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Data Summary of Municipal Solid Waste Management Alternatives

Volume V: Appendix C—Fluidized-Bed Combustion

SRI International
Menlo Park, California

NREL

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Report Organization

This report, *Data Summary of Municipal Solid Waste Management Alternatives*, comprises 12 separately bound volumes. Volume I contains the report text. Volume II contains supporting exhibits. Volumes III through X are appendices, each addressing a specific MSW management technology. Volumes XI and XII contain project bibliographies. The document control page at the back of this volume contains contacts for obtaining copies of the other volumes.

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FLUIDIZED-BED COMBUSTION

C.1 INTRODUCTION/OVERVIEW

This appendix provides information on fluidized-bed combustion (FBC) technology as it has been applied to municipal waste combustion (MWC). A review of the literature was conducted to determine: 1) to what extent FBC technology has been applied to MWC, in terms of number and size of units was well as technology configuration; 2) the operating history of facilities employing FBC technology; and 3) the cost of these facilities as compared to conventional MSW installations. Where available in the literature, data on operating and performance characteristics are presented. Tabular comparisons of facility operating/cost data and emissions data have been compiled and are presented in sections C.3 and C.4, respectively. In summary, the literature review shows that FBC technology shows considerable promise in terms of providing improvements over conventional technology in areas such as NOx and acid gas control, and ash leachability. In addition, the most likely configuration to be applied to the first large scale FBC dedicated to municipal solid waste (MSW) will employ circulating bed (CFB) technology. Projected capital costs for the Robbins, Illinois 1600 ton per day CFB-based waste-to-energy facility are competitive with conventional systems, in the range of $125,000 per ton per day of MSW receiving capacity (521).

C.1.1 Background

Fluidized-bed technology has been used in industrial applications where process requirements dictate a need for good gas/solids mixing and uniform temperatures. Originally used in the chemical processing and petroleum industries, the technology has been adapted to combustion applications, both as a means of burning a variety of industrial wastes and other low-grade fuels as well as burning high sulfur coal to generate steam while meeting increasingly stringent SO_2 emissions requirements.

Initially driven by the energy crisis of the 1970s, coal-fired FBC power generation applications have grown rapidly. Within the past 15 years, FBC technology in the United States has evolved from 20,000 lb/hr pilot scale bubbling-bed units to utility-sized installations using circulating fluid-bed (CFB) technology. In the United States alone, FBC has now established a significant presence within the electric power generation industry, with two 150 MWe coal-fired CFB units as well as several 100 MWe units currently in operation. A 165 MWe unit is under construction, and two 250 MWe CFB boilers have been recently proposed under the U.S. DOE Clean Coal Demonstration program (019).

C.1.2 FBC in Waste Fuels Applications

In waste fuel-fired applications, FBC technology has been widely used to burn sewage sludge, paper mill wastes, and other high moisture, low heating value materials which are difficult to burn in a conventional combustion system. Such units are typically designed to be integrated into industrial waste generators' facilities, and sized to handle just the waste material generated at a particular site. With energy recovery, steam generation capacities are typically in the 20,000 to 100,000 lb/hr range.

Waste fuel-fired FBC applications have not experienced the same level of scaleup that has been seen in coal-fired FBC applications. However, during the mid-1980s, approximately two dozen facilities were built in the anthracite coal mining regions of Central Pennsylvania to burn the coal mining waste (culm) that is piled throughout the region (019). These are cogeneration plants, using CFB technology, typically having an electric generating capacity in the 50 MW range. The benefits provided are: 1) removal of a significant stockpile of waste material that can leach toxic materials into local groundwater supplies; and 2) recovery of energy in the form of electricity and steam. This latter FBC configuration has been proposed for two MSW-fired FBCs in the United States by a European vendor who has demonstrated its successful use in this application in Sweden (019).

C.2 TECHNOLOGY DESCRIPTION

In a fluidized-bed combustor, instead of a grate or hearth supporting a bed of solid fuel, the furnace section contains a bed of refractory sand or limestone supported by an air distributor plate or nozzle system. Air is passed through the bed material at velocities sufficient to fluidize the material. The bed is heated by auxilliary burners and fuel is introduced either by dropping it onto the top of the fluidized bed or injecting it from below where it mixes with air. Under these conditions, air and products of combustion pass through the bed in the form of bubbles.

When the bed is fully fluidized, it looks like a boiling liquid and exhibits a static pressure head. The constant motion of the bed material particles ensures high heat and mass transfer rates and uniform temperatures. When combustible fuel is added to the bed, it tends to be broken apart by the mixing action, increasing the surface area which is exposed to air in the high temperature environment which, in turn, enhances the combustion process.

The bed's large refractory mass, when heated, becomes a "thermal flywheel" which helps to smooth out combustion upsets which can be caused by variability in fuel quality or moisture, which is common to waste fuels, including MSW. In addition, the bed material serves as a heat transfer media, absorbing the thermal energy generated by the combustion of the fuel, then transfering this energy to heat transfer surfaces located within or around the bed in the combustor at high rates.

Because of the high rates of heat and mass transfer within the combustor, complete combustion can be obtained at lower operating temperatures (typically 1500 - 1600 degrees F) than those normally found in the furnace of a conventional grate type boiler. Lower combustion temperatures tend to suppress the formation of NOx in the combustion process. An added advantage of CFB systems is that they can be operated in a staged combustion mode, further suppressing NOx formation. In addition, when limestone is used as all or a part of the bed material, SO_2 and HCl are absorbed within the bed. However, based on test data from Sundsvall, Sweden reported by Gotaverken (435), under certain operating conditions, addition of limestone may increase formation of NOx generation in the CFB combustor. Further, in-bed scrubbing of HCl is inefficient, because that reaction occurs more rapidly at lower temperatures than typical in-bed levels. By reducing limestone injection rates to the bed, SO_2 capture is still achieved, and NOx is reduced to acceptable levels. HCl is then removed using a downstream scrubbing system in addition to in situ acid gas control where temperatures favor that reaction.

C.2.1 FBC Combustor Types

There are generally two different types of FBC systems in use today; the bubbling bed and the circulating bed (CFB). In a fluidized bed of solids, as air velocity through the bed increases, the bed remains static or slumped until a distinct point at which time it fluidizes. This velocity is known as minimum fluidization velocity. As air passes through the bed and travels through the freeboard or the space within the furnace above the bed, some bed material and unburned carbon is entrained in the flow and carried out of the combustor. Typically, mechanical particulate collection devices are installed at the combustor flue gas outlet to catch this material and return it to the bed to conserve bed material and improve combustion efficiency. As the velocity is increased, the rate at which bed material is carried out of the combustor increases to the point where all of the bed material becomes entrained in the gas flow and exits the furnace section. It is then captured by the collection device and returned to the bottom of the combustor.

A bubbling bed FBC is typically operated in the range of one to two times minimum fluidization velocity. With the exception of the fines lost from the vessel due to attrition, the bed material remains in the combustor. In the CFB, operating velocities are typically 20 times the minimum fluidization velocity, causing bed material to be continuously circulated through the solids collection device and back into the combustor.

Depending on the design, in the bubbling bed, heat transfer is effected by means of a combination of in-bed heat transfer surface, radiant surface in the freeboard, and convective surface external to the combustor (644). A schematic representation of this type of system is shown in Figure C-1. Where fuel quality is extremely low due to high amounts of non-combustibles or moisture, heat transfer surface within the bed is not used. The combustor may consist of a simple refractory-lined vessel with an external waste heat boiler. In extreme cases, auxiliary fuel may be introduced into the bed to sustain combustion and/or bed temperature. This configuration has been widely used to burn sewage sludge having an 85 percent moisture content.

In the CFB, heat is transferred from the bed material to waterwall heating surfaces for the entire height of the combustor or furnace section, with the balance of the steam generation duty being accomplished in a conventional convective section located after the combustor (see Figure C-2). By varying the fluidization velocity within the combustor, the amount of heat transfer surface in contact with bed material within the furnace can be varied to effect load or temperature control. Some CFB designs, such as the multi-solids system designed by Battelle Columbus Laboratories (Figure C-3), provide additional heat transfer surface in an auxiliary bubbling bed heat exchanger section, located within the solids circulation system of the unit. The amount of heat recovery can also be varied by modulating the fluidization velocity within this section.

In addition to the bubbling and circulating bed designs, a revolving FBC design has been used in Japan which is actually an enhancement of the bubbling bed design. In this system, offered by Ebara (Figure C-4), differential fluidizing air velocities across the air distributor system are used in combination with bed containment vessel geometry to induce a higher degree of lateral mixing than that which is found in conventional FBCs. It is claimed that this technology can be used to burn unshredded MSW whereas other FBCs (bubbling and circulating) require a prepared fuel when burning MSW.

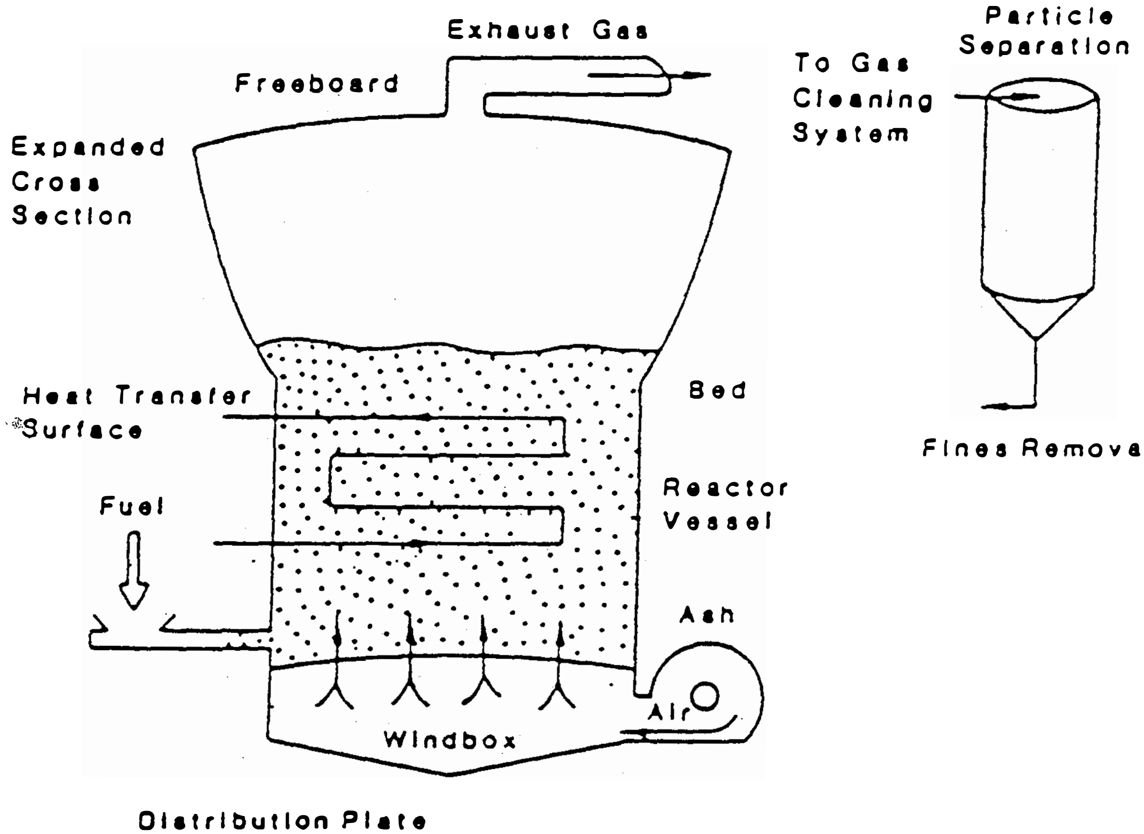


Figure C-1. Elements of a Fluidized Bed Combustor – Bubbling Bed (644)

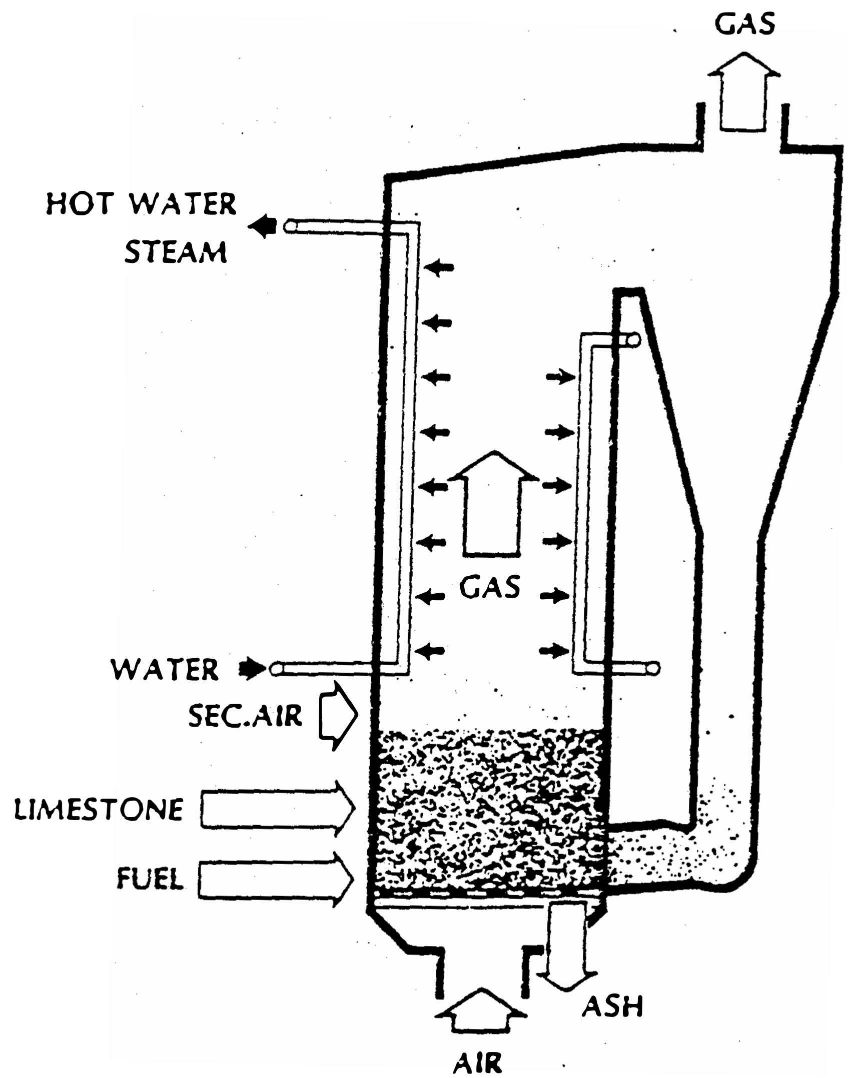


Figure C-2. Gotaverken Circulating Fluidized Bed Combustor (644)

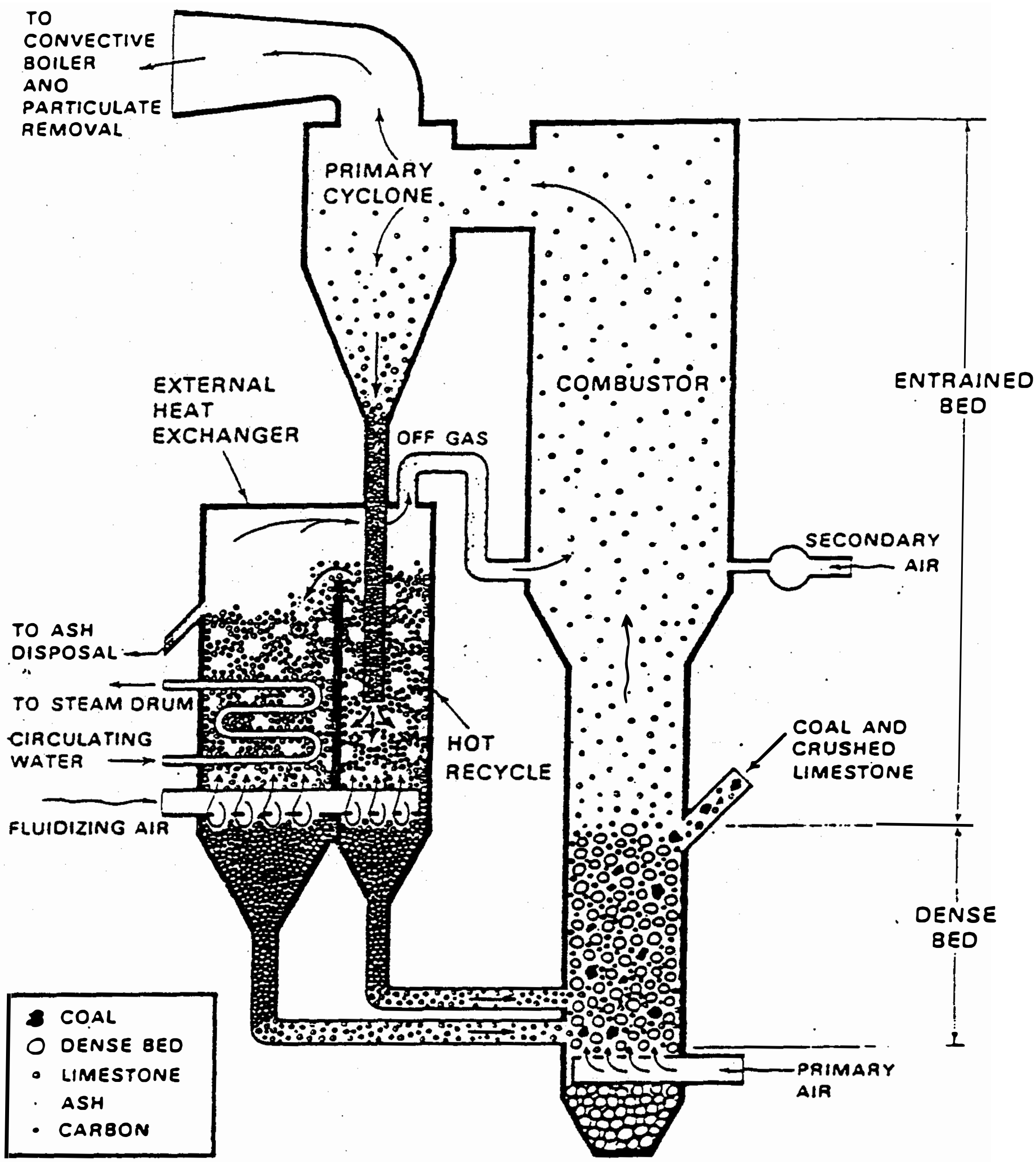
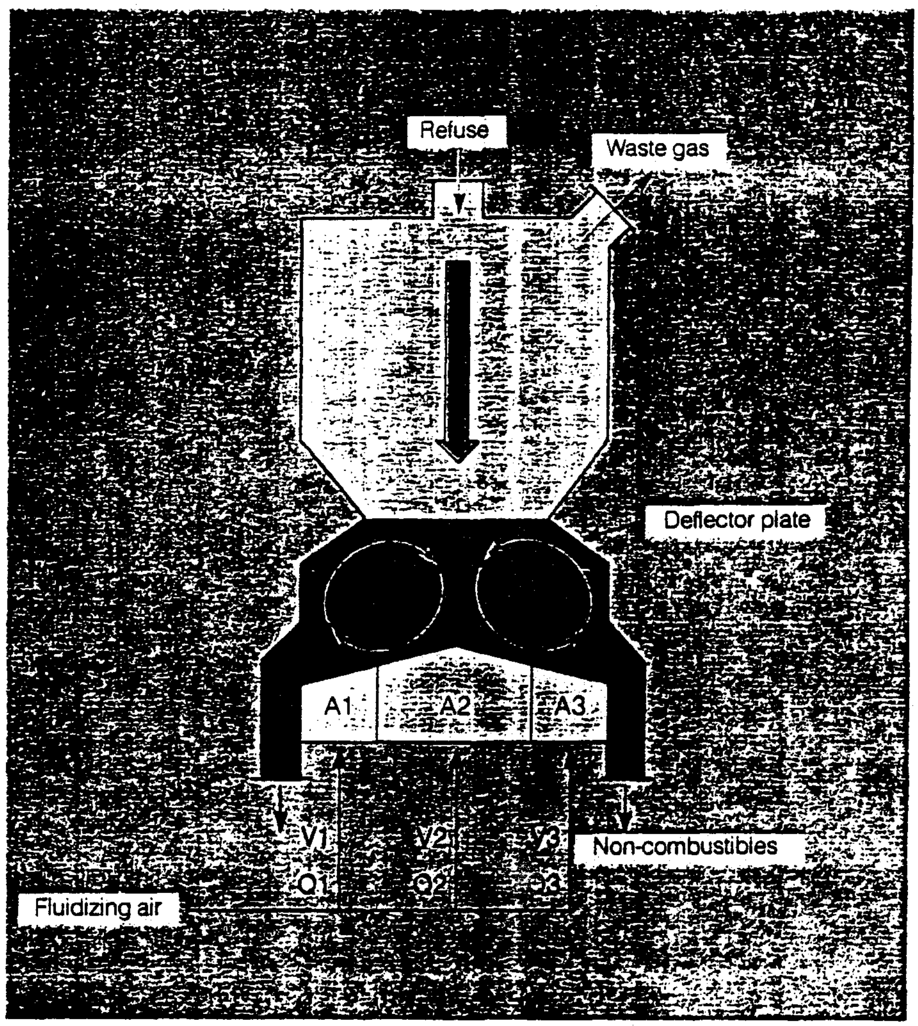


Figure C-3. Multisolid Fluidized Bed Combustor (644)



Superburn Revolving Fluidized Bed

Figure C-4. Ebara Fluidized Bed Combustor (796)

C.2.2 Front End Processing Requirements

In most FBCs, some degree of fuel preparation is required when firing solid waste because the fuel itself must be able to be fluidized, or at least partially supported within the bed for good mixing. The processing of MSW into refuse-derived fuel (RDF) generally consists of size reduction with non-combustibles removal. This is due to the fact that the ability to fluidize a given material at a specific gas flow depends primarily on the bed material's particle size and density. Large sized or heavy objects such as pieces of concrete, steel, or even large sized pieces of wood would tend to fall to the bottom of the bed if not removed from the feed. When non-homogeneous waste materials do not remain mixed within the bed, they tend to build up at the bottom of the combustor on the air distributor causing localized de-fluidization which can cause temperature excursions and increased CO generation, among other problems.

Further, the bed material itself can agglomerate into larger sized particles which can de-fluidize and sink to the bottom of the vessel causing similar problems. The bed material agglomeration phenomenon is more likely to occur in the presence of glass or ash with a high sodium content, both of which are likely to be found in MSW (275). Left unchecked, build-up of this material will cause the remainder of the bed to de-fluidize causing the unit to shut down. Like a conventional grate type boiler, bed material is drawn out of the bottom of the combustor and screened, with the fine portion being returned to the combustor to conserve bed material and reduce the amount of solid residue generated.

A description of the front-end operation unit processes typically used to produce various grades of RDF is provided in Appendix B -- RDF Technologies. Also included are the costs, environmental issues, and energy requirements that can be expected.

C.2.3 Specific Facilities

Information on existing FBC systems firing waste fuels is presented in the following sections.

C.2.3.1 Duluth, Minnesota

The Western Lake Superior Sanitary District (WLSSD) provides wastewater treatment for a 500,000 square mile area that includes the City of Duluth and 15 surrounding communities. The treatment plant, completed in 1978, produces 340 tons per day of sludge. The WLSSD also has responsibility for solid waste disposal in the district. In the early 1970s, multiple hearth furnaces fired with #2 fuel oil were considered as a means of sludge disposal through incineration. However, the oil embargo of 1973, caused the district to evaluate alternative options, because of the fear of escalating fuel oil costs. The FBC co-disposal technology was selected because of its ability to provide the desired sludge incineration capability without using a premium fuel; and further, it would provide a means of solid waste volume reduction through incineration, with capital and operating costs projected to be lower than the multiple hearth option (073).

The WLSSD installed a system utilizing Copeland FBC technology at its wastewater treatment complex in Duluth, Minnesota in 1979. The co-disposal system was designed to be operated on a combination of sewage sludge and RDF.

C.2.3.1.1 Process Description. A process flow diagram of the original sludge/RDF co-combustion facility is shown in Figure C-5. The RDF production system consisted of two processing lines; each line had a capacity of 30 tons per hour and consisted of a primary shredder, magnetic separator, secondary shredder, and air classifier system. A common RDF storage silo was used to store RDF fuel for feed to the combustion system.

Two 20-foot diameter bubbling type fluidized-bed combustors form the heart of the combustion system. A material handling system was designed to allow feeding of the RDF into the combustor either above or below the bed. Early operation of the system indicated high levels of freeboard burning, particularly when using the above-bed feed system. In-bed feeding of RDF, using a pneumatic injection system helped to reduce, but not eliminate, this problem. Excessive freeboard burning can cause poor combustion efficiency as well as high temperature excursions with resultant slagging in the freeboard or particulate clean-up system (073). Because of its aerodynamically light nature, RDF is a particularly difficult fuel with which to achieve high levels of in-bed burning in a bubbling-bed FBC. Sufficient freeboard space and low operating velocities must be employed to achieve reasonable combustion efficiencies.

Sludge was separately fed to the system using a belt feeder and motor driven cake breaker arranged to drop the sludge onto the top of the fluidized bed through a port in the combustion vessel's roof. Each FBC employed a twin cyclone system to catch particulate in the form of ash, unburned fuel, and elutriated bed material. From there, flue gases passed through a waste heat boiler system having a rated steam generating capacity of 100,000 pounds per hour at 250 psig (saturated). The only air pollution control equipment employed by the system was a wet venturi scrubber system for particulate removal.

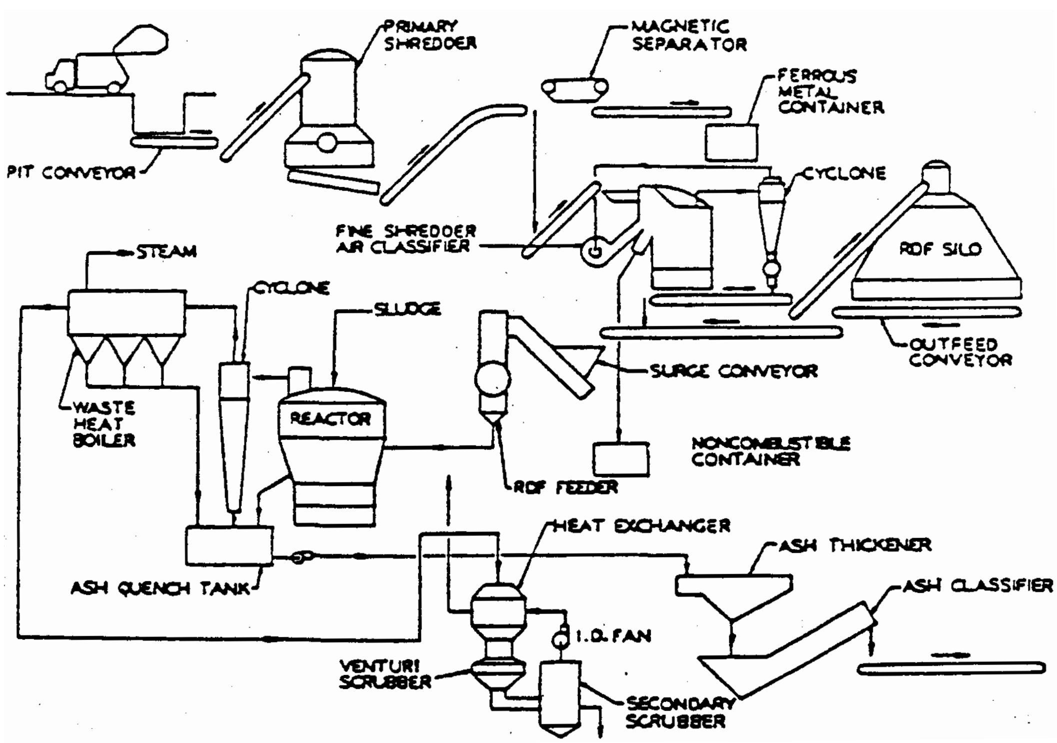


Figure C-5. Duluth, MN Codisposal Facility

Original Plant Flow Diagram (073)

The liquid effluent from the scrubber was fed to the front end of the wastewater treatment facility for treatment as a liquid waste. A stirred ash quench tank was used to collect bed material from a discharge port in the FBC, the cyclone catch, and material collected in the dropout sections of the waste heat boiler. A standard ash thickening and de-watering system was employed to process the ash slurry prior to disposal.

C.2.3.1.2 Operating History. Initially, the facility experienced severe operating problems due to clinker formation in the fluidized bed sections. It was determined that this was due to low melt temperature compounds being formed by glass and other constituents in the RDF. Major changes were made to both the fuel processing and the combustion systems. According to 1988 reports, the plant has operated reliably since the modifications were completed in 1985, with an availability of 95 percent for the RDF processing section and 85 percent for the FBC section (633).

The changes to the RDF system included the addition of a primary disc screen to remove glass prior to shredding, consolidation of the shredding operation in an isolated building for blast protection, and the addition of a secondary disc screen to recirculate the oversized RDF fraction back through the shredder for better size control. Further, a wood chip receiving and metering system was added to allow the sludge burning operation to continue using wood waste as a fuel when the RDF production line was not operating. Figure C-6 illustrates the modified system (073).

Improvements to the combustion system included the addition of multiple feed nozzles for better fuel distribution and the addition of overfire air in the freeboard section for improved combustion and carryover control. These changes, along with the improvements in RDF quality due to glass removal and size control, resulted in improved RDF production rates and reliability, reduced slagging and fusion problems in the bed, and reduced bed material buildup (due to less glass and other non-combustibles in the RDF). Additionally, the overfire air system improved the control of freeboard temperature excursions to the point where slagging in the cyclones was almost eliminated. Figure C-7 provides a schematic representation of the modified fluidized-bed reactor system.

Production rates reported at the time modifications were completed have exceeded 70 tons per hour. During the week, MSW deliveries to the RDF processing facility have varied between 150 and 350 TPD. (073) Operating data available from the facility indicates that the RDF production facility has a 30 kwh/ton electrical power requirement. The fuel produced has a heating value ranging from 5700 to 7700 Btu per pound, moisture of 15 percent to 20 percent, and an ash content between 8 percent and 13 percent. The RDF yield from the process is reported to be between 50 percent and 60 percent. Sludge solids content is 15 percent (516, 518).

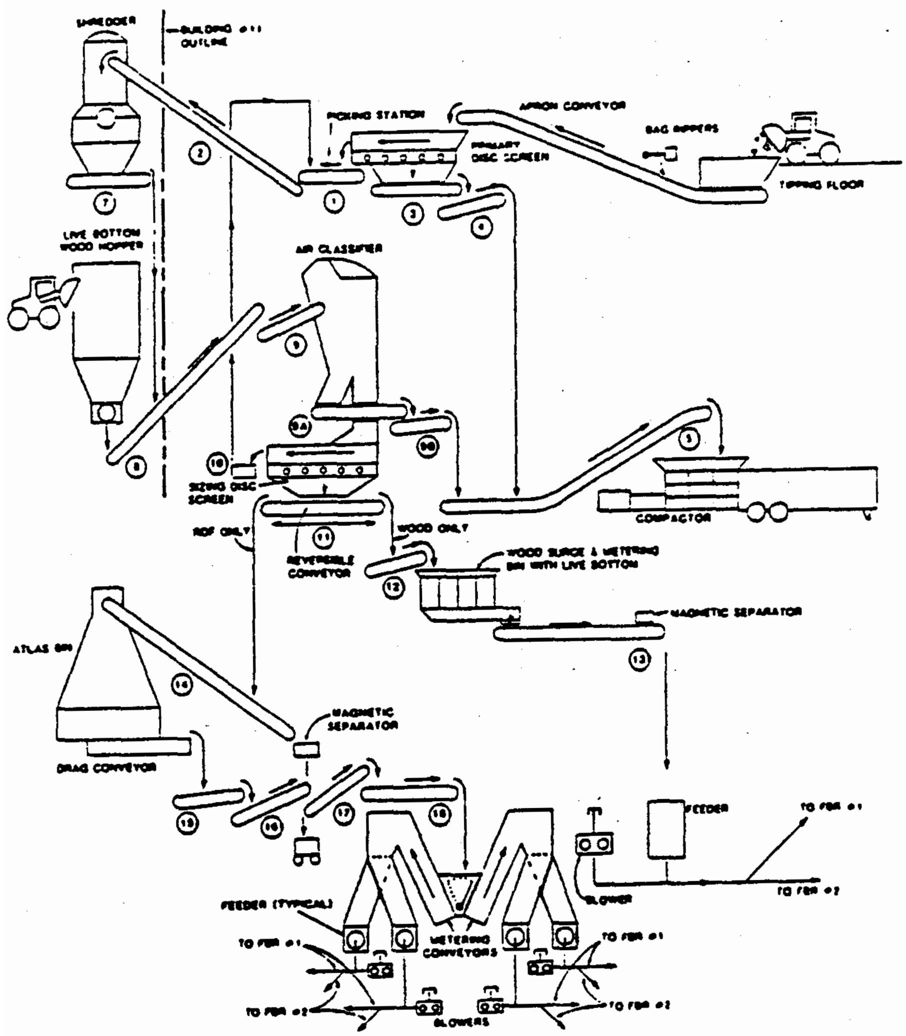


Figure C-6. Duluth, MN Codisposal Facility

Modified RDF System Diagram (073)

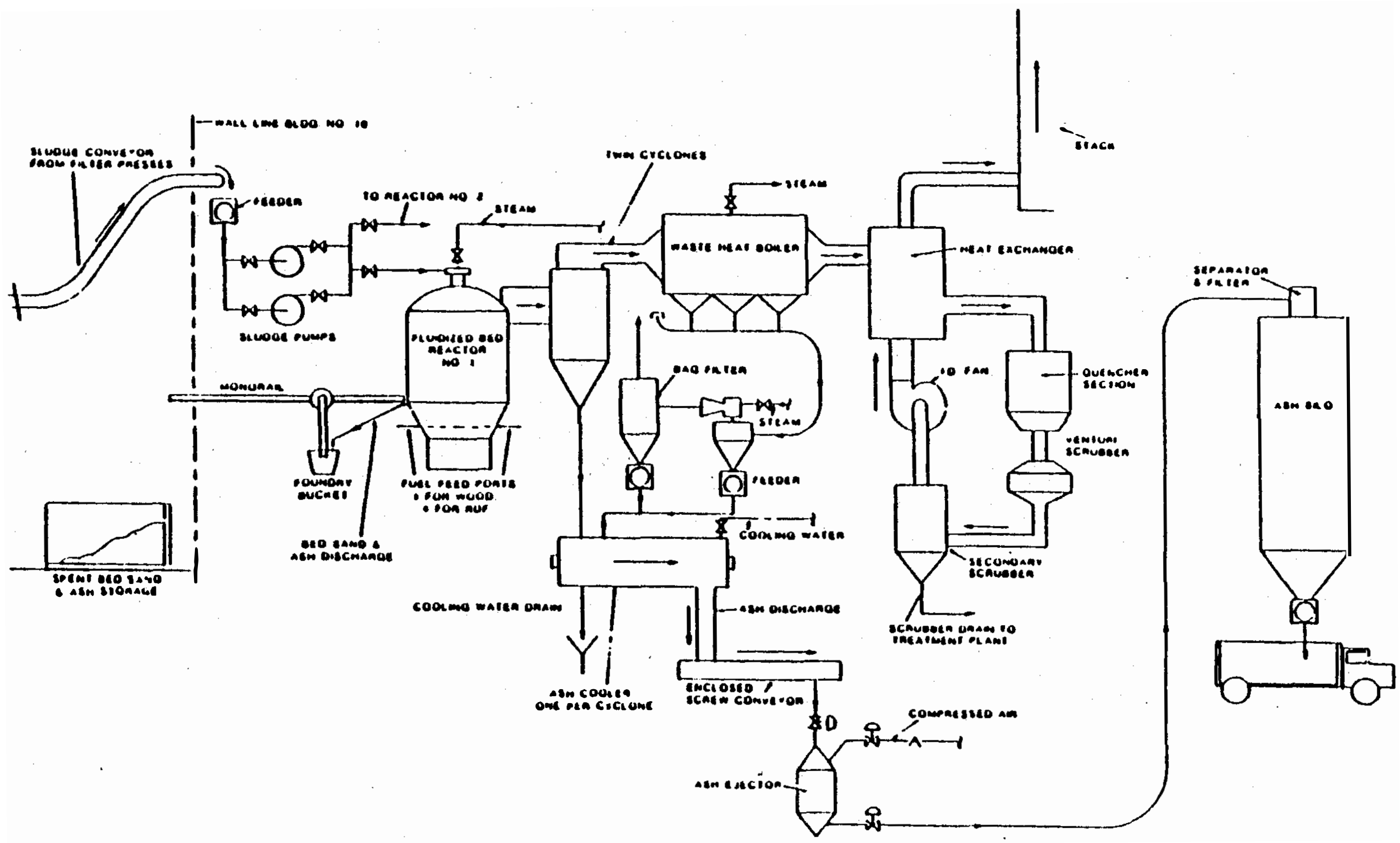


Figure C-7. Duluth, MN Codisposal Facility
Modified Fluidized Bed Reactor Diagram (073)

C.2.3.1.3 Emissions. As mentioned above, the only air polution control equipment installed is a wet venturi scrubber for particulate control. A series of facility emissions tests were conducted in 1987 (408). The particulate emissions rate averaged 1.03 pounds per hour, with particulate concentration averaging 0.0049 grain per dry standard cubic foot.

Stack emissions data for other gaseous pollutants, trace metals, dixoins and furans, as well as PCBs and HCBs has also been recorded, as have the results of dioxin and furan testing of flyash samples (408). These data are summarized in Section C.3 and compared to other FBC facilities.

C.2.3.1.4 Capital Costs. Capital cost information for the WLSSD facility is as follows:

Original Construction	$ 20,000,000 (1977 dollars)
1980-1981 Modifications	$ 1,500,000 (1980 dollars)
1984-1985 Modifications	$ 4,500,000 (1984 dollars)

C.2.3.2 Tacoma, Washington

This project involved the retrofitting of two existing pulverized coal-fired boilers at a municipal utility in Tacoma, Washington. The total electric generating capacity of Tacoma Public Utilities - Light Division, Steam Plant No. 2 is nominally 50 MWe. External bubbling bed FBC units with refractory-lined hot cyclones, designed by Energy Products of Idaho (EPI), were added to the system while the remaining plant systems, including the pollution control equipment, were upgraded to meet current environmental requirements.

The system is designed to operate on a fuel mixture consisting of 50 percent coal, 35 percent wood, and 15 percent RDF as calculated on an assumed lower heating value basis. The equivalent weight percentages are 27.4 percent coal, 53 percent wood, and 19.6 percent RDF. The rated steam generating capacity for the plant is 528,000 pounds per hour at 400 psig and 750 degrees F. The design fuel mixture is presented in Table C-1.

TABLE C-1. DESIGN FUEL MIXTURE, TACOMA, WA (543)

Fuel Component % Weight	Coal	Wood Waste	RDF	Fuel Mix (1) 50% Coal 35% Wood 15% RDF
1. Carbon	57.6	26.00	28.24	35.08
2. Hydrogen	3.9	3.00	3.76	3.41
3. Nitrogen	1.2	0.05	0.42	0.44
4. Sulfur	0.5	0.05	0.17	0.20
5. Oxygen	11.8	20.50	21.89	18.39
6. Chlorine	0.05	--	0.42	0.09
7. Ash (Solid non-combustibles)	11.95	0.40	8.60	5.17
8. Moisture	13.00	50.00	36.50	37.22
TOTAL	100.00	100.00	100.00	100.00
(HHV) btu/lb	10,080	4,250	4,725	5,939
(LHV) btu/lb	9,550	3,451	4,000	5,228

(1) Fuel mixture percentage is based on a Lower Heating Value Btu Basis. Mixture by weight is approximately 27.4% coal; 53.0% wood, and 19.6% RDF.

The original generating plant was built in 1931 to be used as a backup to the City's hydroelectric generating system. It was modified in 1953 to increase its generating capacity and to allow it to fire No. 6 oil. The plant was mothballed in 1973 due to superheater failures, and the City of Tacoma began working toward placing it back in service in 1979. The existing multifueled facility is a result of that effort.

FBC technology was proposed in 1984 on the basis that it would allow the municipal utility to recommission an idle facility, reducing its reliance on purchased power from outside the region, while burning locally available fuels which would otherwise create a burden on local landfills.

C.2.3.2.1 Process Description. A diagram of the overall fuel and limestone receiving, storage, and metering system is provided in Figure C-8. RDF is produced at a municipal solid waste processing facility located at a City-owned landfill. The production process consists of primary and secondary hammermills with screening systems for oversize control, ferrous removal, and air classification. Packer trucks ship the material to a wood/RDF storage building located at the plant. RDF yield from the MSW is approximately 50 percent. A characterization of the RDF product is as follows (543):

Moisture: Nominal 26%, Maximum 40%
Size: 100% < 6 inches, 95% < 3 inches
Glass Content: < 0.5%
Ferrous Metals Content: < 0.1%
Non-Ferrous Metals Content: < 1.1%
Total Non-Combustibles: < 11%

Wood fuel is received as hogged waste wood and bark with the following specifications (543):

Moisture: Nominal 50%, Maximum 55%
Size: Nominal 3 inches, Maximum 6 inches

The wood, as received, is screened using a disk screen to remove oversized materials, then stored in the wood/RDF storage building.

Coal is received in 5500-ton ocean going barges. The plant's receiving system offloads the ground coal from the barge at a rate of 300 tons per hour to a storage pile. Coal is reclaimed by a 60 ton per hour reclaim system and stored in day bins. From these bins, a 40 ton per hour reclaim system retrieves material for delivery to the FBC fuel metering system. The coal is received in ground form. The specifications for the as-received coal are as follows (543):

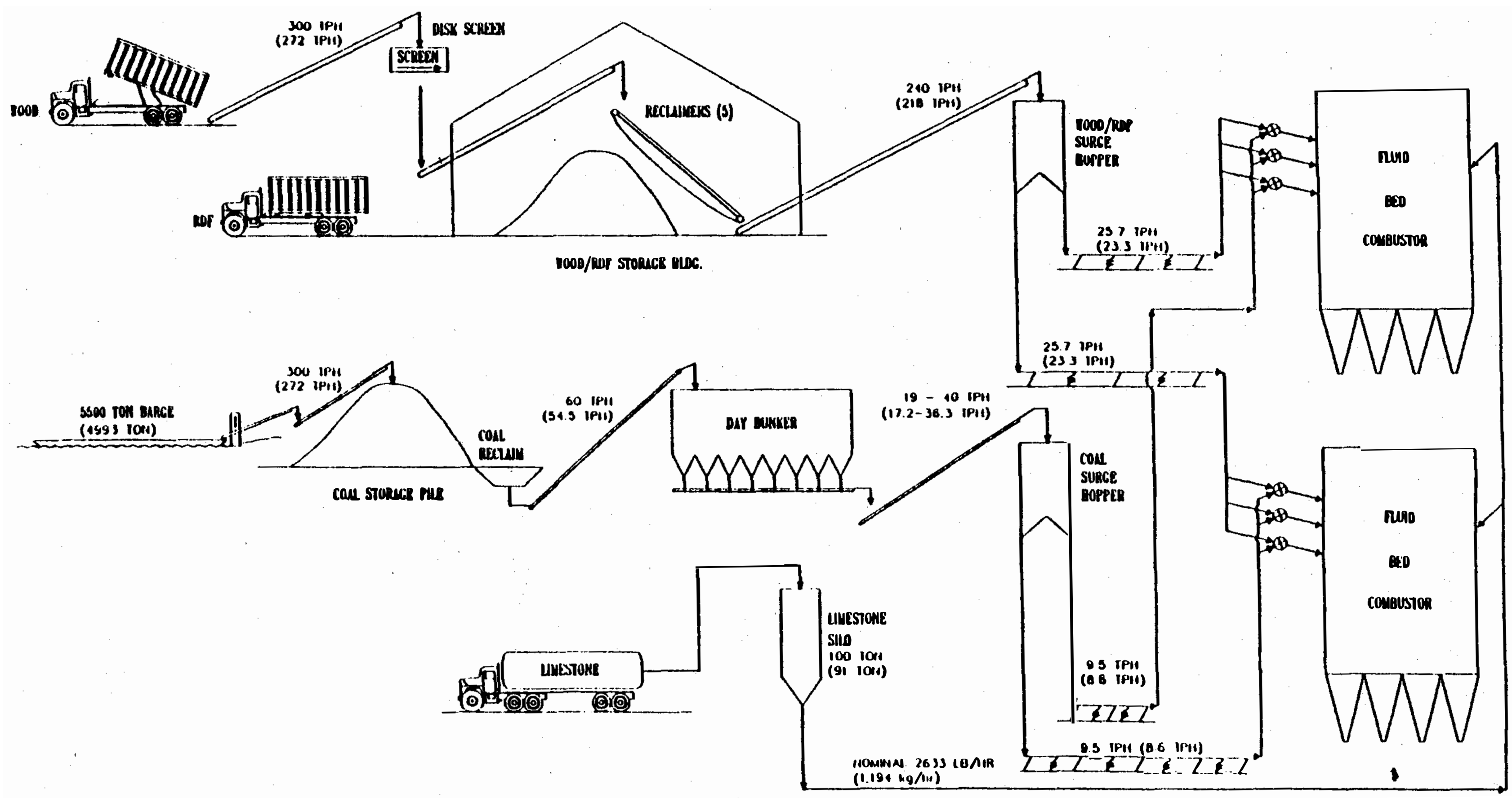


Figure C-8. Tacoma, WA Fuel Handling/Feed Systems (543)

Total Moisture: 13%

Air Dried Moisture: 5%

Hargrove Grindability Index: 43

Size: 50-25 mm 5%; 25-5 mm 35%; 5-2 mm 30%; 2-0.5 mm 20%; 0.5-0.2 mm 6%; 0.2-0.0 mm 4%.

In addition to the three fuels, crushed limestone is delivered by truck and pneumatically off loaded into a 100-ton storage silo. This material is metered to the combustors for in situ SO_2 control.

The combustion system consists of two atmospheric bubbling bed combustors retrofitted to each of the two steam generating units. An in-bed heat transfer surface has been installed and interfaced with the existing steam generating system. The original superheaters have been removed and replaced with new ones designed to operate with the new combustors. Each system has a steam generating capacity of approximately 250,000 pounds per hour, with approximately 59 percent of the evaporation occurring in the in-bed sections. An auxilliary fuel-fired air preheater on each unit is used only for bed preheat and system start-up. The original air preheaters have been removed and replaced with economizers. Air preheat is normally not used during operation. Figure C-9 depicts the process flow for the combustion, energy generation, and air pollution control portion of the plant.

C.2.3.2.2 Emissions. During normal operation of the FBC units, bed temperature is held between 1400 and 1600 degrees F to maximize in-situ SOx removal while minimizing NOx generation. The lighter density fraction of the fuel (RDF, coal fines, sawdust) is blown out of the bed and tends to bum in the freeboard, resulting in a freeboard temperature of 1800 degrees F. The operating permit for the unit defines good combustion practice as providing a 1-second gas residence time in the combustion section. Currently, the facility is petitioning to have the permit requirements changed to 5 seconds at 1650 degrees F in the freeboard (543). This would allow more in-bed burning and additional steam generation to occur at that point in the system.

Flue gas exits the combustor through two parallel, refractory lined cyclones which capture entrained unburned char and reinject it into the bed to improve combustion efficiency. In addition to the SOx and NOx control afforded by the design of the combustors, a pulse jet fabric filter is employed for particulate control. The facility's allowable emissions limit for particulates is 0.0068 grams per dry standard cubic foot (543).

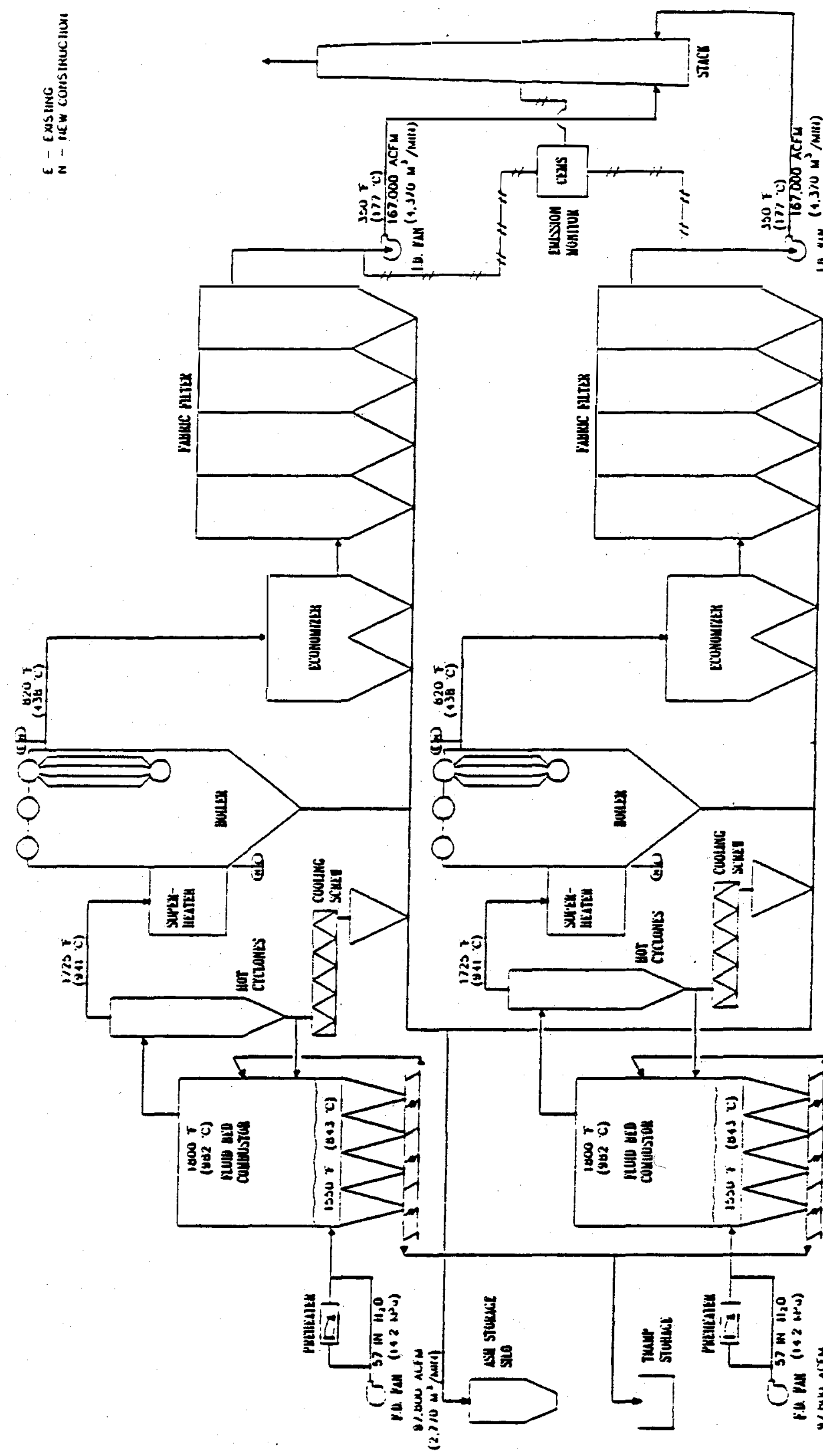


Figure C-9. Tacoma, WA Combustion Air and Flue Gas Systems (543)

C.2.3.2.3 **Capital Costs**. The cost for conversion of Steam Plant No. 2 is estimated at $43,000,000, including approximately $15,000,000 obtained as a grant from the Washington State Department of Ecology. (634)

C.2.3.3 Northern States Power, LaCrosse, Wisconsin

Northern States Power Company (NSP) operates a 30 MWe FBC system at French Island, La Crosse, Wisconsin, which co-fires wood waste and RDF. The system consists of two coal-fired steam generators, both of which were converted to oil firing in the 1970s. In 1981, as part of an effort to upgrade a number of its older and smaller generating plants, NSP converted its French Island Unit #2 to a waste wood-fired FBC unit. The existing boiler was retrofitted with a fluidized-bed combustor, designed by Energy Products of Idaho (EPI). The unit was operated for two shifts/day, five days per week on wood waste until 1987, when blending of RDF was initiated on a full-time basis. During the interim period, NSP had participated in an Electric Power Research Institute (EPRI) study to evaluate the plant's performance when firing a variety of alternative fuels at the French Island facility. During the test program, the unit's capability to fire a blend of RDF and wood waste was successfully demonstrated.

In 1984, based on the successful results of the EPRI sponsored study, NSP submitted a bid to La Crosse County to receive and process MSW at the French Island generating station. The proposal called for NSP to build a 50 ton per hour RDF production facility, bum the RDF with wood waste in the existing FBC converted unit, and convert the second steam generator to a similar co-fired FBC system. NSP was eventually awarded a contract to process 73,000 tons per year of MSW from within La Crosse County, with an option to secure an additional 104,000 tons per year from outside the county. Initial operation of the RDF production facility and the two FBC combustion facilities began in October of 1987. (564)

C.2.3.3.1 **Process Description**. The RDF production facility consists of a tipping floor for pre-inspection of the incoming waste, and a processing area. The process line, as shown in Figure C-10, consists of an infeed conveyor feeding a flail mill, which reduces the material to a nominal 12-inch particle size. A belt-type magnetic separator recovers ferrous material from the waste stream at this point. Depending on ferrous metals market conditions, this material stream can be further cleaned or landfilled. Two disc screens in conjunction with magnetic separators and air classifiers are used for size control and recovery of recyclables in the processed waste stream. The secondary disc screen and cleanup air classifier recover a small-sized organic fraction for combustion, further reducing the amount of material going to landfill. The RDF yield from this process is 70 percent. Processed RDF is conveyed to a storage bin which serves to de-couple the RDF production line and the FBC combustion system.

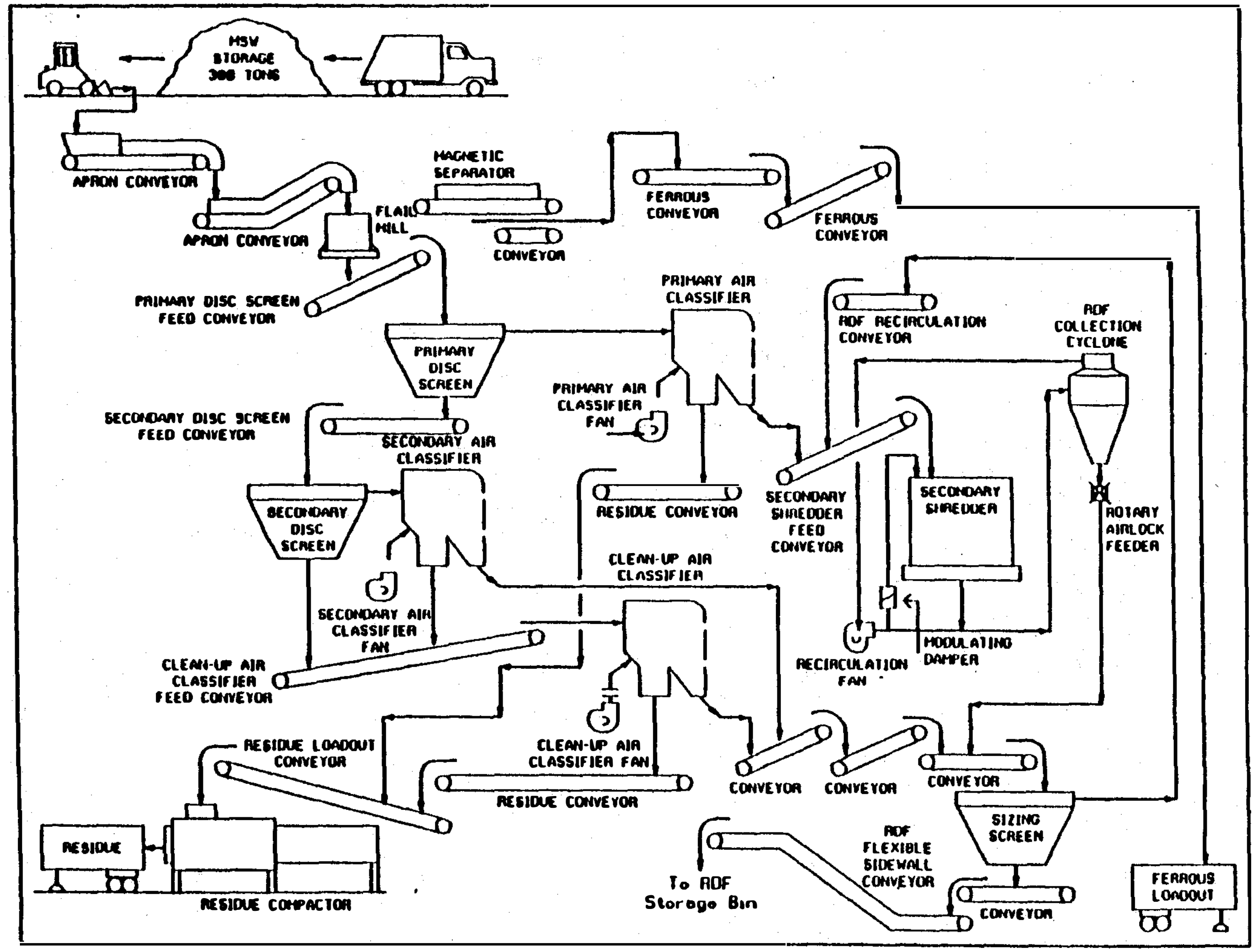


Figure C-10. NSP French Island Plant RDF Process Flow Diagram (564)

RDF is metered to the FBC feed system volumetrically by feeders located in the RDF processing building. A reclaim system pneumatically transports the RDF into a blending hopper at the front of each combustor. Wood waste is similarly metered and transported to the blending hopper from a separate storage area. The blended wood and RDF is then metered to the boilers using air swept, spreader type feeders in response to a fuel demand signal.

The combustion system consists of two atmospheric bubbling bed combustors retrofitted to each of the two existing steam generating units. The conversion was accomplished by fitting an air plenum, distributor plate, and bed containment section under the existing furnaces of the coal-fired units. In-bed heat transfer surface has been installed and interfaced with the existing boilers' pressure parts. The fluidized bed is normally operated at a temperature of 1500 degrees F. Each system has a steam generating capacity of approximately 150,000 pounds per hour. An auxilliary fuel-fired air preheater on each unit is used only for bed preheat and system start-up. Fuel is fed to the combustor via an overbed feed port located in the side wall of the FBC section. Figure C-11 illustrates the configuration of the FBC retrofit, along with some of the ancillary systems added to the boiler, including a bed material screening and recirculation system.

The combustor is designed to operate with a fuel mixture of 54 percent RDF and 46 percent wood on an energy input basis. The predicted performance of the plant, firing the design fuel is shown in Table C-2. As shown in the table, the station, including FBC units 1 and 2, has the capacity to bum approximately 20 tons per hour of RDF. At the stated RDF processing yield, the plant (both units) has a capacity to process over 600 TPD of incoming MSW on a 24-hr operating basis, assuming an 85 percent availability.

TABLE C-2. NSP FRENCH ISLAND PLANT PREDICTED PERFORMANCE (564)

Item	Unit #1	Unit #2
Turbine Gross Generation*	13.0 MW	15.2 MW
Turbine Net Generation*	11.7 MW	13.7 MW
Input in Fuel (RDF/Wood)	21,698/20,332 = 42,030 lb/hr	24,545/23,000 = 47,545 lb/hr
	10.85/10.17 = 21.02 tons/hr	12.27/11.5 = 23.77 tons/hr
	119.34/101.66 = 221.0 Btu/hr x 10^6	135/115 = 250.0 Btu/hr x 10^6
Higher Heating Value of Fuel (RDF/Wood)	5,500/5,000 Btu/lb	5,500/5,000 Btu/lb

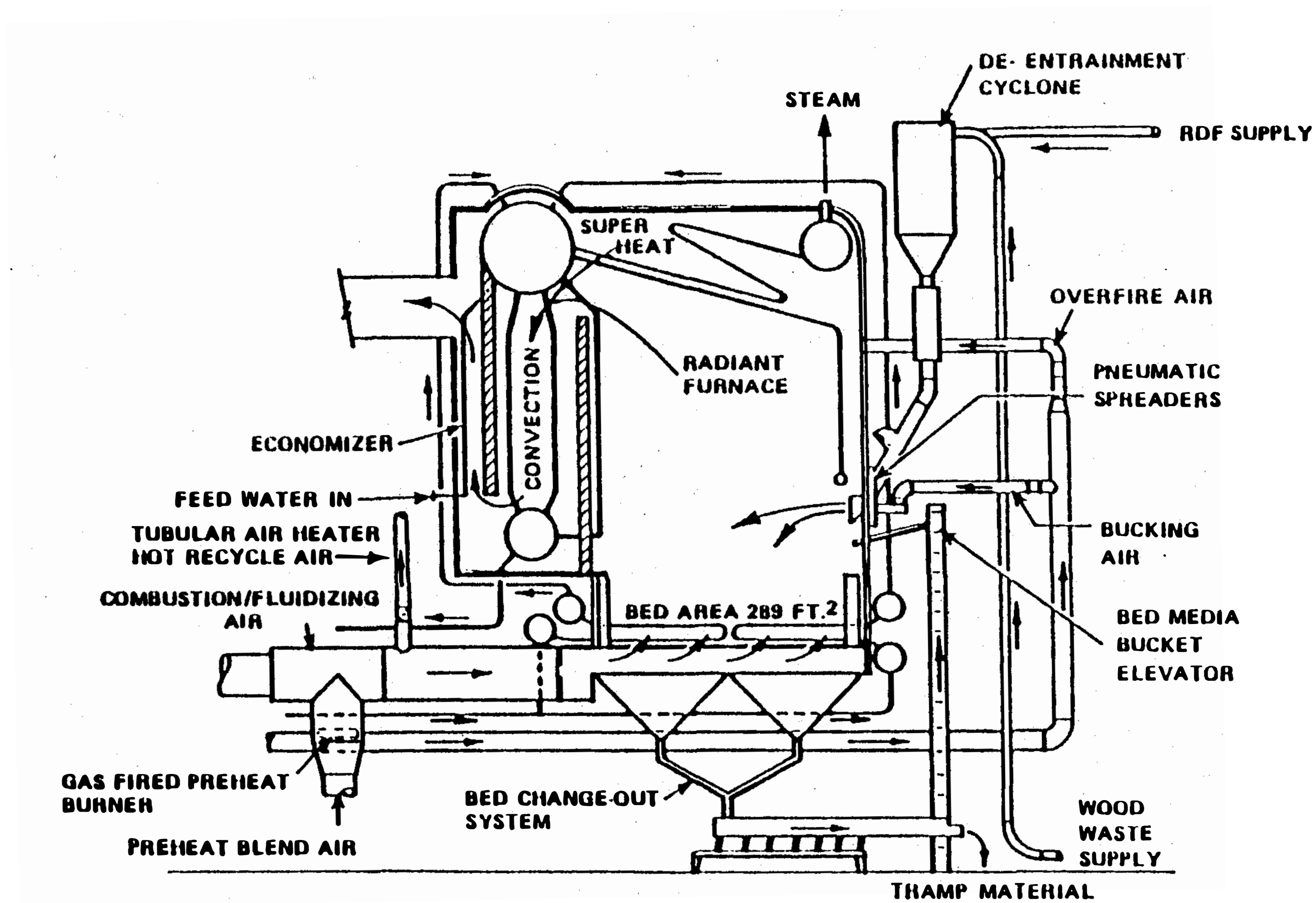


Figure C-11. NSP French Island Boiler Conversion Diagram (564)

C.2.3.3.2 **Operating History**. The plant has been in operation since 1987. Since that time, it has allowed NSP to extend the useful life of an older power generating station while providing a means of solid waste disposal for the surrounding communities. The plant has experienced operational problems typical of this type of facility. Some of the FBC-specific problems that have been encountered and resolved through system modifications include de-fluidization as well as bed agglomeration due to excessive amounts of tramp material and glass in the prepared fuel stream. Installation of a cleanup magnet and adjustments to the fuel preparation system's air classification equipment were recommended as solutions for these problems. Erosion of in-bed heat transfer surface was also experienced. Addition of sacrificial deflection surface to the in-bed tubes was implemented to reduce this phenomenon. The occurrence of these types of operating problems points out that fluidized bed combustion, while well suited to low grade, variable quality fuels, is not immune to the effects of typical extremes in waste fuel quality.

C.2.3.3.3 **Emissions**. An electrically charged granular bed filter is used for control of particulate emissions from the plant. No other active pollution control equipment is employed by the facility. Emissions testing was performed on Unit 2 in 1988 as follows (564):

Particulate Emissions: 0.06 lb/10^6 Btu
SOx: 0.01 - 0.1 lb/10^6 Btu
NOx: 0.25 - 0.4 lb/10^6 Btu
CO: ~500 ppm
HC: None Detected
HCl: 3-7 ppm, wet corrected to 12% CO_2

The relatively low uncontrolled emissions levels for the gaseous pollutants is attributed to combustion system design and fuel composition; i.e., acid gas control is inherently afforded by the presence of alkaline wood ash in the well mixed fluidized-bed combustor, and the FBC's low combustion temperatures provide reduced levels of NOx.

A 1988 study (516), sponsored by U.S. EPA references test results done at the facility which showed HCl emissions at 190 ppm uncontrolled, and 25 ppm with lime injection. This test series also reports tetra-octa CDD/CDF emissions rates of 14.3 ng/dscm, corrected to 7 percent O_2.

C.2.3.3.4 **Costs**. The capital cost for the RDF production facility portion of the project was $10,500,000, and the cost of the FBC retrofit was $13,000,000. A tip fee of $44.90/ton of MSW is charged at the facility, including a pass-through for residue disposal.

C.2.3.4 Gotaverken Energy Systems – RDF-fired CFBs

Gotaverken Energy Systems is a Swedish manufacturer of circulating fluidized boilers. Gotaverken CFB systems are operated in Europe to fire a variety of waste fuels, including RDF and other biomass fuels. Most of the company's RDF operating experience has been obtained from two of their installations; the Sande Paper Mill in Norway, and the Sundsvall Resource Recovery Plant in Sweden. Both facilities have fired a variety of waste fuels, as well as 100 percent RDF.

Within the past several years, Gotaverken technology has been proposed for use in two major U.S. waste-to-energy projects. One is a 700 ton per day facility, proposed for Erie, Pennsylvania, which will produce 23 MW of electric power. The other project is a 1600 ton per day facility in Robbins, Illinois, that will use CFB technology to produce 47.5 MW. Both systems will employ front-end processing to produce an RDF fuel for firing in CFB combustors. Projected performance data appears to be based on test data obtained from RDF firing at Gotaverken's Sundsvall plant. The company and project developers are confidant that the proposed plants can meet or exceed all of the emissions requirements currently being imposed on conventional MWCs in the United States. (633)

C.2.3.4.1 Process Description. Both of the proposed facilities will employ two CFB combustors operating at a bed temperature between 1500 degrees F and 1700 degrees F. The furnace section which houses the fluidized bed and freeboard section is of a waterwall construction. Both of the units will employ a combination of in-situ scrubbing (for SO_2) and flue gas dry sorbent injection systems for control of HCl emissions. This combination approach has been found to be the optimum approach for acid gas control, based on results from Sundsvall. Table C-3 summarizes design operating information for the two facilities.

C.2.3.4.2 Operating History. Both of the Gotaverken installations cited have been on line since 1984. The Sundsvall facility claims an on-line availability of 86 percent since that time. These facilities are considered successful commercial operations.

TABLE C-3. DESIGN INFORMATION (1989) - PROPOSED ERIE AND ROBBINS CFB FACILITIES (633)

Item	Erie, Pennsylvania Facility	Robbins, Illinois Facility
Private Owner/Operator	Reading Energy Company	Reading Energy Company
Fuel	RDF (2 in. max)	RDF (4 in. max)
Furnace/Boiler Type	CFB Waterwall (Gotaverken)	CFB Waterwall (Gotaverken)
Combustor Capacity	Two units @ 355 TPD each	Two units @ 600 TPD each
Bed Temperature	1,500 - 1,700 F	1,500 - 1,700 F
Excess Air	Approximately 30%	Approximately 30%
Steam Production	110,000 lb/hr per unit @ 800 psig, 770 F	225,000 lb/hr per unit @ 835 psig, 775 F
Energy Recovery	23 MW electric power	47.5 MW electric power
Air Pollution Controls	In-furnace Scrubbing (SO_2) Flue gas dry injection Scrubbing (HCl) Baghouse	In-furnace Scrubbing (SO_2) Flue gas dry injection Scrubbing (HCl) Baghouse
Status	Permits granted 1987	Permit applications submitted

C.2.3.4.3 **Emissions**. Extensive testing by Gotaverken at its Sundsvall facility in 1985 and 1988 has revealed that both SO_2 and HCl can be controlled by injection of limestone into the FBC. However, the test results also show that at the limestone injection rates required to achieve acceptable HCl control in the furnace, excessive generation of NOx was recorded. This phenomenon has also been reported at coal-fired FBC facilities (019). Further, the reactions involved in SO_2 capture occur rapidly at the typical bed/furnace operating temperatures, while the HCl absorption reactions are more likely to occur at the lower temperatures found after the boiler's steam generating bank. Based on this information, Gotaverken has determined that SO_2 can be efficiently captured in the furnace at limestone injection rates which do not adversely affect NOx generation, while HCl can be captured by introducing hydrated lime using a Venturi type in-duct injection system located just ahead of the baghouse. This combined control method has been determined to be the optimum approach, from both a practical and an economic standpoint, and has been proposed for both the Robbins and Erie facilities.

At the time stack testing was performed, the Sande plant was combusting 100 percent RDF, employed no in-furnace or flue gas scrubbing, and used an ESP for control of particulate emissions. Data from the 1986 tests are presented in Table C-4. All the measured emissions levels are within the limits currently specified in the U.S. under EPA's New Source Performance Standards for MWCs.

Emissions data from the Sundsvall facility is provided in Table C-5. Originally equipped with an ESP for particulate control, the facility had been retrofitted with a baghouse prior to these 1988 tests. SO_2 and HCl emissions levels were measured with and without in-bed limestone injection. The table shows that while reductions in both SO_2 and HCl on the order of 95 percent were obtained by this control method, NOx was more than doubled when introducing limestone to the combustor, leading Gotaverken to incorporate the combined acid gas scrubbing method into its facilities in order to guarantee NOx emissions below 200 ppm.

CO data for both the Sundsvall and Sande facilities indicate that combustion efficiency for the RDF-fired CFB combustors is high at their normal opeating temperature of 1500 degrees F. Although EPA's good combustion practice (GCP) for conventional MWCs dictates a furnace temperature of 1800 degrees F, recommendations have been made to define a 1500 degree F bed temperature as GCP for FBCs, because of the good thermal homogeneity afforded by the technology. (516)

TABLE C-4. EMISSION TEST RESULTS FOR GOTAVERKEN CFB FACILITY AT SANDE PAPER MILL, NORWAY -- 1986 (633)

	Test A	Test B	Test C
Fuel	100% RDF	100% RDF	100% RDF
Combustion Temperature (^oF)	1450	1500	1510
Air Pollution Controls	ESP; no in-furnace of flue-gas scrubbing		
Emissions:			
CO (ppmv)	89	96	73
NOx (ppmv)	129	110	168
Dioxin Test Equiv. Eadon Method (ng/Nm^3)	0.7	1.4	0.5

TABLE C-5. EMISSION TESTS RESULTS FOR GOTAVERKEN CFB FACILITY AT SUNDSVALL, SWEDEN -- 1988 (633)

	Test Number 1	2	3	4	5	6
Fuel	<------ 100% RDF ------>					
Combustion Temp	<------ Approximate 1,500° F ------>					
Air Pollution Controls	BH	BH	IFS/BH	IFS/BH	IFS/BH	IFS/BH
	(Baghouse Only)		<------ (In-furnace scrubbing, plus baghouse) ---------->			
Furnace Limestone Injection (kg/hr)	0	0	500	500	500	500
Emissions (ppmdv @ 7% O_2						
CO	9	9	18	4	5	13
NOx	152	163	333	337	333	277
Dioxin Toxic Equiv,Eadon Method	6.2	7.8	0.7	0.7	1.0	1.4
	(w/o scrubbing)		<------ with scrubbing ------>			
HCl	285	324	19	13	14	10
	(uncontrolled)		<----- (97-97% reduction from uncontrolled levels) ----->			
SO_2	55	53	<3	<3	<3	<3
	(uncontrolled)		<-------- (95% reduction from uncontrolled levels) ----->			

Notes: 1) Sundsvall is a 200 TPD CFB facility operated at 95% of full load during all tests.
2) Sampling and analysis by Swedish test methods, similar to EPA-approved methods commonly used on incinerators in the U.S.

Dioxin emissions data for the existing Gotaverken facilities are reported to be in the range of 0.4 to 1.4 ng/Nm^3. However, the data from Sundsvall indicates that a significant reduction in dioxin was seen when injecting limestone for SO_2 and HCl control versus without injection. As shown in Table C-6, Gotaverken has projected that the proposed facilities for Robbins and Erie will be able to meet or exceed a 2.0 ng/Nm^3 limit for dioxin. Table C-7 provides a comparison of dioxin/furan emission concentrations between the Sundsvall and Duluth, Minnesota FBC MWCs with similar data from other conventional MWCs throughout the country.

Testing of the ash residue from the Sundsvall facility reveals that unlike much of the test data from conventional MWCs in the U.S., both the bottom ash and the flyash pass the EPA's Extraction Procedure Toxicity test (Table C-8). Test data from conventional MWCs has repeatedly shown high levels of lead and cadmium in the flyash of these units. It has been speculated (633) that the metals in question, notably lead and cadmium, volatized as a normal part of the combustion process and that in the FBC, they are mixed with limestone, silica, and ash constituents at bed operating temperatures for a sufficient amount of time to allow them to chemically bond with the calcium and siliceous constituents. The result of this process could be considered similar to chemical fixation methods employed by ash and hazardous waste treatment technologies.

C.2.3.4.4 <u>Costs</u>. The capital cost of the Robbins facility is projected to be $200,000,000 for a 1600 ton per day MSW throughput. The cost of the RDF production portion of the facility is $20,000,000 (521).

TABLE C-6. PERMIT LIMITS FOR PLANNED CFB FACILITIES (633)

Pollutant/Parameter)	Erie, PA Facility Existing Permit (1987)	Robbins, IL Facility Proposed Limits (1988)
Particulate, Total	0.015 gr.dscf	0.010 gr/dscf
Particulate, PM10	No Limit	0.010 gr/dscf
HCl	30 ppmdv (1 hr), or 90% control (1 hr)	50 ppmdv (1 hr) or 90% control
SO_2	50 ppmdv (1 hr), or 70% control (1 hr)	30 ppmdv (8 hr), or 75% control
CO	100 ppmdv (8 hr), or 32 lb/hr	100 ppmdv (1 hr)
Combustion Efficiency	99% (1 hr)	99.9% (1 hr)
Dioxin/Furan	2.0 ng/Nm^3 toxic equivalents (EPA Method)	BACT
NO_2	No specific Limit	200 ppmdv (30 day)
Opacity	<10%, escept <30% for period(s) totalling not more than 3 min/hr	<10%. exce[t <30% for period(s) totalling not more than 3 min/hr
Combustion Temperature	Aux. fuel burners engage if combustion temperature drops below 1450°F	Combustion temperature ≥1500°F, gas residence time ≥3 seconds

Note: All concentration values (gr/dscf and ppmdv) are stated as corrected to 7% O_2.

TABLE C-7. MEASURED DIOXIN/FURAN EMISSION CONCENTRATIONS AT MODERN RESOURCE RECOVERY FACILITIES (633)

Facility	Size/Type[a]	Air Pollution[b] Control Equipment	PCDD + PCDr Emission Concentration ng/Nm^3 @ 7% O_2 Eadon Toxic Equiv
Fluidized-Bed Incinerators			
Duluth, MN	400/RDF	MC/WS	0.09 - 0.14[c]
Sundsvall, Sweden	200/RDF	IFS/FF	0.5 - 1.1 (4 tests)[d]
			Approx Avg = 0.5 (Eadon)
Grate-Bum Incinerators			
Commerce, CA	380/MB	SDA/FF	0.03
Marion County, PR	1100/MB	SDA/FF	0.2
Bristol, CT	650/MB	SDA/FF	0.1
Millbury, MA	1500/MB	SDA/ESP	0.6
Claremont, NH	200/MB	DS/FF	0.4 (Unit 1) 0.5 (Unit 2)
Hartford, CT	2025/RDF	SDA/FF	1.95
Biddeford, ME	607/RDF	SDA/FF	0.09
			Approx Avg = 0.7 (Eadon)

Notes: a) Size represents total facility waste throughput in tons per day TPD)
MB - mass bum, RDF - refuse derived fuel

b) IFS - in-furnace scrubbing; FF - fabric filter
MC - mechanical collector; ESP - electrostatic precipitator
WS - wet scrubber; SDA - spray dryer absorber
DS - dry scrubbing (dry in-duct injection)

TABLE C-8. EP TOXICITY TEST RESULTS FOR GOTAVERKEN CFB RESIDUE – 1986 (633)

	Allowable Limit (ppm)	Sundsvall CFB Bottom Ash	Sundsvall CFB Fly Ash
Arsenic	5.0	.007	.17
Barium	100.0	.1	.3
Cadmium	1.0	.05	.03
Chromium	5.0	.12	.04
Lead	5.0	.35	.04
Mercury	0.2	.0002	.001
Selenium	1.0	.01	.02
Silver	5.0	.04	.02

Note: Sundsvall CFB facility burning RDF, with ESP and with in-furnace limestone scrubbing. Bottom and fly ash samples obtained and analyzed by EPA-certified laboratory.

C.2.3.5 MWCs Using FBC Technology in Japan

Japan appears to have the greatest amount of commercial operating experience with fluidized-bed combustion of municipal refuse, as well as sewage sludge, and other specific industrial wastes. Because Japan has limited land resources in general, the problem of lack of available space for landfills has been more acutely felt in that country than in Europe or the United States. As a result, over half of all the refuse generated in Japan is incinerated, including over 70 percent of the municipal waste generated. (722)

There are 113 FBC municipal waste combustion facilities in Japan; most of them have been constructed within the past 10 years (722). They are typically equivalent to the small modular facilities found in the U.S., processing less than 400 tons per day of refuse. Volume reduction by incineration is the primary goal. Energy recovery is secondary and is typically employed to produce in-house power to operate the incineration facility or provide thermal energy to local users. These energy users tend to be facilities owned or operated by the host communities and the energy is provided at low or no cost as compensation for allowing the facility to be sited there. Generation of electric power for sale to the utility is prohibited by law (287).

In 1987, it was estimated that 90 percent of the municipalities in Japan practice source separation of the municipal waste in the home. Waste is normally separated into combustible and non-combustible fractions as well as bulky items. These separated items are typically sent to a central processing facility where bulky items are shredded, and ferrous, glass, and other recyclable materials are recovered from the entire stream, using manual sorting. Thus, the as-received waste going to the incineration facilities (both FBC and non-FBC) is really a prepared fuel, having a non-combustibles content of only 4 percent, minimizing residue disposal requirements, and reducing fuel preparation requirements at the FBC facility (012).

C.2.3.5.1 <u>Machida Refuse Resources Recycling Center</u>. The Machida Refuse Resources Recycling Center is a municipal facility constructed by the Machida Municipal Government in Tokyo, Japan In 1982. The facility was designed to handle the waste from a population base of 370,000. It incorporates a "Recycle Plaza" where recyclable material is recovered from the incoming waste. The remaining material is sent to a receiving pit, from which it is fed to a refuse crusher for size reduction to approximately a 4-inch particle size. No further processing of the incoming refuse is employed. The material is then burned in a fluidized-bed combustion system. Energy recovery is employed to generate steam for heating and air conditioning of the Recycling Center. Electricity is generated for internal plant use only.

The MSW combustion system consists of three IHI fluidized-bed combustors, each capable of burning 150 tons per day of incoming refuse. These units are the largest FBCs installed in Japan for the combustion of MSW. Normally, two units are active and one is kept available as a backup. The units are bubbling-bed combustors with a gravity overbed feed system. A bed management system is employed which allows the bed material to be continuously removed, screened, and re-fed to the combustor during operation. This allows the buildup of oversized non-combustibles in the bed to be controlled, an important feature in MSW-fired FBCs.

Each FBC boiler has a steam generating capacity of 36,000 lb/hr at 360 psig. Two 2,000 kW condensing turbines are used to produce power for in-house consumption. Power generation is controlled to maximize electricity production without exceeding the in-house demand because the plant is not permitted to sell power back to the utility (672).

A limestone feed system is employed for in-situ acid gas control, and may provide some level of bed fusion control as well. An electrostatic precipitator is used for particulate emission control. No other pollution control systems are employed by the plant.

At the time the plant was commissioned, performance tests were conducted which indicated that the facility was operating in compliance with its emissions limits at predicted processing rates.

C.2.3.5.2 Koza Garbage Incineration Service Corporation. The Koza Garbage Incineration Service Corporation constructed a fluidized-bed MWC facility for waste disposal in Ebina City, Kanagawa Prefecture, Japan. Operation began in 1977. Commissioned nearly five years before the Machida FBC facility, the overall design is similar in that incoming waste undergoes a size reduction step prior to being fed to the FBC combustor.

The Koza facility contains two 60 ton per day IHI FBCs. Electrostatic precipitators are used for particulate control, and a caustic spray absorption tower is used for HCl control rather than the in-situ limestone injection method used at Machida. A reheater was employed after the wet scrubber to remove the visible plume of condensed water in the flue gas. At the time this facility was built, the objective was to provide an environmentally sound means of incinerating municipal refuse.

Energy production goals were considered secondary, and only 8 percent of the thermal energy is recovered in the form of hot water for use in the incineration facility and a neighboring nursing home. Control of bed temperature is through the use of an auxiliary fuel-fired burner in conjunction with excess air and attemperating water sprays. Minimization of residue quantity through maximization of combustibles burnout was given highest priority. Additionally, a flyash treatment method was employed where the ash was mixed with cement and water, then pelletized. This was apparently done in response to environmental concerns about heavy metals in the flyash residue. (671) Flyash treatment was not included at the Machida facility, indicating that the in-situ HCl control strategy provides the added benefit of ash stabilization.

C.2.3.5.3 Ebara Revolving Type Fluidized Bed Combustor. A variation on the conventional bubbling-bed FBC known as a revolving type fluidized-bed combustor has been developed by the Ebara Corporation, which has installed 40 units for municipal refuse combustion in Japan (179). Of these, 32 are small scale incinerators, with cooling of the products of combustion effected through the use of dilution air and an air preheater for the primary fluidizing air. The FBC units employed at these facilities are small, having a solid fuel combustion capacity in the range of 3,000 lb/hr to 5,000 lb/hr. The facilities employing these FBCs range in MSW processing capacity from 25 tons per day to 120 tons per day. A schematic representation of a cooling chamber type installation is shown in Figure C-12. The remaining eight units use combustors having individual processing capacities between 5,000 lb/hr and 10,000 lb/hr, and the facilities involved range in MSW processing capacity from 120 tons per day to 390 tons per day. Figure C-13 shows a schematic diagram of the boiler type installation. This type of combustor has been used in this application because its design features, many of which are really enhancements of the bubbling bed's attributes, offer a system which is more suited to combustion of municipal refuse as well as other low grade fuels.

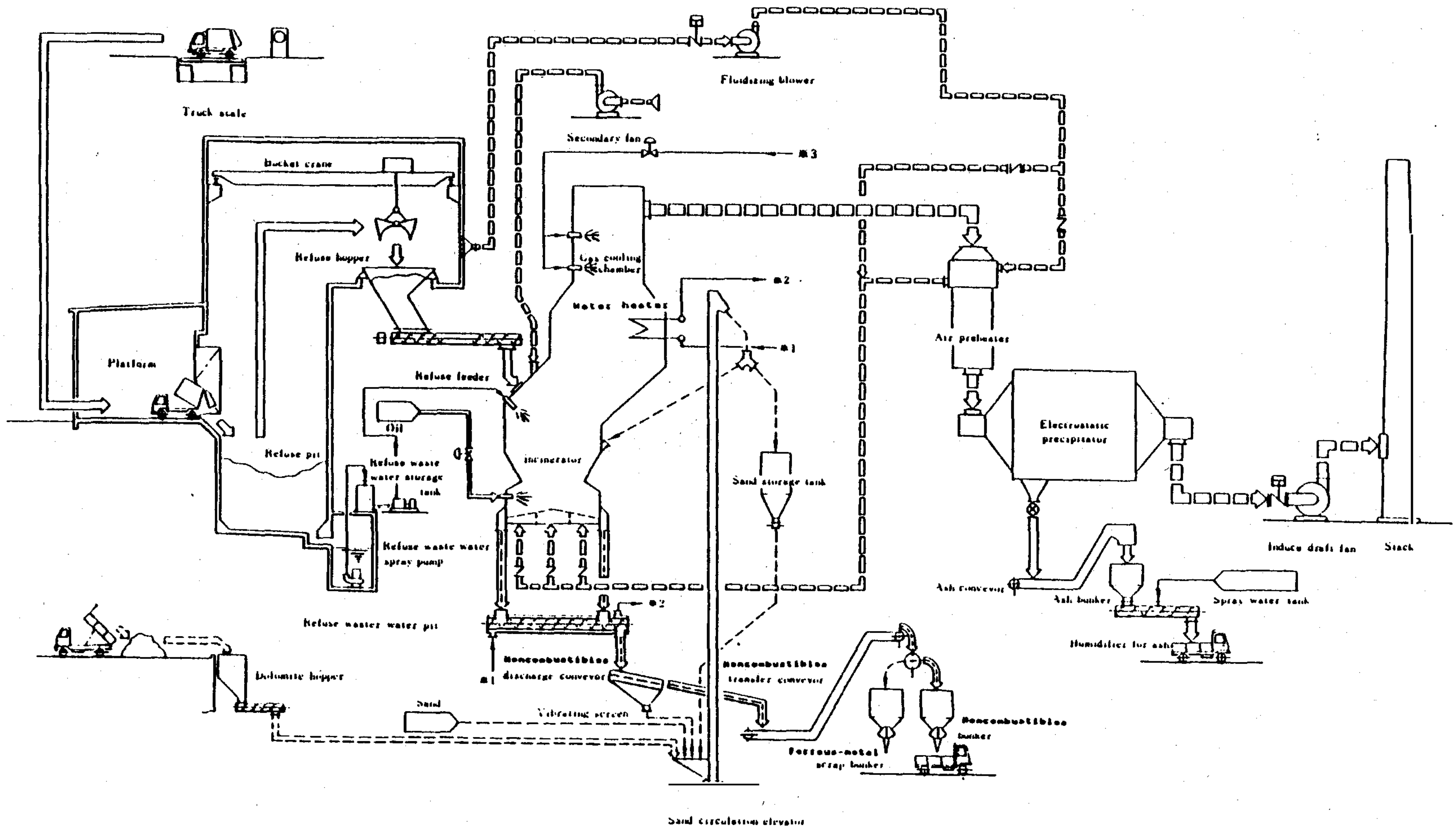


Figure C-12. Ebara Gas Cooling Chamber Type FBC (179)

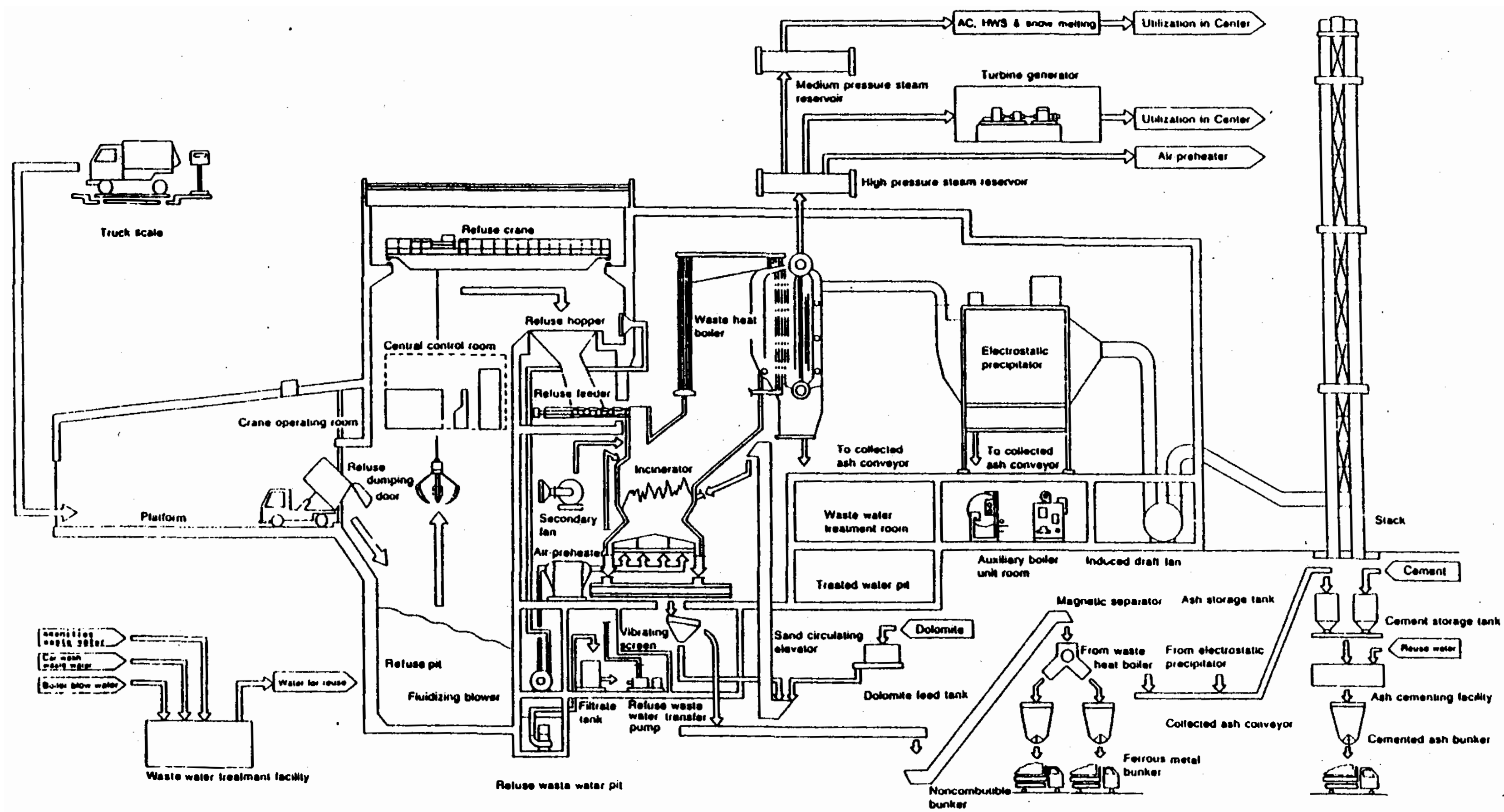


Figure C-13. Ebara Boiler Type FBC (179)

In the bubbling-bed FBC, solid combustible material is fed into a hot, fluidized bed where it is subject to high temperatures and mixed thoroughly with air resulting in the thorough combustion of the fuel. However, little lateral mixing occurs under normal operating conditions, and large, heavy pieces of fuel can sink to an inactive area at the bottom of the bed before they have had a chance to be burned. Another problem is that in an FBC having a large plan area, heavy non-combustibles may sink to the bottom of the bed at or near the position at which they are introduced, which may not coincide with the location of the bed material removal port. In this case, these materials will not be removed from the bed while the unit is on line, and will consequently build up over time causing operational problems.

The Ebara revolving bed claims to have reduced these problems by inducing a significant amount of lateral mixing within the bed by means of variable fluidization velocities across an inclined distributor plate, as well as bed containment vessel geometry. The result is a bed which can be operated at higher velocities in the deep zone helping to break up larger combustibles more easily as well as a distributor plate which slopes toward an opening to a water cooled screw conveyor for bed material removal and classification. By means of a baffle deflector, material from the deep bed, high fluidization velocity zone is deflected to the shallow bed, low fluidization velocity zone, from where it sinks back to the deep zone again, resulting in a "revolving" lateral mixing motion of the bed material/fuel mix. A side view diagram of the fluidized bed is shown in Figure C-4. Ebara claims that the revolving bed design has allowed unshredded MSW to be combusted in the unit (518), however, as reported previously (287) unshredded MSW in Japan is actually somewhat of a prepared fuel having undergone removal of significant amounts of non-combustibles and bulky items at the source.

In municipal refuse applications, Ebara typically employs in-situ HCl control by feeding dolomite into the bed via the bed material classification/makeup system. An electrostatic precipitator is used for particulate control. NOx control is effected through maintaining a uniform bed temperature in the 1500 degree F range, and keeping excess air low. Tables C-9 and C-10 show the results of stack emissions tests published by Ebara for their FBC burning refuse. Heavy metals concentrations in flyash samples have also been analyzed and found to be well within regulated limits, with and without treatment by solidification techniques. Table C-9 shows values of HCl concentration using a variety of control methods. Note that downstream sorbent introduction results in lower HCl emissions.

The capital cost of an Ebara incineration facility, in terms of dollars per ton per day processing capacity is estimated to be between $110,000 and $150,000, depending on whether or not energy recovery is employed and the strictness of the environmental regulations at a given site.

C.2.3.5.4 Other Japanese FBC Installations. Table C-11 presents a list of other FBC installations which are burning municipal refuse in Japan.

TABLE C-9. COMPARISON OF HCl REMOVAL METHODS ON EBARA FBC (179)

HCl Removal Method	Exhaust Value
Dry Systems	
In bed injection of Dolomite or Calcium Carbonate	> 150 ppm
Calcium hydroxide sprayed in flue gas	150 - 100 ppm
Semi-Dry Systems	
Calcium hydroxide slurry sprayed in flue gas	100 - 50 ppm
Wet System	
Alkali aqueous solution used in scrubber	50 ppm or >

TABLE C-10. DUST COLLECTION BY ELECTROSTATIC PRECIPITATOR SELECTED EBARA PLANTS (179)

Capacity t/D	Inlet g/m3	Outlet g/m3	Emission Standard g/m3
120	16.1	0.024	0.05
150	14.9	0.032	0.05
70	6.07	0.053	0.1
150	6.83	0.035	0.05
80	12.4	0.088	0.1
100	19.5	0.029	0.05
360	8.7	0.03	0.05
327	8.13	0.027	0.05

TABLE C-11. OTHER FBC INSTALLATIONS IN JAPAN -- 1987 DATA (673)

No.	Customer	Location	Start of Operation	Type of Fuel	Number of Units	Size of Units (TPD)	Total Rated Capacity (TPD)
1.	Hokuetsu Paper Co.		1965	Wood Bark	1	88	88
2.	Setsu Paper Mfg. Co.	Saka City Saitama Pref.	1968	Black Liquor	1	265	265
3.	Shin Nihon Seitetsu	Takai City Aichi Pref.	1968	Ferrous Chloride	1	309	309
4.	Koza No. 1	Ebina City Kanagawa Pref.	1977	Municipal Refuse	2	66	132
5.	Aioi	Aioi City, Hyogo Pref.	1979	Municipal Refuse	2	33	66
6.	Machida	Machida City, Tokyo	1982	Municipal Refuse	3	165	495
7.	Narashino	Narashino City, Chiba Pref	1983	Municipal Refuse	3	66	198
8.	Chita	Chita City Aichi Pref.	1983	Municipal Refuse	2	66	132
9.	Koza No. 2	Ebina City, Kanagawa Pref.	1984	Municipal Refuse	1	165	165
10.	Ohita	Ohita City Ohita Pref.	1986	Municipal Refuse	2	165	330
11.	Ohtsu	Ohtsu City Shiga Pref.	1988 March	Municipal Refuse	2	99	198
12.	Kisarazu	Kisarazu City Chiba Pref.	1988 February	Municipal Refuse	3	77	231

TABLE C-11. OTHER FBC INSTALLATIONS IN JAPAN -- 1987 DATA (cont)

No.	Customer	Location	Start of Operation	Type of Fuel	Number of Units	Size of Units (TPD)	Total Rated Capacity (TPD)
13.	Ohgami	Hiratsuka City Kanagawa Pref.	1988 March	Municipal Refuse	3	109	327
14.	Hashimoto City	Hashimoto City Wakayama Pref.	1987	Municipal Refuse	2	50	100
15.	Furukawa City	Furukawa City Miyagi Pref.	1988 March	Municipal Refuse	2	44	88
16.	Usuki	Usuki City Ohita Pref.	1989 March	Municipal Refuse	2	44	88
17.	Kito	Tokeo City Saga Pref.	1989 March	Municipal Refuse	3	51	153
18.	Tome	Tome District Migagi Pref.	1989 March	Municipal Refuse	2	44	88
19.	Hukui	Hukui City Hukui Pref.	1990	Municipal Refuse	3	128	384
20.	Kurihara	Kurihara District Migagi Pref.	1989	Municipal Refuse	2	44	88

Total - 11 plants (20 incinerator units) operating, 9 plants (22 incinerator units) under construction

Updated 10/18/87

C.3 ENVIRONMENTAL IMPACT

FBC technology has been applied to a variety of combustion applications in an effort to bum difficult fuels cleanly and completely so as to minimize undesireable gaseous emissions and solid residue. In the case of MSW, fuel quality can vary over a wide range with respect to energy content, moisture, ash content, and particle size (physical homogeneity).

The types of FBC facilities surveyed in the literature vary greatly from a 120 ton per day bubbling bed unit which recovers only a portion of the thermal energy produced as hot water, to a 1200 ton per day dedicated MWC using CFB technology having an electric generating capacity of 50 MWe. However, the facility on the large end of the scale has yet to be built. The emissions data presented herein for that facility are actually the permitted operating conditions the facility will have to meet under the current emissions guidelines for MWCs. Although the facilities surveyed really can not be compared on an equal basis, it can be stated generally that FBCs have demonstrated their ability to burn MSW or RDF alone or in combination with other fuels, and that the measured emissions are well within the range of required levels for MWC facilities in the United States. Stack emissions data for the facilities surveyed are summarized in Table C-12.

C.4 ECONOMIC DATA

The literature survey provides little data on operating costs for MSW-buming FBCs. Of the facilities and technologies surveyed, the one considered most applicable to a modem day waste-to-energy plant is the Gotaverken facility operating at Sundsvall, Sweden. However, this is a relatively small facility compared to the proposed Robbins, Illinois installation, which is more comparable in size to large scale MWCs currently being built in the United States. The capital cost of the Robbins facility is estimated at $200,000,000 or $125,000 per ton per day of MSW receiving capacity (521); this is comparable to capital costs of conventional MWC facilities. Table C-13 compares available cost and operating data for the facilities surveyed.

TABLE C-12. AIR EMISSIONS COMPARISON OF SELECTED FBC FACILITIES

	WLSSD (a)	TACOMA (b)	NSP UNIT 2 (c)	SUNDSVALL (d)	SANDE (e)
STACK EMISSIONS					
PARTICULATE	.004 to .006 gr/DSCF	.0068 gr/DSCF	0.06 lb/MMBTU	< .005 gr/dscf	N/A
SOx	92 - 121 ppm (wet)	N/A	0.01 - 0.1 lb/MMBTU	6 - 31 ppmdv	N/A
HCl	< 1 ppmv (wet)	N/A	3 - 7 ppm (wet)	> 90% Removal @ Ca/S =4	N/A
NOx	15 - 43 ppmdv	N/A	0.25 - 0.4 lb/MMBTU	111 - 138 ppmdv	136 ppmv
HC	N/A	N/A	Not Detected	N/A	N/A
CO	1 - 31 ppmdv	N/A	500 ppm	11 - 20 ppmdv	86 ppmv
DIOXIN	.09 - 0.14 ng/nm3 (EPA Toxic Equiv)	N/A	14.3 ng/dscm tetra-octa CDD/CDF	.03 - .3 ng/Nm3	.87 ng/Nm3 Eadon Test Method

(a) Western Lake Superior Sanitary District; Sludge/RDF Co-Disposal Facility; Interpoll Laboratory Test Report; Reference 516
(b) Tacoma Public Utilities - Light Division Steam Plant No. 2, Tacoma, WA; FBC Retrofit; Reference 543
(c) Northern States Power; French Island Generating Station - FBC Retrofit; 1988 Test Results; Reference 564
(d) Korsta Facility, Sundsvall, Sweden; Gotaverken CFB; Reference 517
(e) Sande, Norway Paper Mill; Gotaverken CFB; Avg Values of 3 Tests - 1986 Reference 435

TABLE C-12. AIR EMISSIONS COMPARISON OF SELECTED FBC FACILITIES (cont)

	MACHIDA (f)	KOZA (g)	ERIE (h)	ROBBINS (i)
STACK EMISSIONS				
PARTICULATE	.02 g/Nm3	0.1 g/Nm3	0.015 gr/dscf	0.010 gr/dscf
SOx	3.6 ppm	4.666 Nm3/h	50 ppmdv or 70% Control	30 ppmdv or 75% Control
HCl	75 ppm	5 ppm	30 ppmdv or 90% Control	50 ppmdv or 90% Control
NOx	129 ppm	250 ppm	No Specific Limit	No Specific Limit
HC	N/A	N/A	N/A	N/A
CO	N/A	N/A	100 ppmdv	100 ppmdv
DIOXIN	N/A	N/A	2.0 ng/Nm3	BACT

(f) Machida Refuse Resources Recycling Cultural Center - Tokyo, Japan; Avg of 3 Test Results; Reference 672
(g) Koza Garbage Incineration Incineration Corporation - Ebina City, Japan; Permit Limits; Reference 671
(h) Proposed 710 T/D MWC for Erie, PA; Gotaverken CFB; Reference 633
(i) Proposed 1200 T/D MWC for Robbins, Ill; Gotaverken CFB; Reference 633

TABLE C-13. COST AND OPERATING DATA OF SELECTED FBC FACILITIES

	DULUTH, MN CO-DISPOSAL FACILITY	TACOMA, WA STEAM PLANT NO. 2	FRENCH ISLAND STATION UTILITY GENERATING STATION	SUNDSVALL RESOURCE RECOVERY PLANT	SANDE PAPER MILL	MACHIDA REFUSE RESOURCES RECYCLING CENTER
	FACILITY #1	FACILITY #2	FACILITY #3	FACILITY #4	FACILITY #5	FACILITY #6
LOCATION	DULUTH, MN	TACOMA, WA	LA CROSSE, WI	SUNDSVALL, SWEDEN	SANDE, NORWAY	TOKYO, JAPAN
OWNER/DEVELOPER	WESTERN LAKE SUPERIOR SANITARY DISTRICT	TACOMA PUBLIC UTILITIES	NORTHERN STATES POWER COMPANY	SUNDSVALL RESOURCE RECOVERY PLANT	SANDE PAPER MILL	MACHIDA MUNICIPAL GOVT
FBC VENDOR	COPELAND	ENERGY PRODUCTS OF IDAHO	ENERGY PRODUCTS OF IDAHO	GOTAVERKEN	GOTAVERKEN	IHI
START DATE	1979/ Modified 1986	1990	1987	1984	1984	1982
FUEL	SEWAGE SLUDGE/RDF	COAL/WOOD/RDF	WOOD/RDF	RDF	RDF	MSW
DESIGN CAPACITY (T/D)	240 T/D (RDF) 690 T/D (SLUDGE)	1000 T/D (COAL/WOOD/RDF)	600 T/D (WOOD/RDF)	200 T/D		450 T/D
CAPITAL COST	$ 26,000,000	$ 43,000,000	$23,500,000	NOT AVAILABLE	NOT AVAILABLE	NOT AVAILABLE
OPERATING COST	$ 12/T (RDF PROCESSING)	NOT AVAILABLE	NOT AVAILABLE	NOT AVAILABLE	NOT AVAILABLE	NOT AVAILABLE
COMBUSTOR TYPE	BUBBLING BED FBC	BUBBLING BED FBC	BUBBLING BED FBC	CFB	CFB	BUBBLING BED FBC
STEAM PRODUCTION (LB/HR)	49,000 X 2	264,000 X 2	150,000 X 2			108,000
ELECTRIC POWER GENERATION	N/A	50 MW	28 MW			4 MW INSTALLED
AIR POLLUTION CONTROL	WET VENTURI SCRUBBER	LIMESTONE INJECTION INTO BED FABRIC FILTER	GRANULAR BED FILTER	LIMESTONE INJECTION INTO BED FABRIC FILTER	FABRIC FILTER	LIMESTONE INJECTION INTO BED ESP
REFERENCES	073, 633, 516, 518	543, 634	564, 516	633, 019, 516	633, 019, 516	672

TABLE C-13. COST AND OPERATING DATA OF SELECTED FBC FACILITIES (cont)

	KOZA GARBAGE INCINERATION SERVICE FACILITY #7	ERIE, PA WASTE-TO-ENERGY FACILITY (PROPOSED) FACILITY #8	ROBBINS, IL WASTE-TO-ENERGY FACILITY (PROPOSED) FACILITY #9
LOCATION	EBINA CITY, JAPAN	ERIE, PA	ROBBINS, IL
OWNER/DEVELOPER	KOZA GARBAGE INCINERATION SERVICE CORPORATION	READING ENERGY COMPANY	READING ENERGY COMPANY
FBC VENDOR	IHI	GOTAVERKEN	GOTAVERKEN
START DATE	1977	N/A	N/A
FUEL	MSW	RDF	RDF
DESIGN CAPACITY (T/D)	120 T/D	710	1200
CAPITAL COST	NOT AVAILABLE		$ 200,000,000
OPERATING COST	NOT AVAILABLE	NOT AVAILABLE	NOT AVAILABLE
COMBUSTOR TYPE	BUBBLING BED FBC	CFB	CFB
STEAM PRODUCTION (LB/HR)	2 MMBTU/HR HOT WATER GENERATED	220,000	225,000 X2
ELECTRIC POWER GENERATION		23 MW	47.5 MW
AIR POLLUTION CONTROL	WET SCRUBBER STACK PLUME RE-HEAT ESP	LIMESTONE INJECTION INTO BED DRY SORBENT INJECTION FABRIC FILTER	LIMESTONE INJECTION INTO BED DRY SORBENT INJECTION FABRIC FILTER
REFERENCES	671	633	633

C.5 SUMMARY

While considerable experience exists in Japan and Europe (especially in Sweden) burning municipal refuse in FBC systems, there are differences between those facilities and what would be considered a state-of-the-art, dedicated municipal waste-fired FBC in the U.S. today. Such a facility must compete with large scale mass-burn facilities, which have compiled a record of reliability and performance over the past 10 years.

As described in this appendix, the first such dedicated facilities being built in the U.S. will be large scale plants, incorporating front end processing with materials recovery and CFB technology. Because the two projects proposing this technology are still in the development phase, capital and operating cost data, except as previously noted, are unavailable. From the literature surveyed, it was determined that capital and operating cost data for refuse-fired FBC systems is generally unavailable, due to the state of evolution of the technology with respect to this application.

Like RDF-fired conventional MWCs, FBC-based systems require considerable front end processing. However, given the current industry trend towards including materials recovery in some form in all solid waste management options, this requirement need not be considered a handicap. In addition, once the fuel processing requirement is established, CFB combustion technology appears to be better equipped to provide reliable, environmentally sound energy recovery, firing RDF, than conventional combustion systems.

C.5.1 CFB Attributes

In municipal waste combustion systems, mass burn facilities attempt to achieve complete combustion of a heterogeneous fuel by allowing sufficient residence time in a large furnace. RDF systems attempt to improve upon this by homogenizing the fuel through size reduction and removal of non-combustibles, thereby allowing a more controlled, complete combustion process to occur in a conventional solid fuel fired boiler, minimizing emissions.

Fluidized-bed combustion provides complete combustion because, in the process of burning the fuel, the combustor itself completes the job of homogenizing the fuel. However, with RDF, even this may not be enough, considering the potential slagging problems associated with its ash constituents and/or aluminum. Because of its higher operating velocities, the CFB provides an even more aggressive agitation of the fuel and bed material. In addition to reducing fuel preparation requirements, this also tends to alleviate bed fusion problems experienced in bubbling beds; as agglomerates form, they tend to be broken apart as the bed material impacts the combustor walls and solids recycle system components as it circulates through the unit. This type of combustion environment provides a better means to achieve and maintain controlled combustion of a relatively heterogeneous fuel. Properly managed through bed screening and attention to bed chemistry, it also minimizes production upsets due to slagging.

From an energy production standpoint, CFB technology promises to provide higher efficiencies through more complete combustion, and better turndown capability due to its ability to operate over a higher range of velocities in conjunction with its arrangement of furnace heat transfer surface.

Reported benefits of FBC-based MWCs include smaller capital outlay and O&M cost for downstream scrubbing equipment. According to a report published by Japan's National Institute for Environmental Studies (287), due to front end fuels processing requirements and the higher fan horsepower requirements needed to overcome the air distributor and bed pressure drop, FBC operating costs can actually be 20 to 50 percent higher than a comparably sized stoker type unit. This assessment is made in the context of Japanese FBC experience, which is based on relatively small scale bubbling-bed combustors, and may not be applicable when the proposed Robbins and Erie CFB facilities are considered.

C.5.2 Current Status of FBC MWC Technology

There are no FBC facilities in the United States currently burning MSW or RDF alone, however, several facilities exist which burn RDF in conjunction with one or more other fuels. In Europe, RDF combustion has been successfully demonstrated in CFB systems in Sweden, but these systems are normally operated on a combination of RDF, wood waste, and other biomass fuels. From the literature survey, it is apparent that Japan has the largest amount of dedicated MSW-fired FBC experience. However, Japanese MSW is actually a source separated fraction of MSW which has had non-combustibles and substances unfit for combustion manually removed. The resulting Japanese MSW reportedly has less than 4 percent non-combustibles (351).

Two large scale dedicated RDF-fired FBC plants are currently in the development stages in the United States. Both facilities will feature front end materials processing coupled with Swedish CFB combustion technology supplied by Gotaverken. An Erie, Pennsylvania facility will use two 355 ton per day combustors while the Robbins, Illinois facility will feature two 600 ton per day units.

Because the CFB facility proposed for Robbins is considered to be what will be the state of the art in FBC type MWCs, some of its design features are presented here in greater detail. This information was obtained from the Request for Proposals for operators for the facility issued by the Robbins Resource Recovery Company (521). While still in the development phase, the project is proceeding, with 37 communities committed to long term waste contracts. Tables C-14 and C-15 summarize some of the operating features of front-end processing system as well as the CFB and associated pollution control equipment.

The Robbins facility's design capacity of 1600 tons per day and its electric generating capacity of 50 MW places it on an equal standing with existing large scale MWCs. In its development of the current performance based emissions standards for MWC facilities, the U.S. EPA has focused on the concept of good combustion practice (GCP) as a basis for minimizing pollutant emissions. In conventional grate type boilers, minimum time and temperature conditions have been established to insure that combustion occurs completely. In applying FBC technology to municipal refuse incineration, proponents are looking toward its inherent ability to ensure good combustion by means of its high mass and thermal transfer rates, and that it will be able to do this more consistently as waste quality and quantity varies. Further, as shown in Table C-8, there is evidence that the flyash generated from the system will pass toxicity tests without treatment. Projected capital costs for the facility are on the order of $125,000/TPD, a figure which is comparable to similarly sized conventional plants. If the promised higher levels of performance are achieved by this first-of-a-kind application of the technology, it will represent a significant contribution to the MWC industry.

The proposed system employs a front end processing facility which serves the dual function of performing materials recovery and preparing the remaining MSW for firing in the CFB combustor. The processing line will have the provision to remove ferrous metal, mixed color glass cullet, old corrugated cardboard, yard waste, plastics, and compostible organics for recycling or composting. Sufficient operating flexibility and redundancy have been incorporated into the system design to allow high levels of on-line reliability. For example, the system includes two parallel processing lines having a processing capacity of 85 tons per hour. The operating plan calls for them to be operated normally at 64 tons per hour for 88 hours per week. If one line is down for an extended period, the other can be operated for 133 hours per week at its full capacity to keep up with the processing requirements. Different degrees of materials recovery can be employed depending on regulatory requirements, materials markets, etc. In doing so, quality of the RDF will be impacted, but the CFB's inherent operating characteristics will minimize significant degradation in performance due to these fluctuations.

The energy recovery and production portion of the system will employ two Gotaverken CFB combustors, each having a steam generating capacity of 225,000 lb/hr burning 1200 tons per day of RDF. Similar sized CFBs have been built by Gotaverken and operated in the U.S. in two biomass-fired applications in California. The company claims this provides the needed scaleup experience, and their Swedish experience provides the needed application experience with RDF firing.

The air pollution control technology to be employed will incorporate the good combustion attributes of FBC as well as the capability for in-situ SO_2 and HCl absorption, a state of the art dry scrubber/baghouse for acid gas and particulate control, thermal de-NOx, and complete continuous emissions monitoring systems.

TABLE C-14. PROPOSED RDF PROCESSING SYSTEM
ROBBINS RESOURCE RECOVERY COMPANY

UNIT OPERATION	FUNCTION	MATERIAL RECOVERED	INPUT % OF MSW RECEIVED
TIP FLOOR	RECEIVE;INSPECT;REJECT	REJECTS (ASSUMED %)	4.0%
INFEED CONVEYOR	FEED PROCESS	MIX	
PICK STATION 1	REMOVE NON-PROCESSIBLES	REJECTS	0.0%
PICK STATION 2	RECOVER CORRUGATED/YARD WASTE	CORRUGATED/YD WASTE	0.0%
TROMMEL 1	REMOVE METALS;ROCKS	FERROUS METAL/REJECTS	
MAGNET 1	REMOVE FERROUS FROM TROMMEL 1 UNDERS	FERROUS METAL	
PICK STATION 3	PICK HDPE & PET FROM TROMMEL 1 OVERS	HDPE/PET (ASSUMED %)	0.0%
HAMMERMILL	REDUCE TROMMEL 1 OVERS	RDF W/FERROUS	
MAGNET 2	REMOVE FERROUS FROM HAMMERMILL OUTPUT REMAINING MATERIAL TO RDF STORAGE	FERROUS METAL RDF	
TROMMEL 2	PROCESS TROMMEL 1 UNDERS	MIX	
AIR CLASSIFIER	TROMMEL 2 - 1-1/4" UNDERS LIGHTS TO RDF	MIX RDF	20.0%
MAGNET 3	REMOVE FERROUS FROM A/C HEAVIES	FERROUS METAL	
GLASS RECOVERY JIG	AIR CLASSIFIER HEAVIES RECOVER GLASS CULLET RECOVER ORGANIC FRACTION	 GLASS COMPOST	 10.0% 10.0%
TO RDF STORAGE	TROMMEL 2 2-1/2" UNDERS TO RDF	RDF	
ALUMINUM RECOVERY	TROMMEL 2 OVERS	ALUMINUM CANS	0.7%
FERROUS LOADOUT	TOTAL FERROUS PRODUCT RECOVERED	FERROUS METAL	4.8%
RDF STORAGE	RDF PRODUCED	RDF	70.5%

TABLE C-15. PROPOSED CFB MUNICIPAL WASTE COMBUSTION SYSTEM
ROBBINS RESOURCE RECOVERY COMPANY

SYSTEM	CAPACITY/PEFORMANCE	OPERATING DATA
CFB BOILER		
FUEL INPUT	1200 TPD RDF	6,170 BTU/LB RDF 1500 - 1700 F BED TEMPERATURE
STEAM GENERATION	2 UNITS @ 225,000 LB/HR	800 PSIA 770 F
TURBINE GENERATOR	50,200 KW	CONDENSING/EXTRACTION TURBINE w/ DUMP CONDENSER EVAPORATIVE COOLING TOWER

SYSTEM	DESCRIPTION	OPERATING DATA
AIR POLLUTION CONTROL		
NOx	COMBUSTION TEMPERATURE THERMAL DE NOx	1500 - 1700 F BED TEMPERATURE SNCR METHOD; NH3 INJECTION
CO	CFB COMBUSTION ATTRIBUTES	
SO2	PROVISION FOR IN BED LIMESTONE INJECTION DRY SCRUBBER	85% REDUCTION
HCl	PROVISION FOR IN BED LIMESTONE INJECTION DRY SCRUBBER	95% REDUCTION
TSP	FABRIC FILTER	0.01 GR/DSCF
CEM	CONTINUOUS MONITORING OF: OPACITY SO2 CO2 CO NOx	

APPENDIX C. FLUIDIZED-BED COMBUSTION REFERENCES

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16. Abstract (Limit: 200 words)

The overall objective of the study in this report was to gather data on waste management technologies to allow comparison of various alternatives for managing municipal solid waste (MSW). The specific objectives of the study were to:

1. Compile detailed data for existing waste management technologies on costs, environmental releases, energy requirements and production, and coproducts such as recycled materials and compost.
2. Identify missing information necessary to make energy, economic, and environmental comparisons of various MSW management technologies, and define needed research that could enhance the usefulness of the technology.
3. Develop a data base that can be used to identify the technology that best meets specific criteria defined by a user of the data base.

Volume I contains the report text. Volume II contains supporting exhibits. Volumes III through X are appendices, each addressing a specific MSW management technology. Volumes XI and XII contain project bibliographies.

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