily by environmental concerns. FBC's potential to minimize both SO_2 and NO_x emissions made it attractive for Eastern Canada, where the only indigenous fuel available is coal, most of it containing from 3 to 10% sulphur. In Western Canada possible applications were seen in utilizing high-sulphur residues from heavy oil upgrading, and high-ash rejects from coal preparation plants.

CANMET, the research arm of Energy, Mines and Resources (EMR), accordingly initiated a pilot-scale FBC research program in 1975, that focused on bubbling bed technology. An industrial-scale demonstration was undertaken shortly thereafter, prompted by the sharp rise in oil prices.

Summerside Project

Plant Description

To meet the challenge of utilizing indigenous coal in an environmentally acceptable manner the federal government sponsored a demonstration of fluidized bed combustion technology in a heating plant at Summerside, Prince Edward Island. CANMET was responsible for design development and accomplished this through competitive design contracts which incorporated American and British technology. Key specifications are given in Table 3.

Table 3 - Design specifications for Summerside fluidized bed heating plant

No. and capacity of boilers:	2, each rated at 18 tph of steam, 760-965 kPa.
Boiler efficiency (HHV or ASME basis):	80%
Design coal:	
Type:	High-volatile bituminous
Moisture:	0-10%
Ash:	16-22%
Sulphur:	5-6%
Volatile matter (dry basis):	33.5%
Fixed carbon (dry basis):	47.2%
Calorific value, gross:	23.2-27.7 MJ/kg
Allowable emissions:	
SO_2:	705 ng/J of heat input
Particulates:	86 ng/J of heat input

The successful design was a shop-assembled, natural circulation boiler, shown schematically in Fig. 3. A main feature is a waterwall furnace divided into two unequal beds, called preferential and secondary beds. The smaller, preferential bed provides the first 40 to 50% of steam capacity, and is equipped with the light-up burner. It is cooled only by the circumferential waterwalls. The secondary bed is brought into service for the upper half of the load range. In addition to the circumferential cooling it has an array of inclined evaporator tubes passing through the bed. The secondary bed is ignited from the preferential bed by means of a gate in the waterwall which divides them. All fuel feed is overbed, accomplished by spreader stokers. The freeboard is several times the bed depth and allows ample time for complete combustion. Details of Canada's first full-scale coal-fired FBC installation completed in December 1982 are reported elsewhere (4).

Design Improvements

Frequently the case with demonstrations of emerging technology, the Summerside plant experienced a variety of operational problems. These and their resolutions are documented elsewhere (4,5). The two most serious issues related to erosion were resolved by CANMET.

Erosion of the heat exchange surfaces in contact with the bed became evident in the first month. During the first three heating seasons various corrective measures were implemented, with unsatisfactory results. Rate of metal loss on the waterwalls enclosing the beds was as high as 0.4 mm/1000 h of operation, and varied substantially, as shown in Fig. 4. Rate of metal loss on the in-bed tubes in the secondary bed was as high as 1.7 mm/1000 h of operation. It also varied circumferentially but according to location in the bed as well. Through extensive erosion mapping programs the rate of erosion was correlated to physical features of the bed such as fly ash reinjection ports, a few extra-large bubble caps which had been installed to prevent peripheral downwash, and size segregation of the bed material induced by the solids injection and removal systems.

Simple protective hardware consisting of pin studs on the waterwalls and longitudinal rods on the in-bed tubes effectively prevented further wastage of pressure parts. In 10 000 h of operation the pin studs only lost 10 to 20% of original length, with a few small areas losing 50%. Heat transfer from the bed was increased, which improved boiler performance.

The second erosion issue was excessive maintenance of the pneumatic eductors and double lock hopper systems which were provided for fly ash reinjection from the boiler convection banks and mechanical dust collectors. These were ultimately replaced by a CANMET-patented, L-valve which provides reliable particulates reinjection at low velocity, with no moving parts, and with substantially reduced power requirements.

Demonstration Program

Concurrently, an extensive demonstration program managed by CANMET was incorporated into the daily operation of the heating plant. Five bituminous coals were tested for boiler performance and emissions, at loads from 22 to 100% of maximum capacity rating. Sulphur content ranged from 4.1 to 11.3% and sulphur capture of 80% or more was achieved with Ca/S ratios of about 2:1 at low loads and 3:1 at high loads. Details are published elsewhere (6).

Emissions Testing by the U.S. Environmental Protection Agency

In early 1986, after the reliability of the Summerside fluidized bed boilers was well established, the U.S. Environmental Protection Agency requested permission to conduct a continuous 30-d emissions testing program. The objective was to obtain data on which to base New Source Performance Standards for small FBC boilers. Operating conditions were selected to sustain 90% sulphur capture on a high-sulphur Eastern Canadian coal. The salient results of this rigorously-conducted program are summarized in Table 4.

Table 4 - Results of U.S. EPA tests at Summerside

Coal specifications	
Type:	Bituminous A
Typical moisture, %:	7.2
Typical ash, %:	10.6
Typical sulphur, % wet basis:	5.5 (range: 4.7-7.1)
Size, mm:	25 x 9
Higher heating value, MJ/kg:	26.8
Sorbent specifications	
Size, mm:	2.4 x 0.8
Purity, %:	97.6
Flue gas analysis	
O_2, %:	10.5-11.0
CO_2, %:	9.0-10.5
CO, ppm:	350-600
NO_x, ppm:	250-300
SO_2, ppm:	150-300
Sulphur capture, %:	90 (rolling 30-d average)
Ca/S ratio:	3.5:1

Chatham Circulating FBC Demonstration

Plant Description

While the viability of industrial-scale FBC technology was being demonstrated at Summerside a small-scale electric utility demonstration was being constructed at Chatham, New Brunswick. The objective of this joint venture of EMR and New Brunswick Electric Power Commission was to establish the viability of circulating FBC technology for generating electricity from high sulphur-coal. A new boiler was constrcted to repower an existing 22 MWe turbine. Circulating instead of bubbling FBC technology was selected in expectation of more efficient calcium utilization and more economic scale-up to the large units required by electric utilities.

Performance specifications:

Sulphur capture:	90% with fuel containing more than 258 ng/J of sulphur
NO_x emissions:	maximum of 258 ng/J of fuel input
Particulate emissions:	maximum of 43 ng/J of fuel input

Fig. 5 shows the boiler layout, comprising of: combustor, hot cyclone, external fluidized bed heat exchanger and backpass. The combustor is 3.2 m^2 x 24.4 m high, with the lower 10 m having refractory walls and the upper portion being waterwalls. The cyclone is refractory-lined, and solids captured by it are returned to the combustor either directly, at low load, or via the external heat exchanger at higher loads. The backpass contains convection superheaters, an economizer and an air heater. A baghouse provides final particulate control. Commissioning was completed in August 1987.

The furnace configuration is unusual in that coal is intended to be supplied through either of two chutes in the front wall. Limestone may be introduced pneumatically through two ports near the bottom of the front and right walls. Recycled material from the hot cyclone enters through the right wall and recycled material from the external heat exchanger enters through the rear wall. Primary or fluidizing air is introduced through bubble caps in an area of reduced cross-section at the bottom of the furnace and secondary air was originally introduced at low velocity through large ports in the left wall.

Furnace Mapping

Although the combustor achieved 90% sulphur capture and has performed well in other respects, expectations were not met in terms of calcium utilization. The supplier had predicted 90% sulphur capture with a Ca/S ratio of 1.3:1, but actual performance was about 3.5:1 and occasionally approached 2:1. CANMET sponsored contracts to explore numerous parameters: limestone source and size distribution, reinjection of baghouse ash, mixing limestone with coal, changing the method of secondary air injection and changing the geometry of the furnace exit. No combination produced the desired result.

To explore whether furnace conditions might impede calcium utilization, CANMET sponsored an innovative program of furnace mapping. The University of New Brunswick developed suitable watercooled probes. Ports in the rear wall of the combustor as shown in Fig. 5 were used to measure gas concentrations, temperature, heat flux and solids flux throughout the waterwall portion of the furnace.

Some of the results are shown in Fig. 6. The data represent a vertical slice through the furnace, front to back. Position 0 represents the rear of the furnace, position 4 represents the front, where fuel is fed. Ports 2, 5 and 8 are respectively 11.3 m, 18.7 m and 22.5 m above the distributor plate. This information clearly shows that lateral mixing in the furnace is poor. The rear portion is largely inactive; little fuel reaches it. Combustion, sulphur release and SO_2 capture are concentrated near the operative fuel chute, and much of the SO_2 capture may occur in the cyclone.

Calcium utilization improved slightly by mixing limestone with the fuel and feeding through both fuel chutes simultaneously, but a feed system which disperses fuel across the furnace cross-section would doubtless be more effective.

The mapping study also showed that particles from 125 to 700 μm had higher conversion of Ca to $CaSO_4$ than either larger or smaller particles. Presumably conversion of larger particles was inhibited by pore blockage while smaller particles were elutriated and, by nature of the furnace geometry, had minimal exposure to SO_2.

Fuel/Limestone Testing

The Chatham unit was occasionally employed to evaluate fuels or limestones for other agencies. At 22 MWe it is small enough that such work can be carried out at reasonable cost but large enough that results can be safely extrapolated to the +100 MWe blocks that are of interest to most utilities.

With CANMET support, one such program was carried out for Nova Scotia Power Incorporated where circulating FBC was being considered for a 150 MWe power station. Over one month the design coal, containing about 5% sulphur, was fired with five different limestones and varying Ca/S ratios. The limestone was premixed with the coal and 90% sulphur capture was achieved at Ca/S ratios between 2.1:1 and 2.3:1.

In addition to determining the most economical limestone, the tests provided much information. For example, although all the limestones were crushed to less than 8 mm, the rate at which they decrepitated in the combustor varied. This in turn affected heat transfer to the combustor waterwalls and gas temperature into the backpass. Concentrations of NO_x in the flue gas were usually low, often less than 100 ppm, but tended to increase with increases in temperature, oxygen level and

Ca/S ratio. Limestone utilization ranged from 28 to 44%, with the smallest particles, the baghouse ash, having the lowest conversion to $CaSO_4$.

The results of the test program convinced Nova Scotia Power Incorporated that circulating FBC was the appropriate technology for the new power station, and were invaluable in preparing specifications.

Large-Scale FBC Projects

Point Aconi 165 MWe Generating Station

In October 1989 Nova Scotia Power Incorporated signed contracts for what was at that time the largest FBC boiler; a single 165 MWe circulating FBC unit. This was the outcome of a lengthy evaluation of how best to meet a provincial commitment to reduce annual SO_2 emissions to 145 000 t/a while continuing to utilize high-sulphur indigenous coal. Pressurized FBC and integrated gasification combined cycle (IGCC) were also considered but were deemed insufficiently established for commercial application. Pulverized firing with wet limestone scrubbers appeared to be marginally less costly and slightly more fuel-efficient. Hpwever, circulating FBC was selected because of lower waste disposal costs, better NO_x control and greater fuel flexibility.

The design coal is high-volatile bituminous with 12 to 20% ash, 3 to 5% sulphur and 0.2 to 0.4% chlorine. Pilot-scale FBC tests on this fuel indicated that more than 90% of the chlorine is captured as $CaCl_2$ in the baghouse ash and therefore chloride corrosion is not a problem.

The boiler has a fully watercooled furnace with the bottom portion refractory-lined. Gases exit the furnace into two refractory-lined hot cyclones, each with split loopseals. Coal is fed at eight points into the loopseals and through the front wall. There is no external heat exchanger but a portion of the baghouse ash can be recycled to the combustor.

The steam circuit includes reheat. Design flowrates are:

Superheated steam:	527 400 kg/h at 12.78 MPa and 541°C.
Reheated steam:	464 760 kg/h at 3.29 MPa and 541°C.

It is expected, on the basis of the trials with the Chatham boiler, to achieve 90% sulphur capture with a Ca/S ratio of about 2:1. NO_x is expected to be well below the Canadian federal guideline of 258 ng/J and particulates will be controlled by a baghouse having a design efficiency of 99.5%. It consists of ten modules, sized to have an air-to-cloth ratio of 0.6 $am^3/min/m^2$, with eight modules in service. Much attention is also being paid to environmentally-safe disposal of solid residues.

This unit is nearly completed, with commercial operation expected near the end of 1993. The ultimate planned capacity at the Point Aconi generating station is 495

MWe. The additional capacity may be provide by two more circulating FBC units or emerging technology such as pressurized FBC or IGCC.

FBC Research and Development

The foregoing demonstrations and full-scale applications of FBC technology in Canada have been supported by a multi-facetted program of research and development. CANMET has participated in most of it, either as a performer in its own laboratories or as a sponsor of R&D at universities and other research establishments. The following list of activities is by no means comprehensive.

In-house Activities

1. *Pilot-Scale Bubbling FBC*
   A bubbling bed combustor having a bed area 0.4 m^2 and variable in-bed cooling has been used over the past 15 years to develop a database of combustion performance and sulphur capture for various Canadian coals, bitumen upgrading residues and industrial wastes.

2. *Pilot-Scale Circulating FBC*
   A circulating FBC combustor having a bed diameter of 0.4 m, also with variable in-bed cooling, was commissioned in 1990. It has been used to study N_2O formation with the Point Aconi feedstocks and to generate combustion performance data with several fuels, including coal washery rejects and auto shredder waste.

3. *FBC Reactivity Studies*
   A small pilot-scale combustor having an innovative design and operating procedure has been used to classify fuels according to combustion reactivity, and indeed to explore fundamentals of how solid fuels burn. The resulting information is of great value for mathematical modelling of fluidized bed combustion.

4. *Sorbent Reactivity Studies*
   Two pilot-scale procedures have been developed for comparative evaluation of sorbent reactivity with respect to sulphur capture. One procedure simulates a bubbling bed, the other a circulating bed. Both address the issue of sorbent particle size degradation, which conventional thermogravimetric analysis does not, and both have been used to evaluate the Canadian limestones likely to be used as sulphur sorbents.

CANMET-Sponsored Activities

1. *Queen's University Pilot-Scale Bubbling FBC*
   This facility has a cross-section 0.4 m^2 and is very similar to CANMET's bubbling FBC. It has been used extensively for limestone reactivity studies, for correlating pilot-scale performance with that of full-scale plants such as the Summerside

boilers, and for studies of various fuels, supplementary to the CANMET in-house program.

2. *Nova Scotia Power Incorporated 10 000 h Corrosion Test Program*
   This was a joint project of Energy, Mines and Resources Canada and Nova Scotia Power Incorporated conducted from 1981 to 1985. A bubbling FBC having a bed area of 1 m^2 was built and operated for about 11 000 h to study the corrosion and erosion performance of candidate alloys for high temperature superheaters. These were the first tests of such duration and contributed much to the understanding of rapid wastage through removal of corrosion products by erosion.

3. *University of British Columbia Pilot-Scale Circulating FBC*
   This combustor has a 150 mm^2 cross-section. It has been used to study the combustion performance of numerous Western Canadian coals, various bitumen upgrading residues and biomass.

4. *New Brunswick Research and Productivity Council Pilot-Scale Circulating FBC*
   This facility has a combustor diameter of 125 mm. Studies have been conducted to evaluate the merits of oil shale as a supplementary fuel and sulphur sorbent in the combustion of high sulphur coal. It was also used to evaluate various means of increasing calcium utilization, such as hydration of spent sorbent.

5. *Combustion of Syncrude Coke at the Hans Ahlstrom Laboratory*
   Syncrude coke is a high sulphur, virtually volatile-free byproduct of petroleum recovery from Canadian tar sands. Its particle size distribution is too fine for bubbling FBC, except at uneconomically low fluidizing velocities. It was first successfully burned in CANMET-sponsored tests in a pilot-scale circulating FBC in Karhula, Finland.

INTEGRATED GASIFICATION COMBINED CYCLE

Concern over the impact of CO_2 emissions on global warming, and the desire to minimize emissions while maintaining a strong energy base in coal have led to two thorough evaluations of IGCC technology applied to different scenarios.

The first focused on Western Canada with lignite and subbituminous coals as fuels of primary interest, and a high-quality western bituminous coal as an alternative fuel. Three gasifiers and three gas turbine models were evaluated for a single train plant having a net output of about 250 MWe. Major conclusions are:

- No technical barriers exist, although the gasifier is likely to be the highest risk item.

- With low cost fuel only moderate integration of the gasification and steam-raising cycles is economically justifiable.

- Thermal efficiencies slightly in excess of 40% are achievable with low-rank coals, resulting in CO_2 emissions 15 to 20% lower than a pulverized-fired plant of equivalent output.

- Low emissions of NO_x and very low emissions of SO_2 and particulates can be achieved.

- Special provisions primarily in solids handling and sulphur recovery are necessary to achieve 84% availability.

- The bituminous coal offered better efficiency and lower costs than the low-rank coals.

- Capital and operating costs are higher for IGCC than for conventional technology.

The second study focused on Eastern Canada and evaluated four gasifiers using three high-sulphur bituminous coals. Target conditions were 41% efficiency and 85% availability. It was found that the former could be met or exceeded by all the gasifiers, but the latter would require redundant systems in some areas. Sulphur capture of 99% seems achievable with unit capacities ranging from 165 to 292 MWe. Table 5 shows that circulating FBC has a substantial advantage in unit capital cost, but IGCC has the best efficiency and the most favourable operating and maintenance costs.

Table 5 - Cost comparison of three clean coal technologies

	CFBC	Pulverized Coal with FGD/SCR	IGCC
Cycle efficiency %	34.8	36.7	41-42
Relative capital cost per kW	1	1.03-1.19	1.15-1.42
Relative O & M cost per kWh	1	1.49	0.80-0.98

Based on these studies any application of IGCC in Canada is likely to be driven by environmental rather than economic considerations.

CLOSURE

Canadian utilities and research laboratories have in-depth experience in the reliable, efficient use of a wide range of coals for heat and electricity. The transfer and application of research knowledge, technology innovations, proven plant designs, novel pollution abatement processes and advanced expert systems are available to foster the utilization of clean, economical and low risk coal technologies for energy production in Eastern Europe, the CIS and the developing world.

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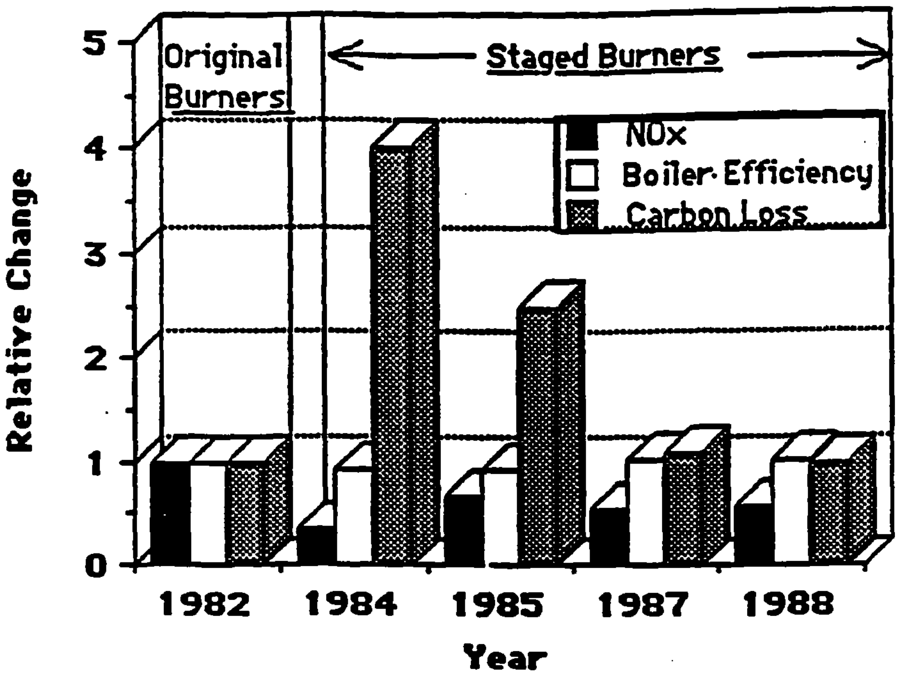

Fig 1. - Changes in NO_2 emissions and boiler performance during LIMB development

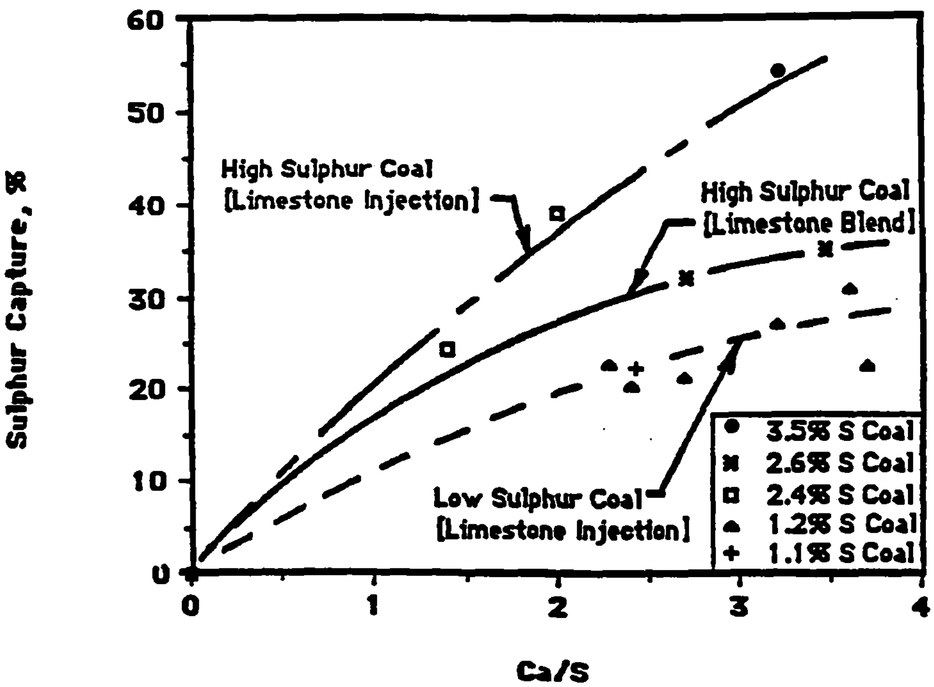

Fig 2. - Sulphur capture with added and injected limestone

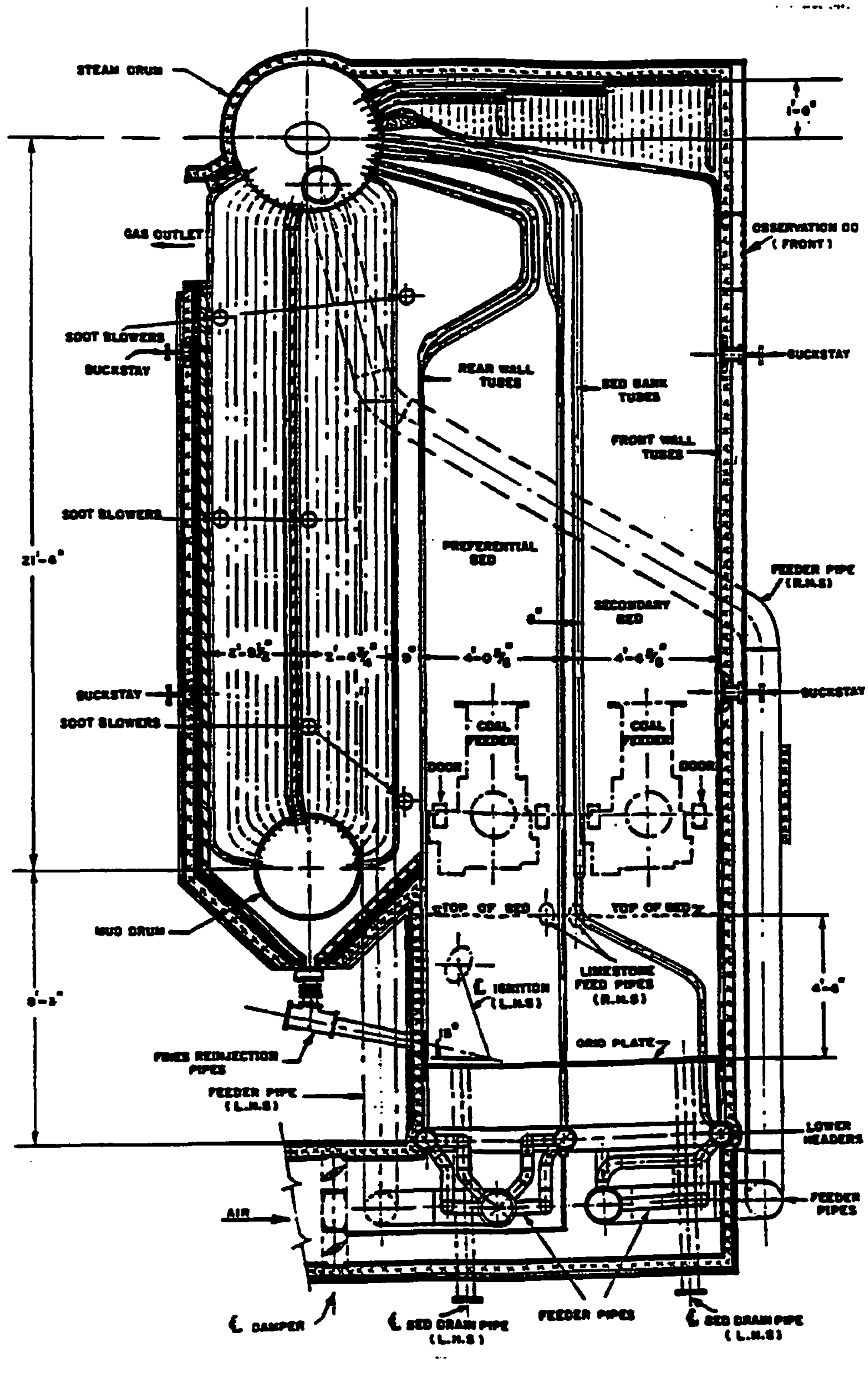

Fig. 3 - Cross-section of Summerside CFB boiler

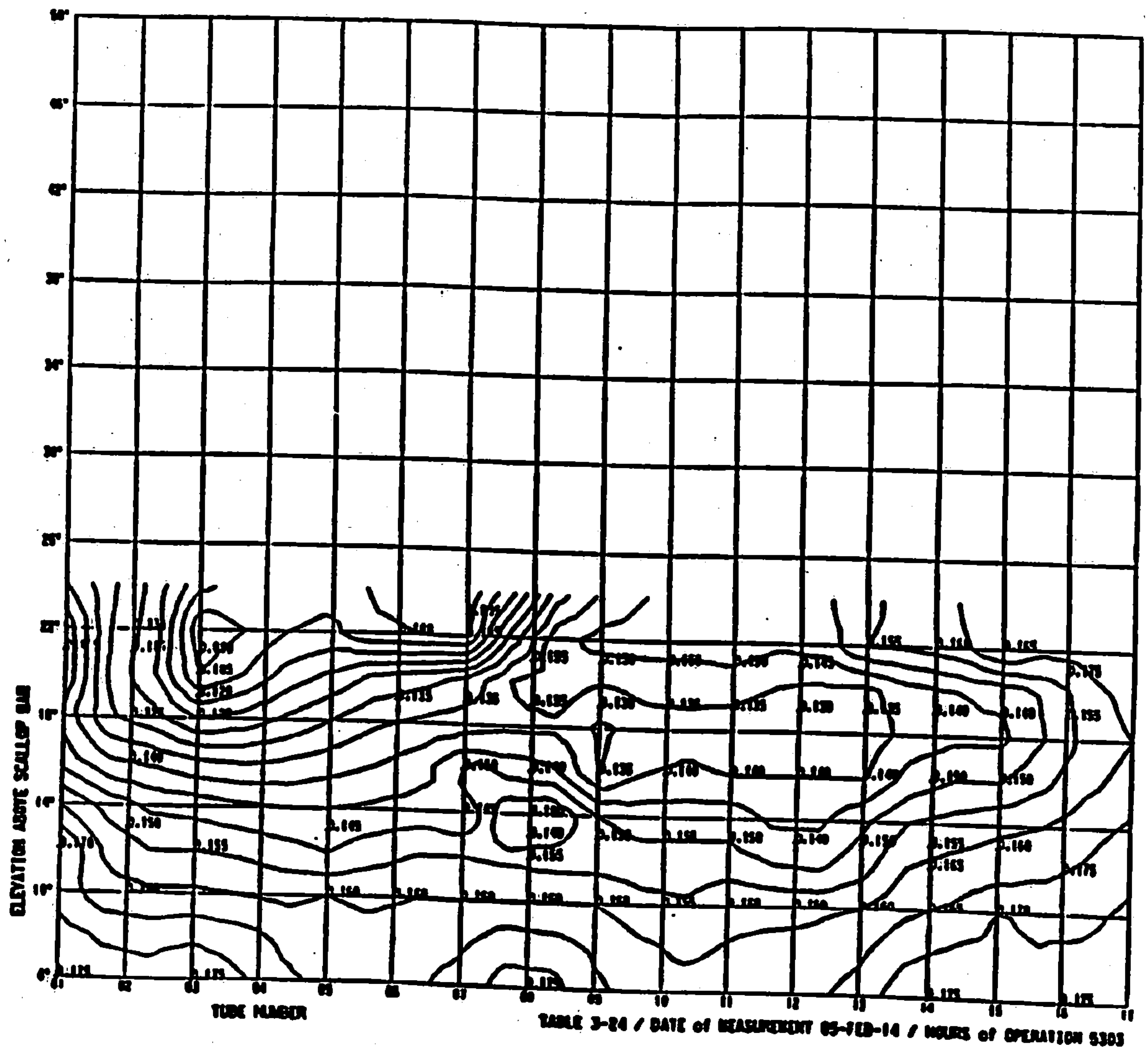

Fig. 4 - Erosion contours of submerged water tubes in Summerside FBC boiler

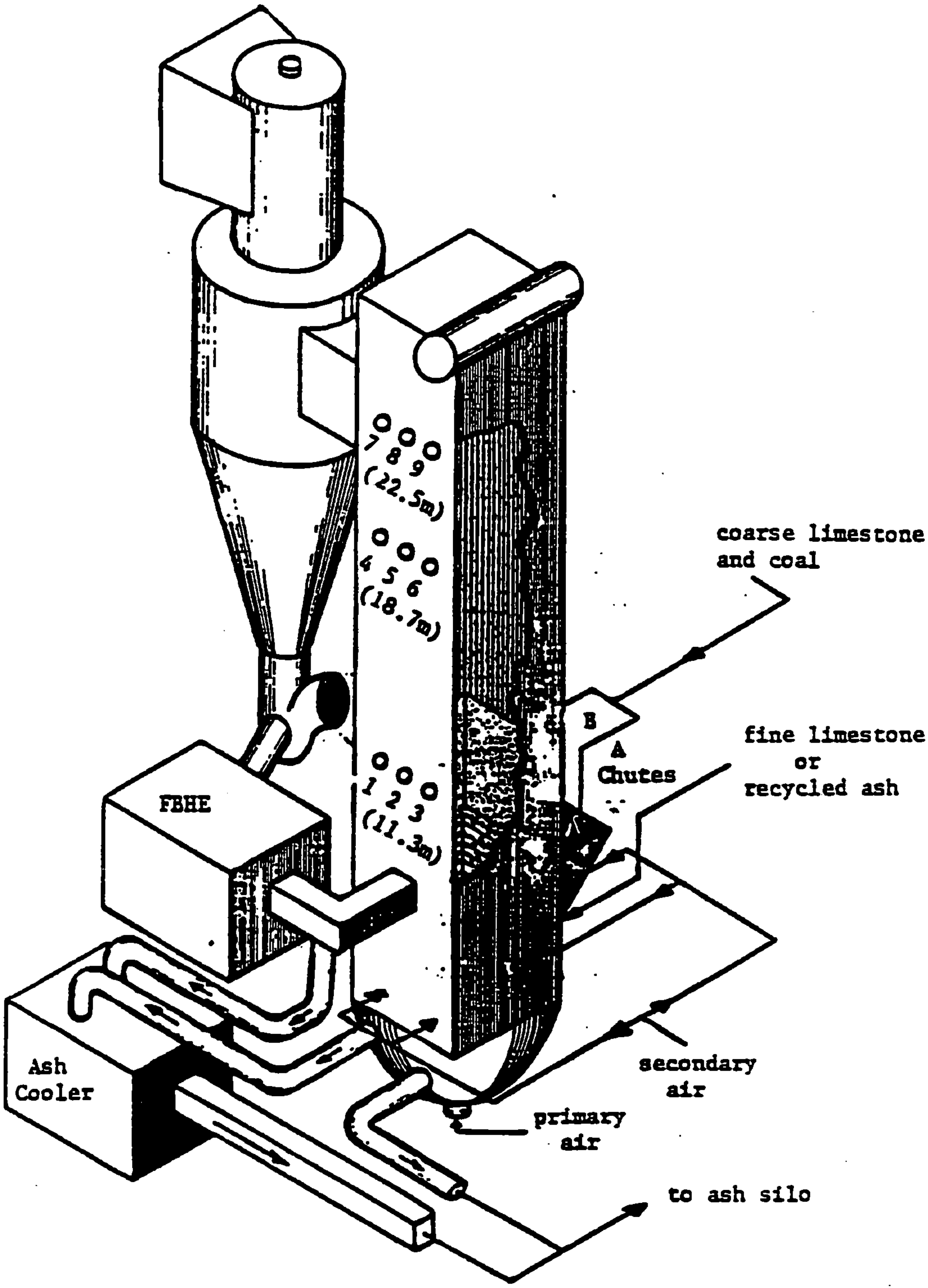

Fig. 5 - Schematic of Chatham CFB Boiler

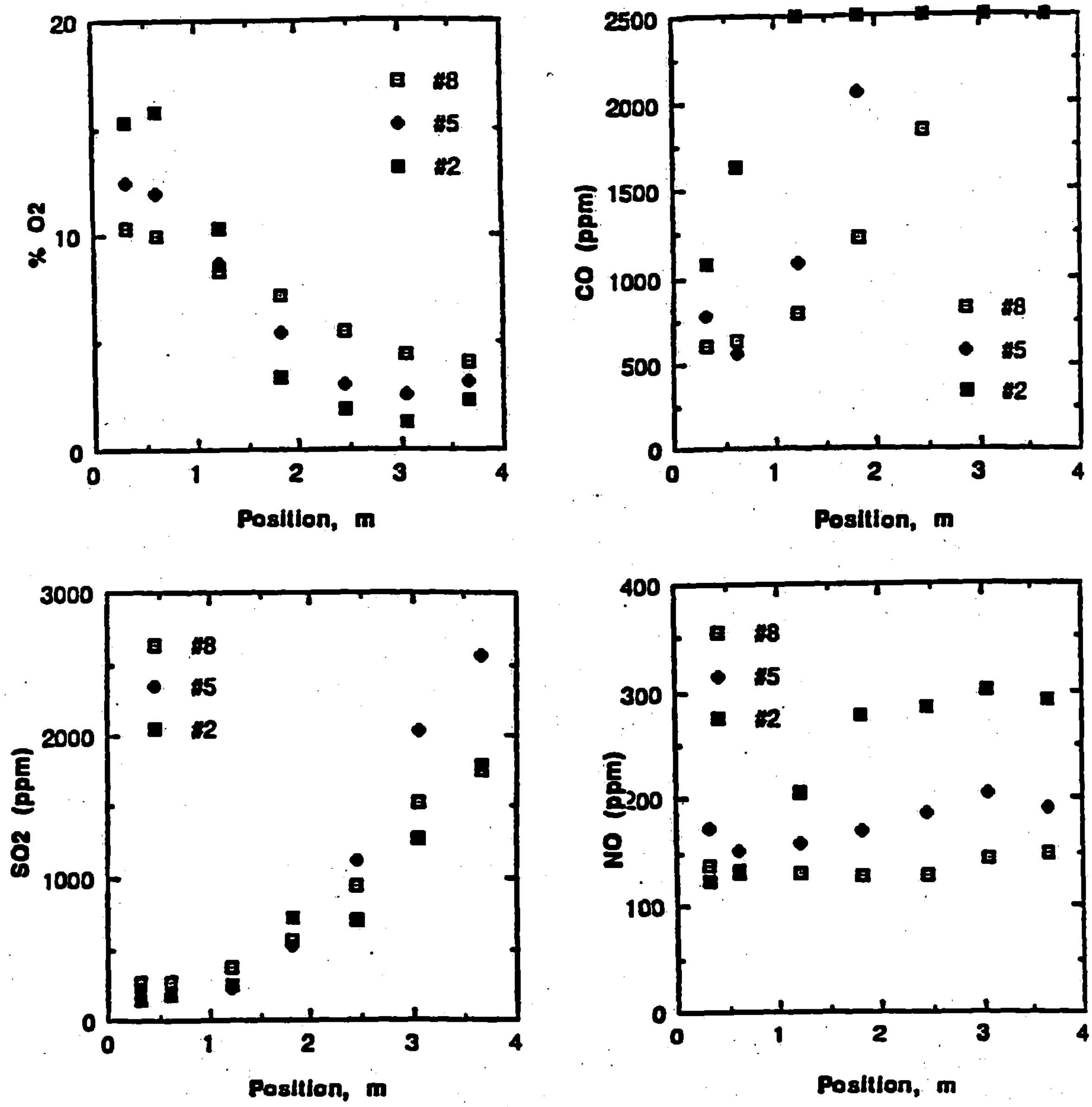

Fig. 6 - Gas concentrations in Chatham combustor with coal chute B in operation. Port location are shown in Fig. 5