THE MULTISOLID FLUIDIZED BED COMBUSTION PROCESS

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SUMMARY REPORT ON THE STATUS OF DEVELOPMENT AND COMMERCIALIZATION
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INTRODUCTION

The Multisolid Fluidized Bed Combustion (MSFBC) concept was conceived in the Columbus (OH) Laboratories of Battelle Memorial Institute. Subsequent development of the concept was undertaken within the Laboratories by the Battelle Development Corporation, a subsidiary of Battelle Memorial Institute whose purpose is to identify inventions and to develop them to a point where commercialization is pursued, either through licensing or venture arrangements with industrial partners. The Multisolid Fluidized Bed is being commercialized through field-of-use licensing arrangements.

In October, 1982 the Riley Soker Corporation (Worcester, MA) was licensed by Battelle to design, manufacture and construct steam generators employing the MSFBC process, and to market them to industry and electric utilities. Riley Stoker, an Ashland Technology Company, supplies boilers, fuel burning systems and plant improvement (aftermarket) services to these market segments.

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Summary Report on the Status of Development and Commercialization

OCTOBER, 1982

Battelle Memorial Institute
Columbus, Ohio

SUMMARY

Battelle developed the Multisolid Fluidized Bed Combustion (MSFBC) process beginning in 1974, in response to a recognized need for an advanced process to burn solid fuels efficiently while meeting emissions standards. In this patented combustion process, a circulating bed of fine particles of ash and limestone is superimposed on a confined fluidized bed of large particles, such as silica pebbles.

Conventional fluidized beds have been under investigation for years because they offer the potential for maintaining low combustion temperatures and, therefore, the ability to capture sulfur with limestone during the combustion process. MSFBC offers additional advantages, including rapid load response, fuel flexibility with regard to type and size, and low operating costs.

This report highlights MSFBC advantages, summarizes its developmental and commercial status, and presents results of studies in Battelle's cold-flow model and in two pilot plants. These studies were directed toward improved understanding of system concepts and characteristics, demonstrating system performance, and establishing a sound basis for commercial design and operation.

COMMERCIALIZATION STATUS

After 8 years of development, including over 7,000 hours of pilot plant operation, the MSFBC process has entered the commercial stage. Large units are now in operation. They include a 5 million Btu/hr fuel testing steam generator built by Struthers Wells in Winfield, KS and a 50 million Btu/hr enhanced oil recovery steam generator for CONOCO in Uvalde, TX. Both were designed and engineered by Struthers Wells with Battelle assistance.

In 1982, a licensing agreement was reached with the Riley Stoker Corporation (Worcester, MA) for the design, manufacture and construction of industrial steam and utility boilers utilizing this process. Riley Stoker is authorized to market the Battelle process throughout the Western Hemisphere.

In addition, development, design, and licensing activities are under way for pulp liquor processing, process heater, oil-shale retorting, gasification and waste disposal applications. Additional applications and licensees are being actively pursued.

PERFORMANCE

The key characteristic of the MSFBC process is its dense bed. This bed givės MSFBC the unique abilitity to provide long residence time and effective mixing within the primary combustion zone. This is accomplished by:

- Using the proper dense-bed material and particle size
- Using the proper recycle rate of the fine ash and sorbent material
- Maintaining optimum gas velocities through the combustor
- Controlling combustion temperatures.

This unique combustion zone gives rise to some important capabilities that have been demonstrated in pilot plant operation.

- High carbon utilization (95-99 percent) with coal and with such unreactive fuels as fluid petroleum coke
- Efficient sulfur capture (85 percent retention) at a Ca/S molar ratio of approximately 2
- Simultaneous control of SO_2 and NO_X emissions to 100 ppm or less by "staging" the combustion.

ADVANTAGES

Results of Battelle pilot plant studies show the following advantages for MSFBC:

- Ability to burn as-received lump coals (up to 1½ inch x 0 in the pilot plants; larger top sizes are possible in commercial units)
- Ability to burn low-quality and unreactive fuels, such as fluid coke, as well as coal
- Compact combustor cross-sectional area, with consequent reduced capital costs
- Minimal boiler tube erosion/corrosion because of benign conditions (low fluidization velocities; clean air as the fluidizing medium) in the external heat exchanger
- Easy start-up, wide range of load response, and adaptability to many heating requirements because of the decoupled combustor/heat exchanger design
- Uniform heat transfer at controlled heat fluxes in the external heat exchanger.

MSFBC CONCEPT

Figure 1 illustrates the MSFBC concept—a recirculating bed of fine particles superimposed on a fluidized dense bed of larger particles. The use of a bed of large, dense particles permits operation at high combustion air velocity (about 30 ft per sec). The combustion reactions for normal (unstaged) operation are largely confined to the dense bed. The recirculating, entrained bed controls combustion temperatures and carries a portion of the

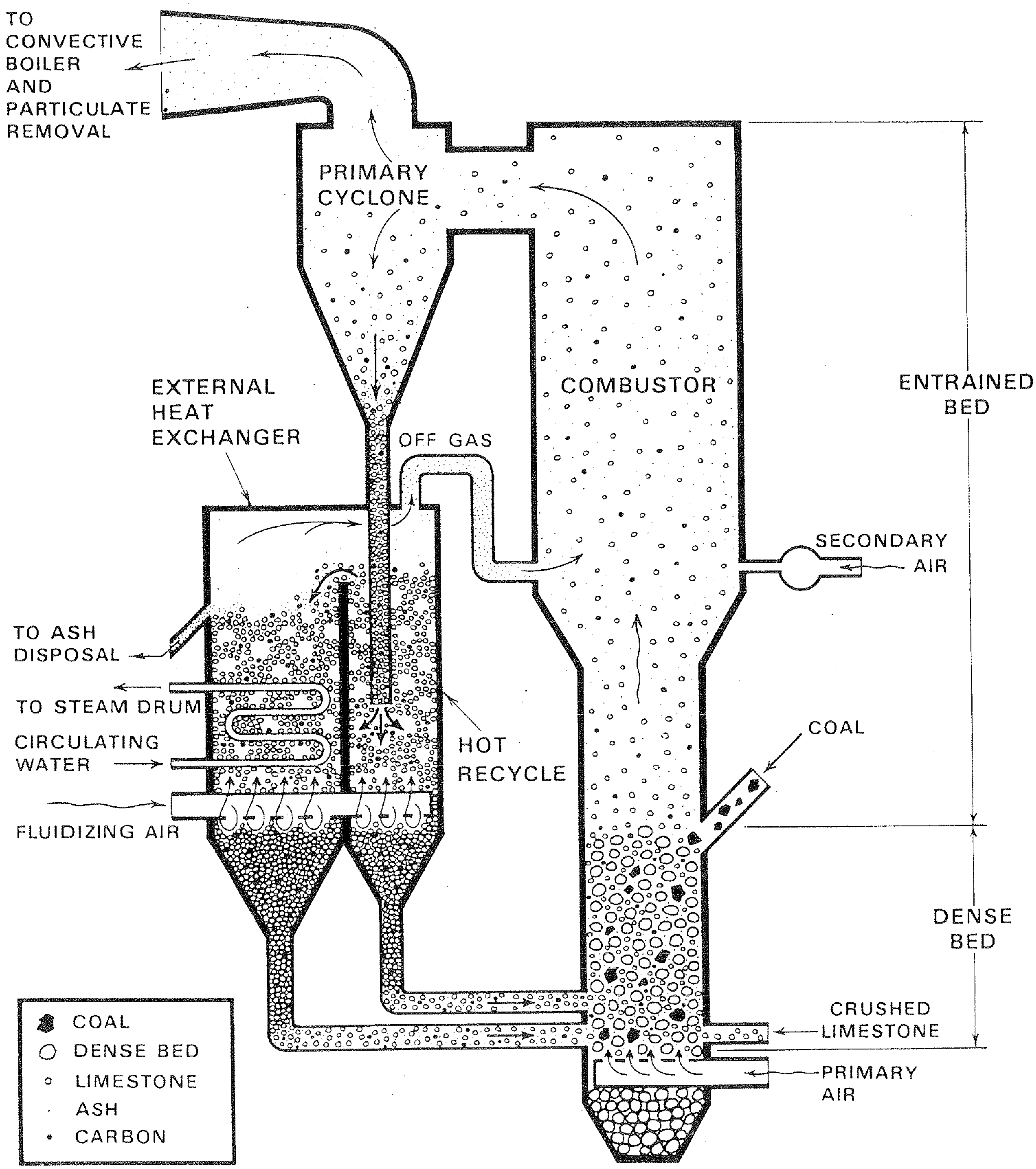

Figure 1 Battelle Multisolid Fluidized Bed Combustor

heat to a separate, low velocity (about 2 ft per sec), fluidized heat exchanger where the heat is given up to the load. Heat also is extracted from the flue gases by conventional boiler techniques, as shown in the complete system schematic (Figure 2). The cooled entrained bed is recycled to the dense bed to control combustion temperatures and to be heated again. Thus, combustion and heat transfer are decoupled, allowing each to be optimized separately. An important element is the use of crushed limestone in the bed providing maximum surface area for reaction with SO_2.

Decoupling the combustion and heat transfer processes allows greater and more rapid load changes than are possible with conventional, tube-in-bed, fluidized bed combustors. The decoupling is particularly advantageous when NO_X emissions must be controlled. Using staged combustion, the dense bed is operated under fuel-rich conditions with combustion subsequently completed above the secondary air inlet in the entrained bed zone. Staged combustion can be readily accomplished without corroding heat exchanger tubes, since there is no heat exchanger surface in the combustor.

MSFBC also is particularly well adapted for over-bed feeding of coarse fuel. Again, there are no heat exchanger tubes in the dense bed to inhibit turbulent and complete mixing of the fuel particles, both laterally and vertically, throughout the bed.

ROLE OF THE DENSE BED

The dense bed of large particles, which do not leave the combustor, is a key to the MSFBC system's superior performance. Its role is to increase the residence time of the entrained bed of ash particles, fuel and limestone in the combustor and to promote proper mixing of these constituents. Basically, the large particles in the dense bed "stabilize" a bed of the fine particles at superficial velocities far above their entrainment velocity. The optimum interaction of dense bed and fine particles leads to the outstanding results obtained with the MSFBC system.

Residence Time

Residence time in the combustion zone is critically important to provide for the combustion, sulfur capture and NO_X reduction reactions that must occur in a successful unit. Extensive studies in Battelle's cold-flow model have delineated this dramatically and show the interdependence of the dense bed and the recycle rate of the fine particles. As a result of this interdependence, the system is readily adaptable to the combustion of less reactive fuels, such as fluid coke.

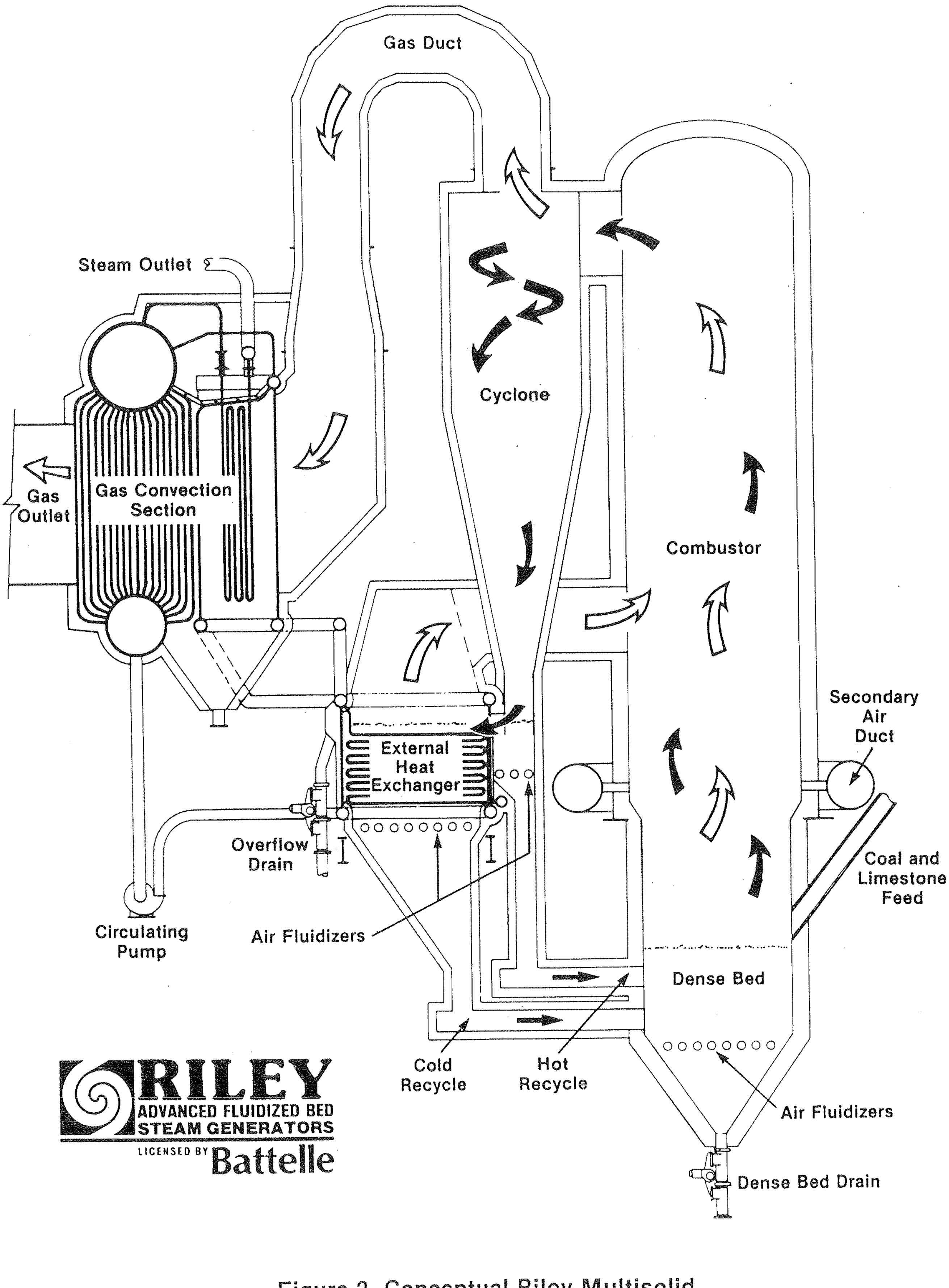

Figure 2 Conceptual Riley Multisolid Fluidized Bed Steam Generator

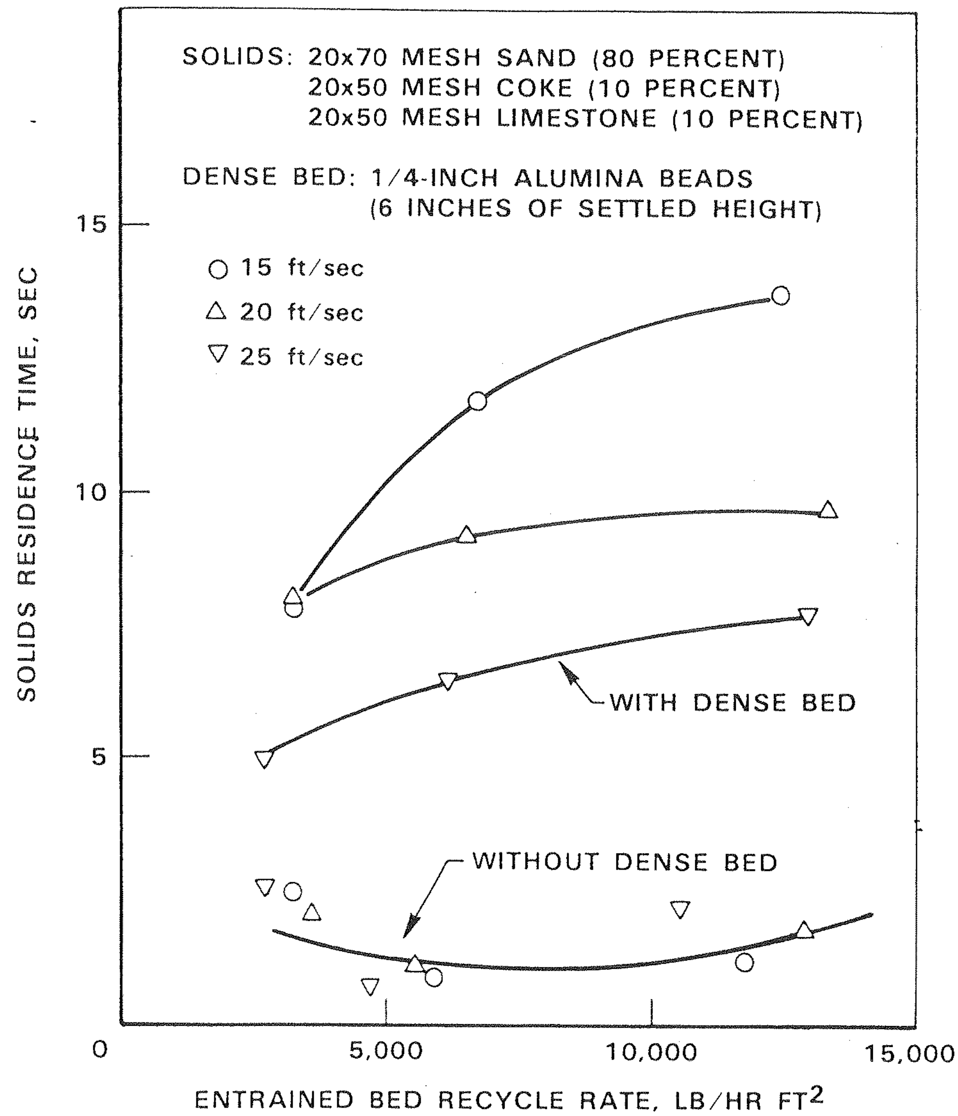

Figure 3 Solids Residence Time Tests

Figure 3 illustrates this effect. These cold model data show that, in the absence of the dense bed, the residence time of entrained bed particles in the column is only 1 to 2 seconds. With the large dense-bed particles present, however, the residence time is increased to 5 to 14 seconds. To achieve comparable residence time, systems not employing a dense bed must operate at lower velocities or at much higher recycle rates than those indicated.

The effect of the entrained bed recycle rate on residence time in the combustor is the reason for the "hot" recycle provisions shown in Figure 2. For some types of loads, the recycle rate of cooled entrained bed materials may be too low to achieve the needed residence time in the combustor. The hot recycle, which neither adds nor removes heat from the combustor, permits the total recycle rate to be controlled independently of the load characteristics.

Key Parameters

To obtain the unique process characteristics that the MSFBC concept offers, the designer must give attention to:

- Dense-bed material and particle size
- Entrained bed recycle rate
- Combustion gas velocity
- Combustion temperature.

Table 1 lists some dense bed materials and particle sizes that have been studied for MSFBC use, along with their key characteristics—thermal stability, attrition rate, and relative cost. The designer will have to consider trade-offs between these characteristics in selecting the proper material and particle size for a particular system.

Dense Bed Material		Specific	Thermal	Attrition	Relative
Type	Size	Gravity	Stability	Rate	Cost[a]
Alumina Beads	1/8"	3.59	Good	Low	High
Crushed Iron Ore	4 x 12 mesh	4.13	Good	Low	Medium
Silica Gravel	1/2" x 1/4"	2.72	Fair	Medium	Low
Alumina Beads	1/4"	3.59	Good	Low	High
Silica Gravel	3/4" x 1/2"	2.72	Fair	Medium	Low
Pelletized Iron Ore	1/2" x 3/8"	4.13	—	Low	Medium

(a) Relative Cost: High, \$0.50~\$1/lb; Medium, \$0.05~\$0.50/lb; Low, <\$0.05/lb.

Table 1 Characteristics of Dense Bed Materials

The range of operating loads for the MSFBC process is important to ensure that neither choking (solids drop out) of the entrained bed nor entrainment of the dense bed occurs in operation. In Figure 4, the upper limit for entrainment is shown for each of the materials studied in terms of superficial velocity of the combustion gas flow and recycle rate of the entrained bed. The lower limit, in terms of superficial velocity, corresponds to the choking velocity for the entrained bed, which typically is in the range of 10 to 12 ft/sec. Proper selection of the dense bed particle as dictated by velocity and recycle rate, will permit operation over a wide range of loads, with and without staged combustion.

The combustion temperature should be controlled to optimize carbon combustion efficiency and reaction of limestone with SO_2. This is achieved by continuously regulating the rate of introduction of cooled solids from the external heat exchanger to the combustor. Control of the cooled solids recycle rate is obtained using a nonmechanical "L" valve.

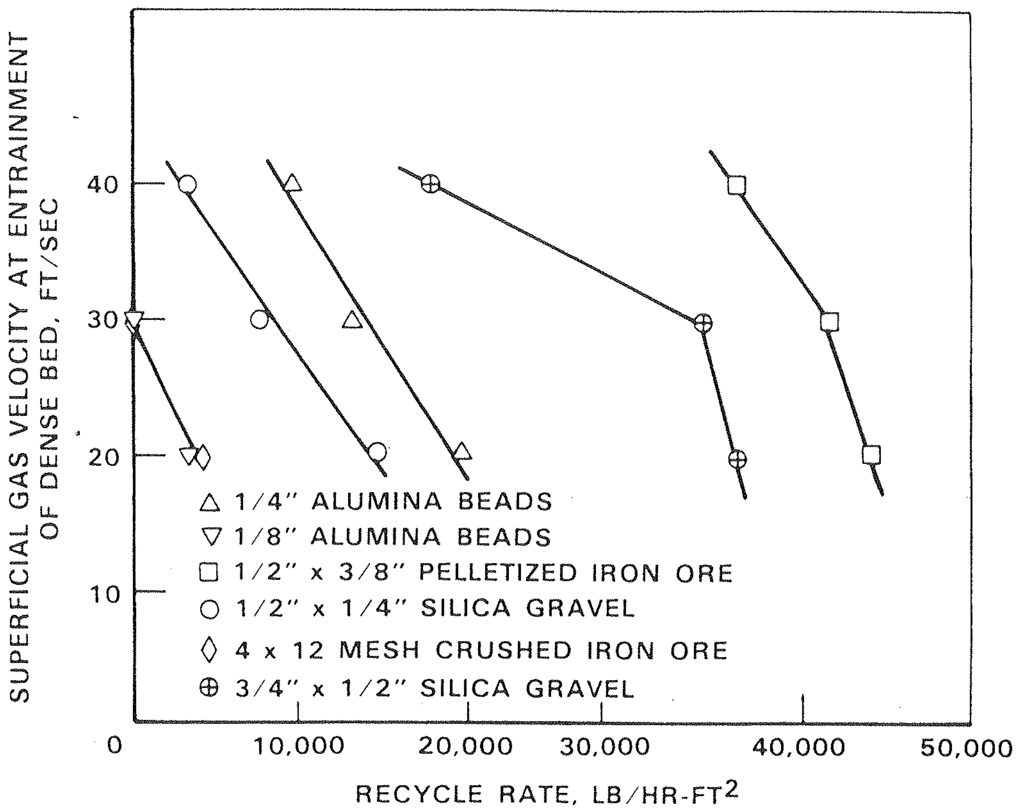

Figure 4 Entrainment of Dense Bed Materials

PILOT PLANT PERFORMANCE

Development work on MSFBC has been accomplished primarily in two pilot plants: a 0.4 x 10^6 Btu/hr unit (MSFBC-04) and a 1 x 10^6 Btu/hr unit (MSFBC-1).

Figure 5 is a schematic diagram of the MSFBC-0.4. The diameter of the combustor in the dense-bed zone is 6 inches (nominal), with the freeboard enlarged to 8 inches to provide greater residence time for gas-solids reactions (overhead space dictated this adjustment).

The configuration of the MSFBC-1 is similar to that of the MSFBC-0.4. However, the combustor has a constant diameter, nominally 10 inches, rather than the stepped diameter of the MSFBC-0.4.

Coarse fuel is fed to the MSFBC-1 by dropping it into the combustor above the dense bed. Fine fuel and limestone are fed by pneumatic injection near the bottom of the dense bed.

The flow of recycled solids is controlled by nonmechanical "L" valves. Provisions are made for extracting samples of the various solid streams.

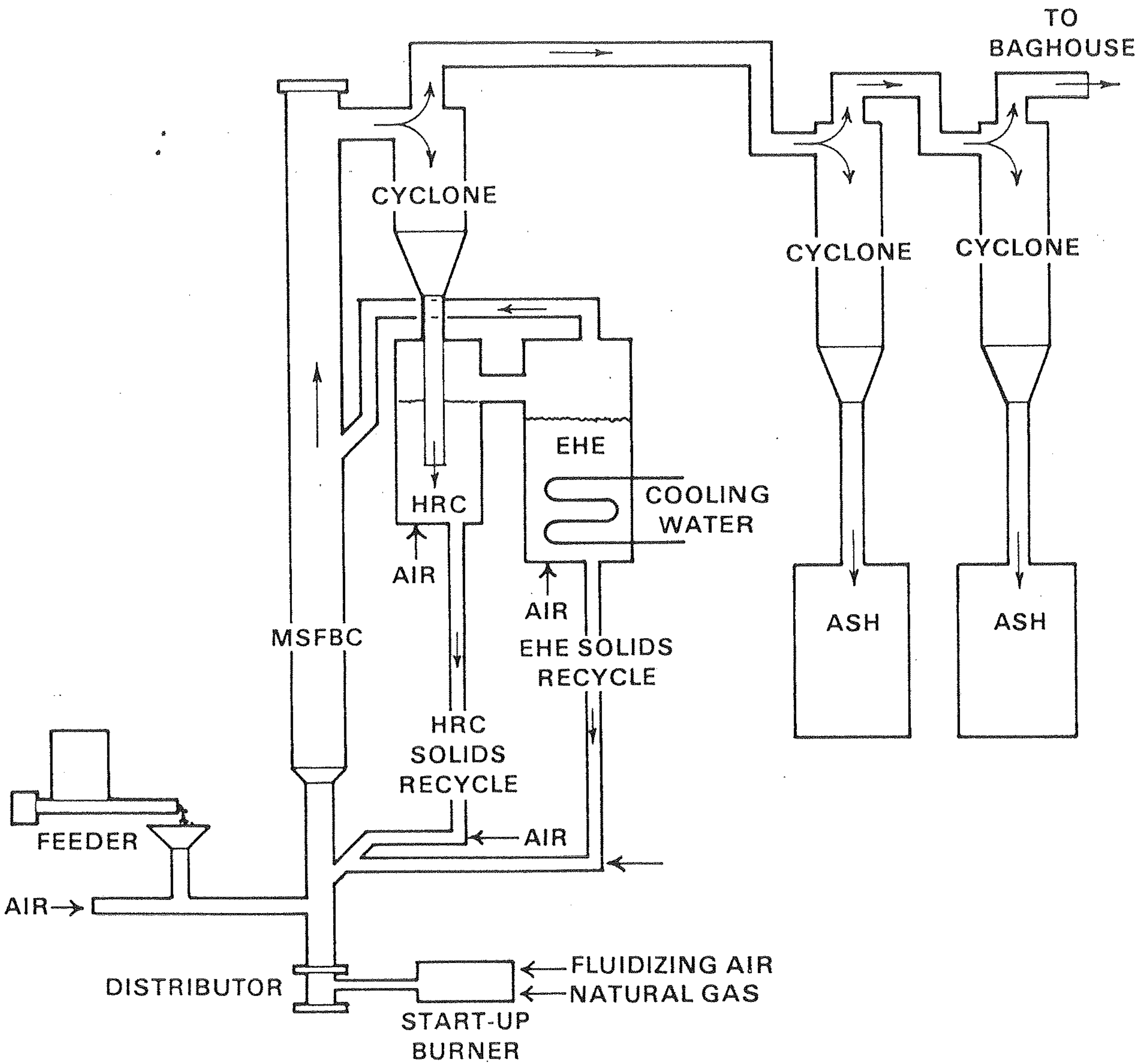

Figure 5 Schematic of MSFB-0.4 Pilot Plant

Using Battelle's pilot plants, over 7,000 hours of operation have been accumulated in the development program since 1974. Combustion tests have covered a variety of fuels and sulfur sorbents over a wide range of operating conditions. The following fuels have been tested:

- Coal
- Kraft liquor
- Wood waste
- Municipal waste
- Sewage waste
- Delayed coke
- Fluid coke
- Char
- Rock containing bitumen

Various limestones and dolomite have been tested as sorbents. Combustor temperatures have ranged from 1100 to 1850 F and superficial combustion gas velocities from 10 to 35 ft/sec.

Observations and conclusions on several important performance factors based on these tests follow.

CRUSHED VERSUS LUMP COAL

Boiler operators, for economy of operation, would prefer to use as-received wet lump coal to avoid the cost of preparation at the mine or on site. One objective has been to demonstrate that MSFBC offers this capability. Data in Table 2 show that MSFBC can use as-received coal with high carbon utilization. The results are essentially the same whether crushed coal is air injected into the bottom of the combustor or lump coal is fed in at the top of the dense bed region of the combustor.

Coal Size	Bed Temperature, F	Combustor Superficial Velocity, ft/sec	Combustion Efficiency, percent
8 x 0 Mesh	1635	23.4	98.8
3/4" x 0	1634	23.5	99.4
1-1/2" x 0	1650	20.0	97.3

*Data on 1-1/2" x 0 coal obtained in 2.4 sq ft. combustor.

Table 2 Comparison of Lump and Crushed Coal Combustion Tests in MSFB-1

COMBUSTION EFFICIENCY

MSFBC can achieve high combustion efficiencies, even with low reactivity fuels. Table 3 illustrates MSFBC performance with several fuels. "Fluid coke", a petroleum coke formed in the fluid coking process, is quite unreactive, but carbon utilizations from 91 to 95 percent have been achieved. These results for fluid coke were obtained at an excess air level of 11 percent, at a temperature of 1650 F, and without ash recycle. In line with the experience with other fuels, higher carbon utilization for the fluid coke was obtained in the MSFB-1 than in the MSFB-0.4.

With more reactive fuels, such as coal and petroleum coke made by the delayed coking process, even higher carbon utilization was obtained. Again, these performances were obtained without ash recycle.

Circulation rate (i.e., entrained bed residence time) is particularly significant when burning low reactivity fuels. Figure 6 illustrates this effect for fluid coke. Note that carbon utilization above 90 percent was achieved in the MSFBC-0.4 and MSFBC-1 using an improved distributor plate design.

	Carbon Utilization*	
Fuel	MSFB-1	MSFB-0.4
Coal	99	97
Delayed Coke	97	96
Fluid Coke	95	91

*Without ash recycle.

Table 3 Combustion Efficiency in MSFBC: Effect of Fuel Reactivity

SULFUR CAPTURE

In conventional fluidized bed combustion processes, emissions of sulfur oxides are controlled by adding coarse limestone to the combustor. In MSFBC, crushed limestone, which subsequently becomes part of the entrained bed, is used. The crushed limestone has greater surface, resulting in more efficient utilization.

Figure 7 illustrates the SO_2 reduction achieved as a function of Ca/S ratio and entrained bed cycle rate (R). Ca/S molar ratios of about 3 are needed to achieve 85 percent sulfur capture at low entrained-bed recycle rates in the absence of the hot recycle. At higher entrained-bed recycle rates using hot recycle, Ca/S ratios of 2 or less are adequate to achieve 85 percent sulfur retention. For areas with more stringent regulations, SO_2 concentrations below 100 ppm can be achieved with Ca/S ratios of 3 or less. Significantly better sulfur capture can be achieved with petroleum coke than with coal under comparable operating conditions. This could be because the organic sulfur that predominates in petroleum coke is more reactive than the pyritic sulfur present in coal.

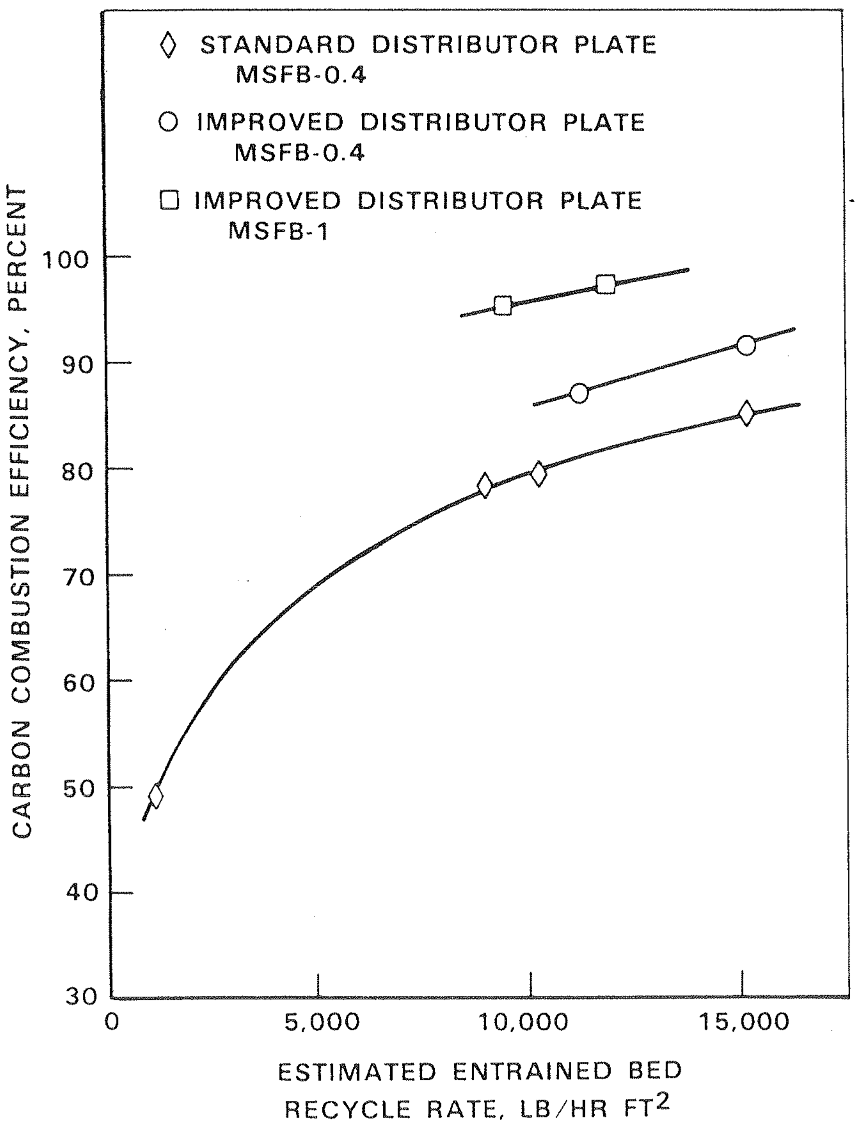

Figure 6 MSFBC Performance with Fluid Coke: Effect of Entrained Bed Recycle

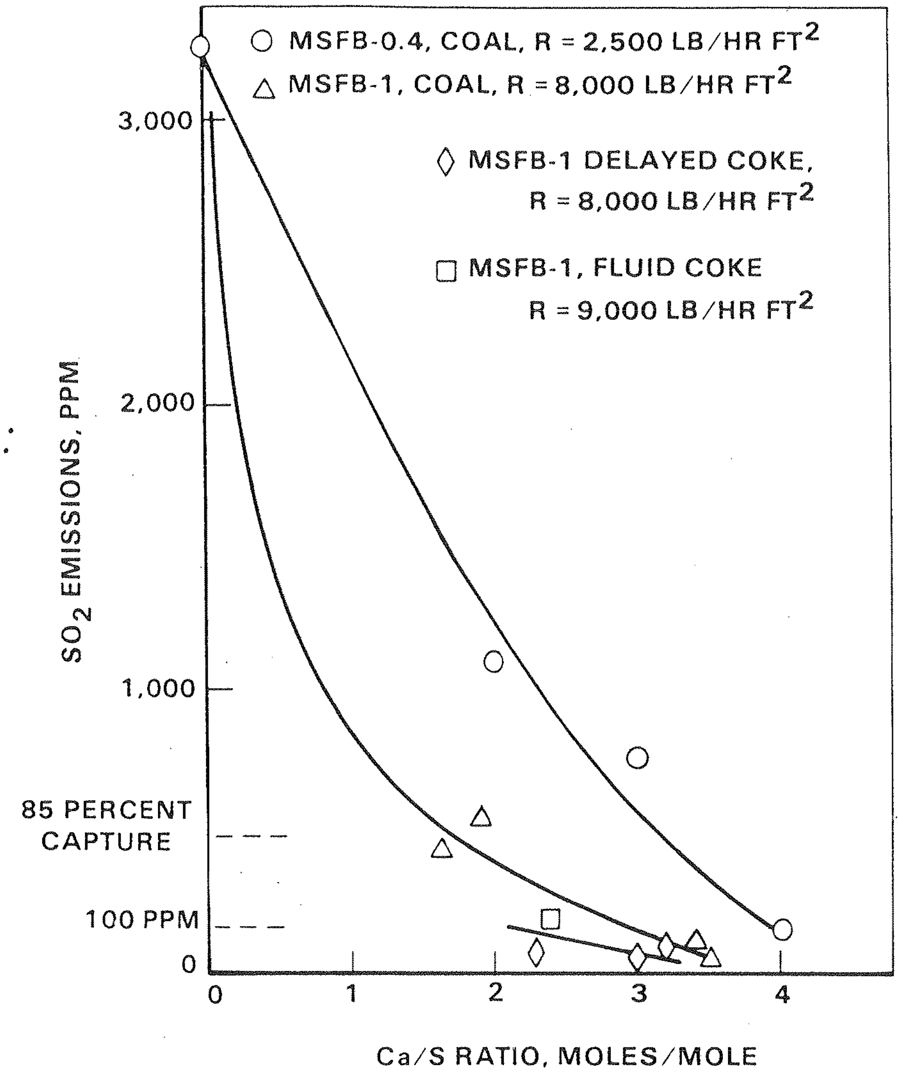

Figure 7 Sulfur Capture in MSFBC: Effect of Entrained Bed Recycle Rate (R)

NO_X CONTROL

Staged combustion in MSFBC has been found to be very effective in reducing NO_X emissions to low levels. Results shown in Figure 8 indicate that the No_X emissions in the 300-400 ppm range in unstaged combustion (at primary air/stoichiometric air ratios greater than l) can be reduced to 100 ppm or less by reducing the ratio in staged combustion. Data presented in Table 4 for staged combustion of delayed coke in the MSFBC-0.4 and the MSFBC-1 also show that simultaneous control of SO_2 and NO_X to low levels can be achieved at Ca/S ratios of about 3. It is expected that the relatively high levels of CO found in these tests can be reduced by providing longer residence time in the combustion zone.

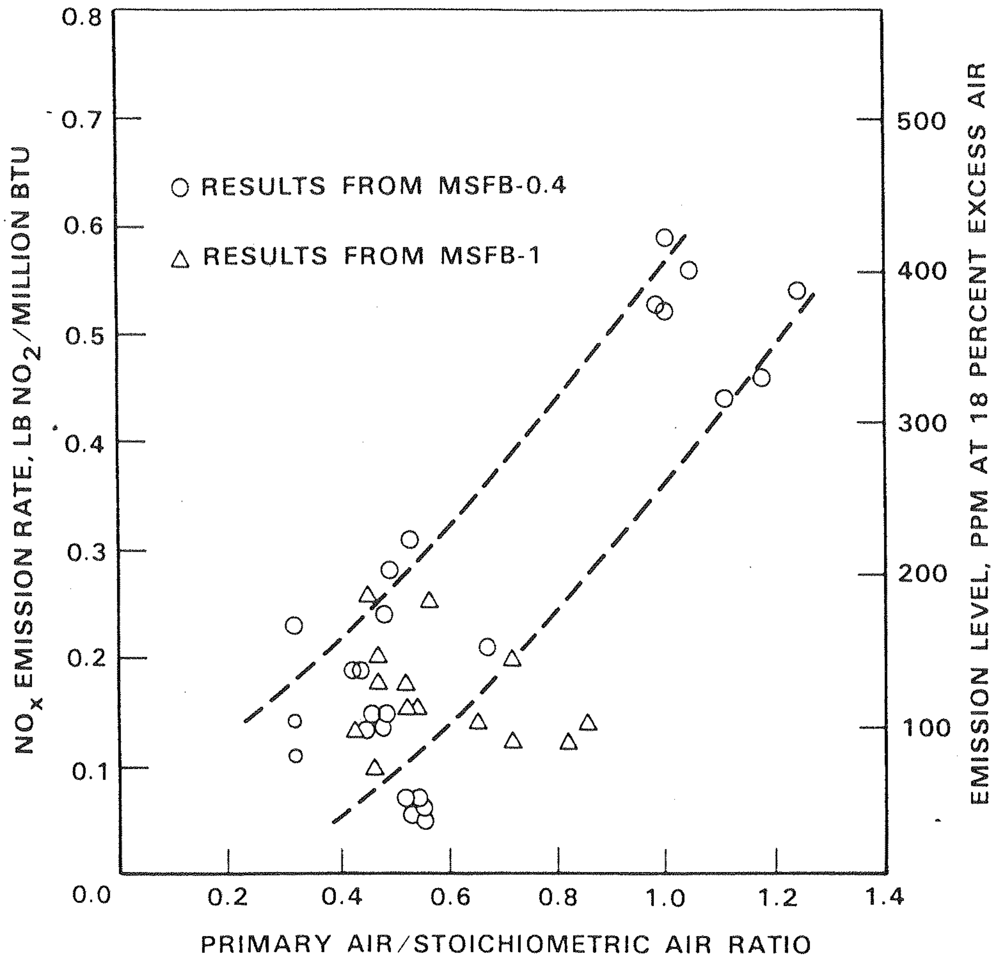

Figure 8 Effect of Primary Air on Nitrogen Oxides Emission (Delayed Coke)

	MSFB-0.4	MSFB-1
Total Air/Stoichiometric Air	1.14	1.28
Primary Air/ Stoichiometric Air	0.51	0.76
NO_x, ppm*	100	76
Ca/S Ratio	2.9	3.2
SO_2, ppm*	91	82
CO, ppm*	412	162

*Corrected to 18% excess air.

Table 4 Effect of Staged Combustion on NO_x and SO_2 Emissions (Delayed Coke)

COMMERCIAL APPLICATIONS

ADVANTAGES

MSFBC offers significant advantages for the commercial user. The ability to feed as-received lump coal or other fuels above the bed substantially reduces coal preparation facilities and the associated operating cost. The turbulent mixing provided by the dense bed enhances lateral mixing of the coal from a minimum number of coal feed points. Because the combustor freeboard is part of the reactor for both combustion and sulfur capture, the fines content of both the coal and the limestone is not a problem to the system. This permits the use of less expensive fuel and limestone.

Decoupling the reaction section (combustor) and the heat exchange section (external heat exchanger, EHE) provides highly flexible load-following capability. The system can operate over a wide range of fuel feed rates and with widely different fuels without affecting the heat balance and optimum reaction conditions. The limit to turndown of the system is the minimum fluidization velocity of the dense bed material in the combustor or the choking velocity of the entrained bed.

The heat exchanger tubes in the EHE are subjected to less severe conditions than in a conventional fluidized bed combustor with in-bed tubes. The lower temperature, lower fluidizing velocity, and reduced potential for cyclic reducing-oxidizing conditions all favor less expensive construction materials in the MSFBC process.

In additon, this decoupled heat exchanger design permits uniform heat transfer at controlled heat fluxes.

DESIGN

Designing MSFBC units for commercial use requires that a design basis be established to cover load, fuel, environmental regulations and configuration. The load must be established either as Btu's delivered or pounds per hour of steam. Also pressure, temperature and variability of the load must be established. Information about the fuel and the limestone are necessary in order to prepare heat and material balances and to specify equipment. EPA New Source Performance Standards will generally be the environmental regulations to be met, unless local regulations are different, as in California or Japan. Finally, the configuration of the unit will depend on whether it is a new installation or a retrofit to an existing installation. The design must address any space limitations or adjacent equipment that must be integrated.

The combustor will be designed to provide the operating conditions necessary for the emission control reactions and for complete combustion. In combustor design, the load is maintained by controlling the coal feed rate, while limestone and combustion air rates will vary proportionally with the coal feed rate. Finally, the combustor temperature is controlled by recycle of solids from the EHE.

The EHE design is determined by the heat exchange tube layout. The bed height establishes the bed pressure drop and the bed cross-sectional area establishes the fluidizing gas flow rate. The EHE bed temperature is selected to provide an adequate temperature differential driving force for heat transfer to the heated fluid.

The recycle solids from the EHE to the combustor are controlled by "L" valves. The solids flow rate is proportional to the aeration gas flow rate so that control is continuous over the operating range. The "L" valve is designed for minimum fluidization of the solids considering the solids characteristics.

The supporting equipment that completes the facility consists of commercially available items, i.e., cyclones, baghouse, water treatment devices, convective boiler and instrumentation. Note that in using MSFBC in a retrofit configuration, the existing boiler can serve as the convective boiler with only minimum modification. Furthermore, the design may permit using the convective boiler under the original firing conditions.

STATUS

The commercial application of MSFBC is most advanced for steam flood generators for enhanced oil recovery. A 50 x 10^6 Btu/hr unit manufactured by Struthers Thermo-Flood Corporation, a subsidiary of Struthers Wells Corporation, was started up in Texas in late 1981 for CONOCO, Inc.

Conceptual designs have been prepared for large industrial and utility boilers, and for retrofit to existing gas/oil fired boilers by Riley Stoker Corporation, one of the Ashland Technology, Inc. companies. Riley Stoker is licensed by Battelle for these applications in North, South and Central America. Other conceptual designs being considered concern:

- Package boilers—small coal-fired units which can be shop fabricated and field assembled
- Oil-shale retorting
- Process heaters—firing coal or waste material to heat a process fluid
- Pulp liquor recovery.