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Project Summary

Technology Overview: Circulating Fluidized-Bed Combustion

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The circulating fluidized-bed combustion (CFBC) process is a second generation FBC system that is well underway toward commercialization in the U.S. The CFB operates at higher fluidization velocity, lower mean bed particle size, and higher recirculation rate than conventional FBC systems. Probable advantages of CFBC over the traditional FBC process include: more flexibility in fuel selection, reduced number of fuel feed points, higher combustion efficiency, better calcium utilization, and lower NOx emissions. Potential process limitations that must still be evaluated, however, include equipment erosion due to the more severe operating conditions, separation of bed material from effluent gas, severity of cyclone separation equipment design, and power requirements for process and auxiliary equipment operation. Battelle Development Corp., Lurgi Corp., and Pyropower Corp. are the major companies now involved in demonstrating the commercial viability of this process in the U.S. Both Lurgi and Pyropower are basing their CFB systems on technology that has already been commercially demonstrated in Europe. Battelle, after proving its process on the laboratory and pilot plant scale, is building (through its licensee, Struthers Thermo-Flood Corp.) the first U.S. commercial plant, which will generate steam for secondary oil recovery operations at a Conoco tar sands facility in Uvalde, TX. Additionally, TVA has initiated construction (at its Shawnee Plant) of a 20 MWe pilot unit, described as a hybrid CFB-AFBC system.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Background

Circulating fluidized-bed combustion (CFBC) is a technological offshoot of conventional FBC, designed to alleviate some of the potential limitations of conventional FBC systems, yet incorporating inherent process advantages. In comparison with classical FBC units, the CFB operates at a higher fluidization velocity (10-30 versus 2-12 ft/sec),* lower mean bed particle size (50-300 versus 1000-1200 μm), and higher solid recirculation rate. In the circulating bed, the entire reactor contains solids of significantly lower density than in conventional FBs, and the degree of gas/solids contact over the entire reactor height leads to longer contact times in the CFB, even at the

* Although EPA's policy is to use metric units in all its documents, this summary uses certain non-metric units for the reader's convenience Readers more familiar with metric units are asked to use the conversion units listed at the end of this summary

higher gas velocities used. For these and other reasons, CFBs have several potential advantages including:

- More flexibility in fuel selection (coal, wood, peat, etc.).
- Lower number of feed points.
- Higher combustion efficiencies.
- Better sorbent utilization.
- Lower NOx emissions resulting from staged combustion.

However, several potential problem areas (depending on specific designs) may require further investigation and evaluation.

- Number, severity of design, and power requirements associated with auxiliary equipment.
- Equipment erosion due to higher velocities and greater solids concentrations.
- Difficulty of separation of bed material from effluent gas.

Most literature on CFB technology has been prepared by companies that are developing and marketing systems for commercialization. The claims of improved combustion efficiency, reduced sorbent requirement, and lower NOx emissions are tentatively supported by limited data from test burns on both commercial (foreign installations) and pilot-scale CFBC units (domestic and foreign)

Process Description and Development Status

The major companies now active in researching, developing, and commercializing CFBC technology in the U.S. include Battelle Development Corp., Combustion Engineering, Conoco, Lurgi Corp., Pyropower, Stone and Webster, and Struthers Thermo-Flood. Synopses of each company's CFBC system and experience are presented in this section. Process design features and commercialization status of the systems are described, as well as a brief discussion of foreign CFBC technology.

In 1973, Battelle began work to improve conventional FBC technology for burning coal As a result, a second-generation FBC process -- a Multisolid Fluidized-Bed Combustion (MS-FBC) system -- was developed and patented. The MS-FBC system, shown in Figure 1, features an entrained bed of small or light particles (typically sand or limestone) and a permanently fluidized dense bed (typically iron ore or silica)-- both in the combustor. The light entrained bed penetrates up through the dense bed and is elutriated from the combustor column. The entrained bed, the heat carrier in the process, is then collected in a cyclone and sent to an external heat exchanger. The cooled entrained bed material is then returned to the combustor. The system can burn either high sulfur coal or coke, or combinations of solid and liquid fuels.

Development work by Battelle has been conducted in 6-in. I.D. (0.4×10^6 Btu/hr) and 10-in. I.D. (1.0×10^6 Btu/hr) pilot plant units. Testing has been carried out on high-sulfur coal from Ohio, Illinois, and Pennsylvania and limestone from Ohio and Virginia. SO_2 levels of 1.2 lb/10^6 Btu have been achieved with Ca/S mole ratios of 1.5 - 2 2 while burning 4% sulfur coal. The effect of entrained bed recycle rate and Ca/S mole ratio on SO_2 emissions in the Battelle pilot plant units is shown in Figure 2.

The MS-FBC is being marketed for various industrial steam generation applications wherein the specific sequence of the heat transfer steps and the particular operating conditions would be optimized for the requirements of any given plant. Commercialization of the MS-FBC has been initiated in conjunction with Struthers Thermo-

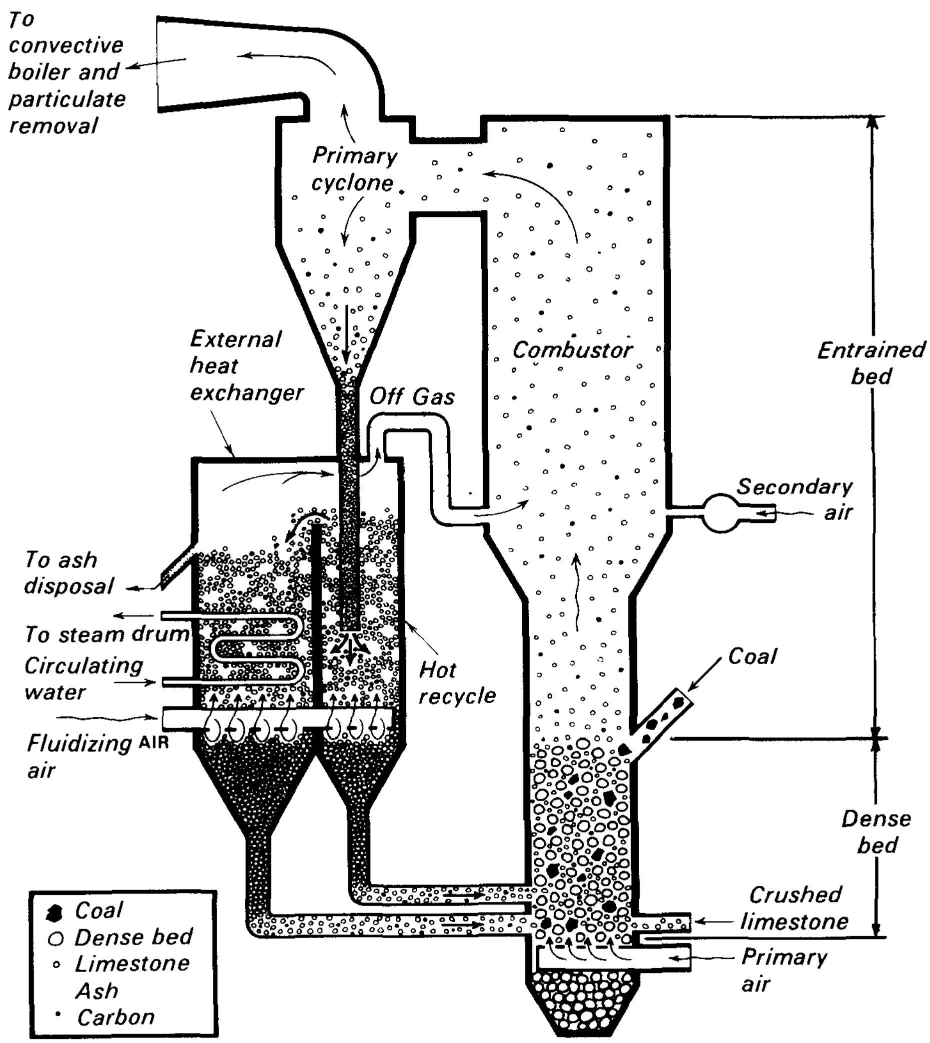

Figure 1. Battelle multisolid fluidized-bed combustor.

Flood Corp. of Winfield, KS. Struthers has concluded a license agreement with Battelle which gives Struthers exclusive worldwide rights to the design for use on secondary oil recovery steam generators. Figure 3 shows the Battelle/Struthers oil field steam production configuration. A 50 x 10^6 Btu/hr unit has been installed and is presently undergoing start-up at a Conoco plant in Uvalde, TX. This steam generator is designed to burn a wide variety of solid fuels including petroleum coke, coal, and lignite for steam injection being utilized in a tar sand reservoir. Steam, at an outlet pressure of 2,450 psia, will be produced from feedwater at temperatures of 70-200°F.

Lurgi Corp., with over 30 years experience in the design and construction of high-temperature FB processes and hardware (some 350 conventional bubbling-bed systems worldwide), began developing CFBC technology around 1960. Their initial application was for calcination of aluminum trihydrate to cell-grade alumina, the Lurgi-VAW process; the first commercial plant went on-line in 1970. Based on their experience with roasting and combustion in conventional FBs, and with the operation of CFB alumina calciners, Lurgi began developing CFBC technology as an alternative approach to coal combustion. This work led to several novel process design concepts, one of which is shown in Figure 4. In this system, fine-sized coal (average particle size of 200-300 μm) and limestone (about the same size) are fed pneumatically to the lower part of the reactor while the combustion air is introduced at two levels.

As a result of favorable tests conducted in their 14-in. I.D. pilot unit in Frankfort, West Germany, Lurgi has been awarded (along with Combustion Engineering) a contract by TVA to perform preliminary design of 200 and 800 MWe utility boilers using the Lurgi CFBC process. Design parameters for the 200 MWe system are shown in Table 1. Lurgi is in the process of commercializing CFB technology in the U.S., although there are no such units yet installed. However, one commercial CFBC unit is being built by Lurgi at the Vereinigte Aluminumwerke (VAW) in Lünen, West Germany. This unit will have a capacity of 84 MWt, will produce high pressure steam (convective section)and will reheat 2.8 x 10^6 lb/hr molten salt heat carrier from 650 to 800°F (FB heater section). On equivalent terms the unit (if designed for steam production only) would produce 220,000 lb/hr. The unit will burn high-ash coal waste (50% ash by weight, dry basis) and is scheduled for commissioning in mid-1982.

The Pyropower Corp., San Diego, CA, is also promoting CFB technology in the U.S., based on research by its parent organization, Ahlstrom Co., Helsinki, Finland. FBC research has been a major project at the Hans Ahlstrom Laboratory--the R&D Department of the Company's Engineering Division in Karhula, Finland--since 1969. Aware of the limitations of conventional FBs, Ahlstrom developed the Pyroflow CFB system in 1976. Pyropower offers two basic systems for steam generation: (1) for low-to-medium-pressure steam applications, a convective boiler bank is required because all of the evaporative duty cannot be done in the combustion chamber (a superheater is at the inlet to the boiler bank, an economizer for heating incoming feedwater is at the boiler bank outlet); and (2) for medium-to-high-pressure steam applications, all evaporation will be done in the combustion chamber and superheating will be done in the convection zone of the boiler (an economizer is also in the convection zone). Depending on the fuel to be used, an air heater may also be included in the second configuration.

Table 2 lists Pyropower's commercial CFB installations since 1976. Since the first CFB system was developed at Ahlstrom, 10 additional systems in sizes up to 200,000 lb steam/hr have been

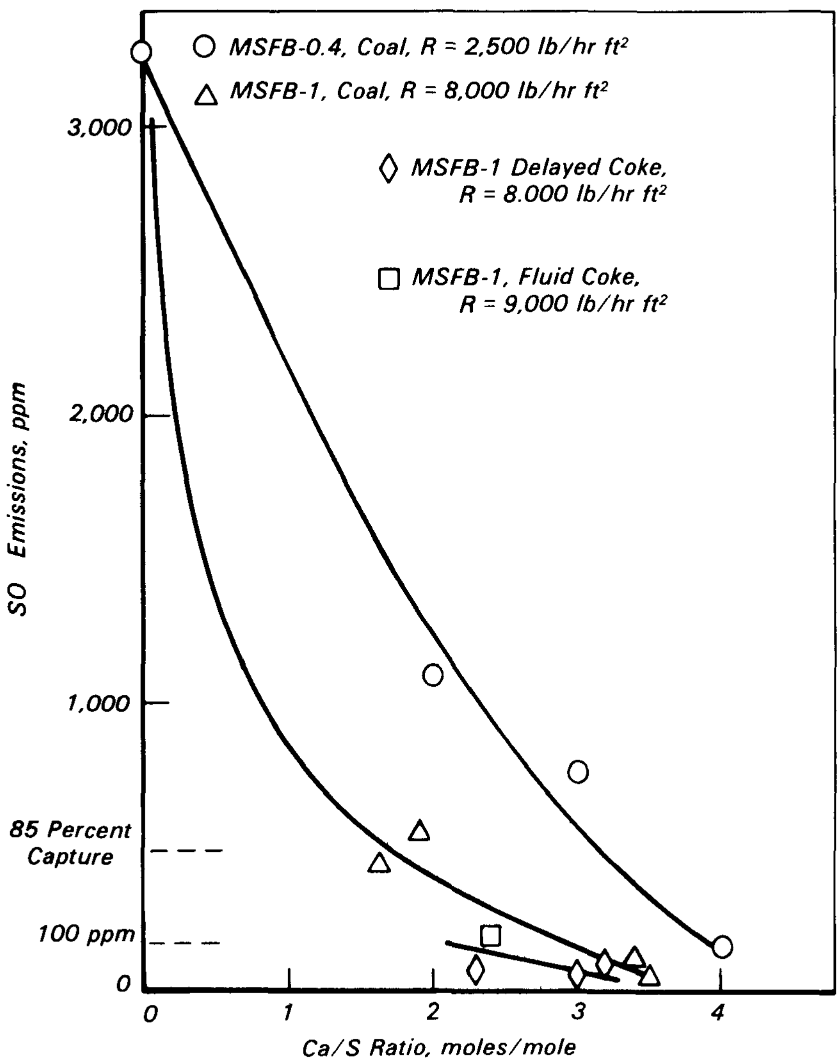

Figure 2. *Sulfur capture in MS-FBC-effect of entrained bed recycle rate (R).*

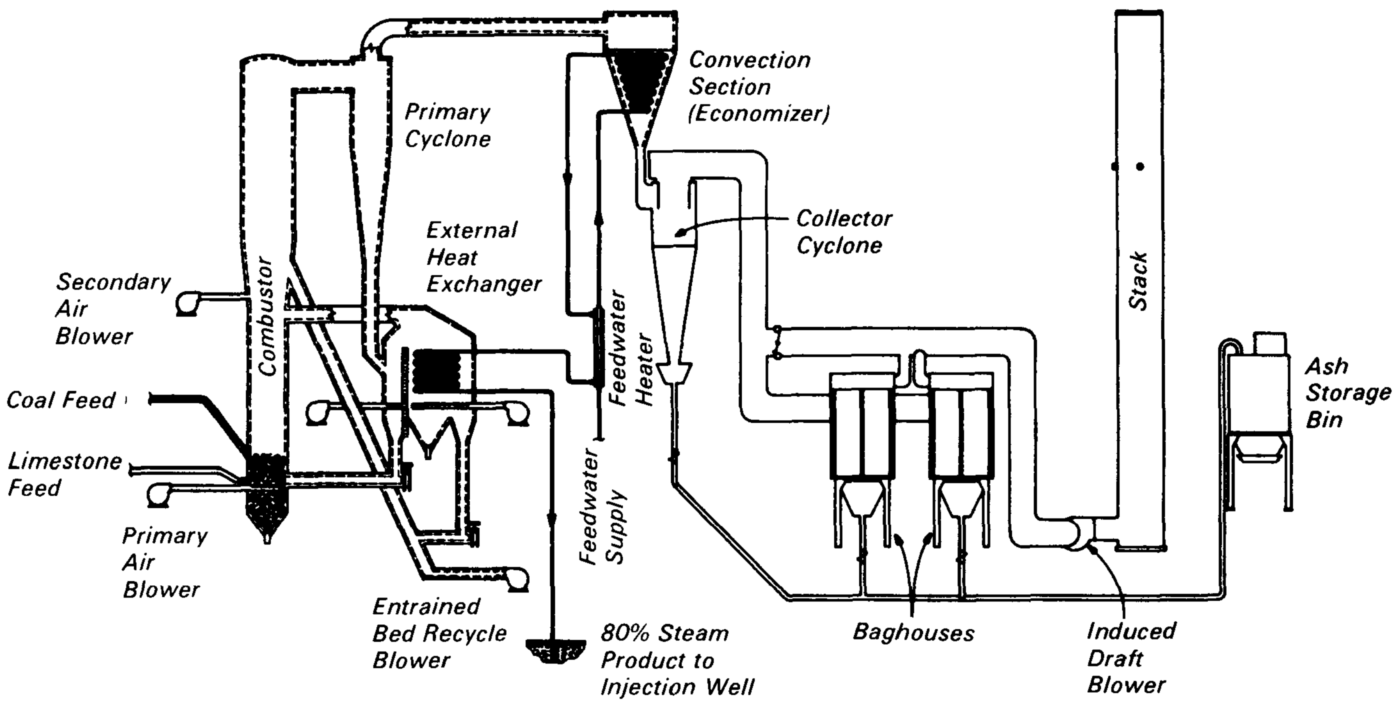

Figure 3. MS-FBC for oil field steam injection.

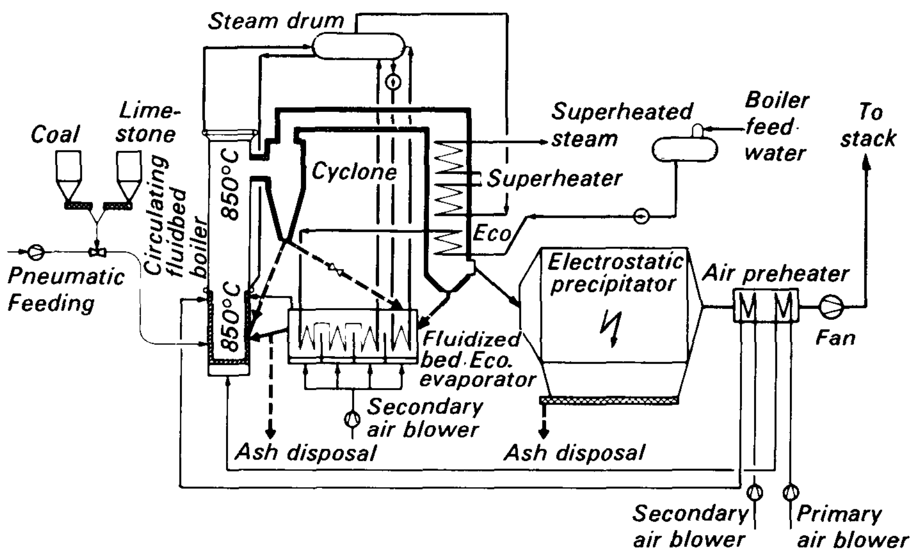

Figure 4. Circulating fluid bed boiler.

sold for commercial operation. One system has operated for 2 years with an availability of over 95%.

Pyropower is now offering Pyroflow systems to the North American market. To support this effort, they initiated a testing program in 1979 in conjunction with the Electric Power Research Institute (EPRI) and TVA. Preliminary results from combustion tests on several U.S. fuels are shown in Table 3

Several other groups and organizations, both in the U.S. and abroad, are or have been involved in research related to CFBC technology. In the U.S., Combustion Engineering, Conoco, and Stone and Webster are involved in a joint venture for developing a Solids Circulation Boiler for industrial application. This concept is basically opposite to that employed in other CFBC configurations in that coal is combusted in the dense (bubbling) bed while heat exchange occurs in the dilute (entrained) bed. Other work in the U.S. has involved EPRI and TVA, as mentioned previously, and the Westinghouse R&D Center.

Outside the U.S., three groups, all in Sweden, have been investigating CFB technology. At the Lund Institute of Technology, a reactor concept that has been demonstrated to work in the gasification of black shale has been developed. At Gotaverken in Göteborg, Sweden, construction has nearly been completed on an 8 MWt demonstration CFBC that will burn coal (with peat and wood as alternate fuels) and will provide steam for the company's shipyard. At Studsvik Energiteknik AB in Nykoping, Sweden, experience with a 250 kW fast FB experimental model designed for cold flow and combustion experiments has led to development of a 2.5 MW prototype module.

Due to the lack of commercial experience (in the U.S.) with CFB technology, capital and operating costs are not well-defined. However, several studies have tentatively concluded that capital costs for a CFB boiler would be about the same as those for a conventional FBC unit and that operating costs for the CFB may be slightly less. For example, a conceptual design study fro EPRI indicates that the capital costs for an atmospheric CFB

Table 1. Design parameters for 200 MWe CFBC conceptual design study.

CFBC	
Combustion temperature	*1560°F*
Excess air ratio	*1.2*
Fluidizing velocity	*19 ft/sec*
Average carbon content of ash	*1 percent*
Combustion efficiency	*99.4 percent*
Ca/S mole ratio	*1.5*
Sulfur removal efficiency	*90 percent*
CFB pressure drop	*104 in. W.C.*
Heat transfer coefficient to CFB tube walls	*30 Btu/ft^2-hr-°F*
Number of coal feed points	*1 per 50 MWe*
Number of limestone feed points	*1 per 100 MWe*
Solids entrainment from CFB furnace	*0.15 lb/ft^3 gas*
Mean coal feed size	*300-500 μm*
Mean limestone feed size	*250-400 μm*
Cyclones	
Axial velocity	*10.5 ft/sec*
Recycling cyclones efficiency	*96 percent*
Secondary cyclones efficiency	*85 percent*
FB Heat Exchanger	
Fluidizing velocity	*3 ft/sec*
Heat transfer coefficient to immersed tube surface	*70 Btu/ft^2-hr-°F*
FB heat exchanger pressure drop	*36 in. W.C.*

may actually be less than conventional FBCs due to reduced combustor size, but that any cost advantage for a pressurized CFB would be questionable. This same study showed that the overall efficiency of an electric utility power plant should be increased by at least 1% over a pulverized coal boiler--using an ACFB boiler, and by at least 3%--using a PCFB boiler. Another study examined the economics of conventional stoker firing as compared to the Battelle MS-FBC and conventional FBC systems. The results of this analysis, although showing a slight economic advantage in terms of total steam cost for the MS-FBC, are judged to be very similar, given the overall accuracy of the component cost estimates.

Conclusions

The concept of CFBC, after having been successfully demonstrated on a commercial scale in Europe, is taking on renewed interest in the U.S. as a result of active marketing efforts by three companies. Battelle Development, Lurgi, and Pyropower are all primarily responsible for the development of this novel FBC technology in the U.S. Additional work that has helped stimulate interest has been performed by or in conjunction with EPRI, TVA, Combustion Engineering, Conoco, Stone and Webster, and Westinghouse. Based on European experiences of both Pyropower and Lurgi, it would seem likely that the industrial market would be more easily penetrated than, say, the utility market for a variety of reasons. The likelihood that industrial plants would have more interest in utilizing alternative fuels such as peat, wood waste, and sludges, and the more critical aspects associated with utility plant operation would be two reasons why industrial applications may see more widespread use of CFB technology. On the other hand, reported advantages of the process relative to net plant efficiency and turndown capabilities are factors which could provide significant economic benefits for utility applications. The 20 MWe hybrid CFB-AFBC unit being built at TVA's Shawnee steam electric generating plant should provide the cost and performance data to better define these benefits.

Metric Conversion

Readers more familiar with metric units are asked to use the following factors to convert the nonmetric units used in this summary.

Non-metric	Multiplied by	Yields metric
Btu	1055	J
°F	$^5/_9$(°F-32)	°C
ft	0.3	m
ft^2	0.09	m^2
ft^3	28.3	1
in.	2.54	cm
$in.^2$	6.45	cm^2
lb.	0.45	kg

Table 2. *Pyroflow® circulating fluidized-bed units in operation or under construction by Pyropower Corp.*

Customer	Start-up	Fuels	Application	Size
Hans Ahlstrom Laboratory Karhula, Finland	1976	Varied	Pilot plant	2 MWt
Ahlstrom Co. Pihlava, Finland	January 1979	Peat, wood wastes, and supplementary coal	Cogeneration for board mill	5.67 kg/s - 15 MWt (45,000 lb/hr steam)
Savon Voima Co. Suonenjoki, Finland	September 1979	Peat, wood wastes, and coal	District heating	7.0 MWt
Kemira Co. Valkeakoski, Finland	1980	Zinciferous sludge	Incineration	0.71 kg/s (5650 lb/hr) (21.5% dry)
Ahlstrom Co. Kauttua, Finland	March 1981	Peat, wood wastes, and coal	Cogeneration	25 kg/s - 65 MWt (200,000 lb/hr steam)
Hyvinkaa Lampovoima Co. Hyvinkaa, Finland	Fall 1981	Coal, primary; peat or oil, alternate	District heating	25 MWt
Skelleftea Kraft Co. Skelleftea, Sweden	Fall 1981	Peat, wood wastes, and coal	District heating	7.0 MWt
Town of Ruzomberok Ruzomberok, Czechoslavakia	Fall 1981	Sewage and industrial sludge	Incineration	1.11 kg/s (8800 lb/hr) (26% dry)
Hylte Bruk Co. Hylte Bruk, Sweden	Fall 1982	Peat, primary; coal, alternate	Cogeneration	18.27 kg/s - 50 MWt (145,000 lb/hr steam)
Alko Co. Kosken Korva, Finland	1982	Peat	Process steam	7 kg/s - 16 MWt (56,000 lb/hr steam)
Kemira Co. Finland	1983	Peat, coal, and coal wastes	Cogeneration	19.5 kg/s - 52 MWt (155,000 lb/hr steam)
Gulf Oil Exploration and Production Co. Bakersfield, CA	January 1983	Coal	Process steam for	50 x 10^6 btu/hr enhanced oil
Production Co. Bakersfield, CA (USA)			enhanced oil recovery	input

Table 3. *Preliminary results of fuel tests for North American market.**

	Fuel			
Parameters	Subbituminous Coal	80 percent Ash Fuel	Ohio No. 6 Coal	Petroleum Coke
Sulfur content, % by wt. in dry matter	0.9	2.5	5.1	3.5
Nitrogen content, % by wt. in dry matter	1.1	0.3	1.5	1.8
Ca/S molar ratio (average)	2.3	2.3	1.8	2.4
SO_2 retention, %	84.0	98.0	90.0	90.0
NO_x, ppm (v)	170.0	200.0	280.0	100.0
Combustion efficiency, %	98.0	98.5	98.5	97.0

**All tests run at 20-30% excess air.*

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***John O. Milliken** is the EPA Project Officer (see below).*
The complete report, entitled "Technology Overview: Circulating Fluidized-Bed Combustion," (Order No. PB 82-240 185; Cost: $9.00, subject to change) will be available only from:

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