# Technoeconomic Assessment of Fluidized Bed Combustors as Municipal Solid Waste Incinerators: A Summary of Six Case Studies

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## Introduction

As part of the activities of the International Energy Agency (IEA) Bioenergy Agreement, members of Task 23: Energy Recovery from Thermal Conversion of Municipal Solid Waste (MSW) and Refuse Derived Fuel (RDF), visited and prepared technoeconomic case studies for several fluidized bed incinerator plants worldwide. Among the plants evaluated were: the Robbins Resource Recovery Facility (Robbins, IL); the Toshima Incineration Plant (Tokyo, Japan); the TIRMadrid Plant (Madrid, Spain); the Valene Plant (Mantes la Jolie, France); the DERL Energy-from-Waste Facility (Dundee, Scotland); and the Lidköping Waste-to-Energy Plant (Lidköping, Sweden). The case studies, on which this summary report is based, follow this summary report.

Fluidized bed technologies from several vendors are employed at these plants, including Kvaerner BFBs at the DERL and Lidköping plants; Foster Wheeler CFBs at the Robbins plant; Ishikawajima-Harima (IHI) BFBs at the Toshima plant; Techniques Modernes de Chauffe (TMC) pyramidal fluidized beds (L4F) at the Valene plant; and Rowitec twin-interchanging fluidized beds (TIF) at the TIRMadrid plant. Rated electrical generation capacity from these plants ranged from 7.8 to 50 MWe, with waste feed capacities of up to 1450 tonnes/day.

Case studies prepared for the IEA Bioenergy Agreement generally examined operation of and problems with the feed preparation and combustion technology, environmental control system, and residue recovery and disposition. Additionally, fuel characteristics, mass and energy balances, and environmental performance were evaluated. Finally, capital, operating and maintenance costs, and the sociological background for each project were examined. This summary of information from the six case studies compares and contrasts, where available, the project drivers and the effectiveness and cost of the selected incineration/environmental control technologies (see Table 1).

## Robbins Resource Recovery Facility (RRRF), Robbins, Illinois [1]

The Robbins Resource Recovery Facility (RRRF), located in Robbins, IL, a suburb of Chicago, represents the largest such project in the world – a waste-to-energy plant capable of handling 1450 tonnes of MSW per day, diverting 25% to recycle, reducing landfill waste volume requirements by 95%, and producing 50 MWe. The RRRF, designed, constructed and operated by Foster Wheeler (FW), but owned by the community of Robbins, began operation in early 1997.

### *Drivers*

The village of Robbins (population 7 500), classified as a disadvantaged community due to high unemployment and low per capita incomes, requested that the waste-to-energy facility be sited within its boundaries. Reasons for Robbins hosting the RRRF are manifold. In addition to both construction and operating jobs, and no-tipping-fee waste disposal, the facility offers opportunities for small business growth to provide support services. Robbins also receives significant host community fees from FW: rent (based on plant profitability) for the site and facility; a percentage of the tipping fees paid by other communities for waste disposal at the RRRF; property taxes; water revenues; and money for scholarship funds and local economic development. In total, the host community benefits were estimated (in 1995) to amount to $1.5 million in fiscal year 1998, escalating to $7.5 million in 2018, with the present value estimated to exceed $40 million. Due to financial difficulties at the RRRF, actual benefits to Robbins have been less than expected.

### *Incineration and Environmental Technology*

In each of the two Foster Wheeler CFB boilers, RDF is fed to the front wall of the 3.7 m x 7.6 m furnace. The top-supported walls are water-cooled, welded tube and fin construction. Except for the furnace roof, no horizontal surface is located in the gas stream. The lower furnace walls are lined with a corrosion-resistant refractory material providing a degree of temperature stability to the bed, despite frequent variations in feed moisture and heating value. Combustion temperatures of 830°C-915°C at atmospheric pressure reduce the potential for ash slagging and tube fouling, as well as minimizing high-temperature chlorine corrosion.

A single, high-efficiency cyclone is attached to each furnace, cooled with steam from the drum. Its temperature is only slightly higher than the furnace waterwall, displaying expansion similar to that of the furnace, and is considered an integral part of the furnace. The cyclone is covered with 50 mm of refractory, retained on studs in a high-density pattern (similar to the furnace). Solids collected in the cyclone are returned to the furnace through a fluidized "J" valve. Downstream of the cyclone, a steam-cooled vestibule encloses the steam generating boiler bank and pendant finishing superheater. The heat recovery area is the final segment of the steam generator, comprised of the primary superheater and economizer. Tubes in the heat recovery area are designed on a large clear spacing with low intertube velocity to minimize accumulation of sticky ash deposits. Since flue gas leaves the economizer at 218°C, and the scrubber reduces the temperature further, to 135°C prior to entering the baghouse, an air heater is not required. Each furnace uses a single induced draft (ID) fan to draw flue gases to a common stack, while a single forced draft (FD) fan provides both primary and secondary combustion air.

At boiler startup, the bed material is sand; as operation progresses, screened bed ash replaces some of the sand. Sand/ash is fed to the furnace along the rear wall. Limestone can be fed into the sand/ash silo if the feed sulphur content warrants it, but this is not planned at present ($SO_2$ emissions are well below the permit value of 30 ppm). The high proportion of inerts circulating in the CFB gives the furnace a thermal inertia, maintaining stable temperatures against variations in the fuel, while allowing 99% combustion efficiency (carbon burnout).

The concentration of chlorine in RDF and flue gases is higher than in MSW due to the concentrating effect of removing recyclables. Chloride corrosion is a function of tube metal temperature, and FW took steps to reduce superheat tube temperatures. A bank of boiler tubes is located upstream of the finishing superheater, which is in parallel flow to the gas stream to maintain low metal temperatures.

Steam sootblowers can accelerate tube wastage when firing high-chlorine fuels, by removing the protective ash layer. Therefore, FW has specified a mechanical rapping system for cleaning the vertical tube banks in the high-temperature vestibule.

The RRRF is equipped with an emissions control system comprised of a selective non-catalytic reduction (SNCR) system (urea injection), a spray dryer absorption flue gas scrubber, and a baghouse. Low CO emissions are achieved by operating the CFBs at 50% excess air, higher than typical for a coal-fired CFB.

The dry flue gas scrubber/baghouse (one system for each CFB) is fed with an atomized lime slurry, which neutralizes the acid gas components (sulphur dioxide, hydrochloric acid and hydrofluoric acid) of the flue gas. Water in the slurry is evaporated by the hot flue gas, producing dry powder reaction products that are removed in the baghouse (fabric filter). Activated carbon is added to the lime slurry (at a rate of 9 kg/h per boiler train) to reduce emissions of trace heavy metals (mercury and others), dioxins/furans (to well below the permit limit of 30 ng/dNm$^3$), and organic compounds.

The treated/cooled flue gas passes through the fabric filters (multiple modular units, with redundancy) which collect particulate matter (flyash, dry scrubber reaction products, spent carbon, and unreacted lime). This material is periodically removed from the bag surface with reverse flow compressed air pulses.

The SNCR system for $NO_x$ reduction is capable of injecting aqueous urea into the ductwork between the cyclone inlet and the backpass. At this point, a temperature range of 870°C-1090°C occurs, ideal for 40-60% $NO_x$ removal. Under present operation, however, $NO_x$ emission levels are well below the permit limit of 130 ppm, such that the SNCR has not been required.

### *Electricity Generation/Balance of Plant*

High-pressure steam (6.2 MPa, 443°C, 28.9 kg/s per boiler) produced in the CFB boilers is used to produce approximately 50 MW of electricity in a condensing, extraction turbine generator. Net electrical generation efficiency, for a feed rate of 545 t/d RDF per boiler (heating value 14.3 MJ/kg) is approximately 23%, based on MSW input. The balance of plant employs standard steam electric power plant equipment including water treatment, stack, cooling tower, and electrical switchgear.

### *Capital/O&M*

Investment costs are based on the turnkey construction costs (US$226 million) plus US$75 million spent during construction for such items as payments to the Village of Robbins, site acquisition and clearing, permits, consulting, ash landfill reservation, capitalized interest (7%-9% during 33 month of construction), development costs and contingency (US$20 million). Investment cost per annual tonne of waste is US$550/t. Total O&M is US$15.9 million annually (US$29/t MSW).

## Lidköping Waste-to-Energy Plant Lidköping, Sweden [2]

This is the main production plant for district heating in the city of Lidköping, situated alongside Lake Vänern, the largest lake in Sweden. The plant is owned by the municipality of Lidköping, and consists of two 20 MW and one 8 MW oil-fired boilers and two 17 MW bio/waste-fueled boilers.

Maximum capacity of the plant is 82 MWth. In addition, there are two electrically-fired boilers, rarely in operation. The bio/waste plant was originally put into operation in 1985, with two 12 MW lines for combustion of waste and biofuel using bubbling fluidized bed (BFB) technology, delivered by Kvaerner. The bio/waste plant has been gradually upgraded to meet more stringent requirements, and in 1994-95 the output was increased to 2 x 17 MW.

Today, 70 000 tonnes of bio/waste fuel is combusted annually in the two solid fuel lines, producing 200 GWh district heat. More than half the fuel received is household and industrial waste (ISW) (maximum of 50 000 t/a), the rest being treated wood waste. The household waste is delivered from Lidköping and seven surrounding municipalities. Private companies deliver the ISW.

### *Incineration and Environmental Technology*

The Kvaerner BFB units have undergone upgrading in 1994 and again in 1999 to improve performance, output and efficiency. During the rebuilding process, the furnaces were modernized, leading to the concept called the Advanced Combustion Zone (ACZ), now used in the design of all new Kvaerner furnaces. During 1999, the furnace section of the boilers was improved again, by adding crosswise air injection. As a result of the retrofits, availability increased to 95%, and the proposed requirement of 50 mg/Nm$^3$ for CO can now be met.

The following changes were made:

- Tapered lower part of the furnace, to improve bottom ash removal and temperature distribution in the bed.
- Pulsating air swept fuel inlet spout added.
- Installed asymmetrical overfire air system in a double arch configuration, creating turbulence in the combustion zone, and plug flow in the upper furnace.
- Addition of flue gas recirculation.
- Increased height of the furnace.

In their current configuration, operational parameters for the Kvaerner BFBs are as follows. The furnace walls are protected with bricks up to the level of the arches, to prevent cooling and mitigate erosion. During start-up, sand (0.5-2 mm, with a bed height of 0.5 m maintained) is heated with oil burners to a temperature of 600°C. Start-up fuel is wood chips. The combustion temperature is about 800°C, and the pressure 5 kPa. Combustion takes place at an oxygen level of about 7.4 vol%, dry gas. Primary air is injected from the bottom of the bed, below the sand. Non-combustibles sink down through the bed and are removed by a cooled screw together with sand that is sieved and returned to the furnace. Approximately 1 000 tonnes of fresh sand is added to the process each year.

Total injected air is about 6.5 Nm$^3$/s, of which 60-65 % is primary air. Ammonium bicarbonate is injected with the secondary air (300 t/a) to reduce $NO_x$ emissions (regulated values are 250 mg/Nm$^3$ through 2005 and 150 mg/Nm$^3$ thereafter). In the upper part of the furnace, the temperature is about 700°C. Downstream of this, an empty draft region cools the flue gases to about 600°C. The empty draft is equipped with screens to increase the cooling surface. The free area for flue gases is 0.4x0.3 m in each passage. In the following convection drafts flue gases are further cooled to 150°C. Residence time in the convection section is kept short to minimize formation of dioxins (the regulated level of 0.1 ng/Nm$^3$ is consistently being met). At the end of the convection section, a first

economizer regulates the temperature into the flue gas cleaning system.
The boiler works as a combined hot water/steam boiler. Hot water from the drum is exchanged at 190°C with the district heating network, and then brought through the furnace and convection section back to the drum. Saturated steam is also generated in the drum at 2.3 MPa. A maximum of 50% of the energy can be taken out as steam. Since the rebuilding in 1994/95, the boilers are equipped with superheaters that today are used as convection surface, as no electricity is generated.

Flue gas cleaning consists of a dry system, with a cyclone as a first step, separating large particles, followed by a baghouse filter. Lime is added prior to the filter, as an absorbent. About 1 000 tonnes of lime is used for this purpose every year (for the two lines together). Lime addition is controlled by the HCl concentration in the clean flue gas.

The cyclone removes about 20-25% of the heavy metals and a few percent of the acid components. After the baghouse filter, almost 100% of the heavy metals have been removed. Clean flue gas still contains 15-20% of the HCl and 40-50% of the $SO_2$, however. Testing is ongoing with sodium bicarbonate as a replacement for lime. In addition to absorbing HCl, bicarbonate will also remove $SO_2$, eliminating the need of a scrubber to meet the 50 mg/Nm$^3$ $SO_2$ regulation.

From 150°C at the inlet to the flue gas cleaning system, the temperature is reduced to 110-120°C (a secondary economizer is placed at the end of the flue gas cleaning train). Finally the clean gases leave the plant through a 70 m stack.

### *District Energy/Efficiency*

The calculated overall efficiency of the solid fuel plant is 88%. Energy production of 198 GWh comes from input fuel energy of 225 GWh. Of the 34 MWth capacity, 2 MW heat is delivered to an animal food factory, and 4 MW steam is delivered to an alcohol factory. The rest is sold as district heat. Internal consumption is about 2 MWe, purchased externally.

### *Capital/O&M*

As originally constructed (1984), capital costs were 104 million SEK (at present, 1 SEK=US$0.11), including the two incineration lines, two oil-fired boilers and buildings. As the plant has been gradually upgraded, it is difficult to estimate what the investments for the same plant would be today. However, the DERL plant (discussed later) is similarly equipped with Kvaerner BFBs. O&M costs for the plant amount to 38.8 million SEK, including residue disposal (US$61/t MSW).

## Toshima Incineration Plant, Tokyo, Japan [3, 4]

### *Drivers*

Japan currently has a population of more than 125 million people, representing 2.2% of the global population; yet her land mass amounts to less than 0.3% of the world area. This inequality, coupled with the fact that significant land area is mountainous, has resulted in a situation where available waste disposal (landfill) area cannot keep up with the rate of waste generation, although that rate, 1.1 kg/person/d, is at or below the world average (the U.S. rate is approximately twice this value). Available landfill space in Tokyo has decreased by 20% in the last decade, and will be totally depleted in 30 years. The severity of the waste disposal situation in Japan suggests the reasoning behind the recent shift away from the traditional focus on treatment and disposal, to a greater emphasis on reduction, advanced treatment and recycling. This in part justifies the willingness of the Japanese to invest in high-cost reduction processes such as the Ibaraki City high-temperature melting facility, and to site incineration facilities in high land value locations (central to the MSW source) such as the Toshima plant.

### *Incineration and Environmental Technology*

The Toshima Incineration Plant is equipped with two 200 t/d atmospheric BFB incineration boilers constructed by Ishikawajima-Harima Heavy Industries (IHI). Fluidized bed technology was chosen due to the necessity of minimizing required plant floor area (inner city location). The furnace's vertical design results in incineration capacity per unit area much greater than for a grate-fired unit.

The BFB units operate by combining fuel (in this case source separated but otherwise untreated MSW) and combustion air in hot sand under vigorous mixing. In the fluidized bed, primary combustion air (approximately 7 550 $Nm^3/h$) is injected. Temperature in the bed is maintained at 550-630°C to drive off volatiles and fully combust the MSW, which is fed at the top of the bed. If temperatures rise above 630°C, cooling water sprays are activated automatically. Sand is separated from the bed ash, graded, and returned to the top of the dense bed. Each incinerator contains 57 $m^3$ of sand (90 t), some of which is lost as fines with the flue gases, or in the ash stream. It is estimated that periodic make-up will result in a complete sand change over a period of one to two years.

In the freeboard, secondary combustion air (approximately 28 800 $Nm^3/h$) is injected at several levels to completely burn off volatiles. The temperature in this region rises steadily from 710°C to 1030°C (cooling water sprays are activated should the temperature exceed 1070°C), and gas velocity is such that a residence time (at 850°C) of at least two seconds is achieved (for dioxins destruction).

The boiler is above the freeboard. With no combustibles remaining in the gas, and with the aid of cooler air injection, temperatures drop rapidly prior to contact with the boiler tubes (approximately 480-580°C). This is a natural circulation water-tube boiler, equipped with a superheater. Steam is generated at a maximum rate of 33.3 t/h from each unit, usually at 3.14 MPa (abs) and 300°C. The high-pressure steam is routed to a steam header, while the flue gases exit the boiler through an economizer to a quick-quench cooling tower. Thermal efficiency of the BFBs is 89.2%.

Flue gas treatment begins at the exit of the economizer, where a water spray cooling tower quickly quenches the gases to 150°C, minimizing dioxins formation (a self-imposed level of 0.1 $ng/Nm^3$ is met). At the entrance to the fabric filter baghouse, slaked lime and powdered activated carbon are injected into the flue gases to remove heavy metals, dioxins/furans and non-combusted organics, while the baghouse removes particulates (0.02 $g/Nm^3$). The design gas treatment rate in the baghouse is about 75 000-109 000 $Nm^3/h$ (dry).

Once leaving the baghouse through an ID fan, flue gases enter a wet caustic soda scrubbing tower that removes acid gases at a gas treatment rate similar to the baghouse (HCl – 15 ppm; $SO_2$ – 20 ppm self-imposed limits). Upon exiting the scrubber, the flue gases are dried and heated, by heat exchange with steam generated in the plant, to 210°C before entering the selective catalytic reduction (SCR) reactor. Here, ammonia is injected into the gas stream as it passes through a honeycomb

catalyst to remove $NO_x$ (60 ppm self-imposed limit).
From the SCR, flue gases enter the 210 m stack (the tallest concrete stack in Japan), containing two flues (one for each incinerator) and an elevator (for maintenance). The inlet temperature to the SCR was chosen for two reasons: to improve the rate of catalytic conversion of $NO_x$ (although a temperature of 250-350°C would have been more appropriate); and to ensure an invisible plume emanating from the stack.

### *Electricity Generation/Balance of Plant*

The plant is equipped with a single condensing steam turbine/generator set which can handle a maximum flow rate of 58.4 t/h of 2.84 MPa steam, and produce up to 7.8 MWe. The maximum figures mentioned are based on firing 400 t/d of waste with a heating value of 13.4 MJ/kg (3 200 kcal/kg), the upper design value. Under current operating conditions, however, with the feed heating value at about 9.4 MJ/kg (2 250 kcal/kg), only 5.3 MWe is generated.

Approximately 15.5 GJ/h (4.3 MWth) is delivered to the adjacent Toshima Health Plaza facilities to provide heating, air conditioning, and water heating for the swimming pool. Other heat energy streams provide heat and process steam to meet the needs of the plant. The plant also requires electricity for operations, approximately 3 MWe. Gross efficiency (from MSW to end use) is 30.5%.

### *Capital/O&M*

Construction cost for the facility, excluding the Toshima Health Plaza, but including all infrastructure modifications was 17 billion ¥ (approximately US$140 million at 1997 average conversion rates). While this appears quite high by North American standards, it must be understood that: (1) the plant is in downtown Tokyo, where real estate and infrastructure costs are extremely high; (2) the location has necessitated the tallest concrete stack in Japan, again at great expense; and (3) the plant, stack and associated buildings were built to earthquake standards. O&M costs have been quoted as approximately ¥14 000/t of waste (about US$127/t). This does not cover waste collection costs, but does include ash treatment, transportation and disposal.

## TIRMadrid Plant, Madrid, Spain [5]

This facility is owned by TIRMadrid (Tratamiento Integral de Residuos de Madrid s.a.) and is situated in Valdemingómez, near Madrid. TIRMadrid has three shareholders: Urbaser (Urban Services) – 66%; Endesa (electric company) – 15%; and Union Fenosa (electric company) – 19%.

### *Drivers*

In 1989 Madrid city council decided to act on waste disposal in the region, as the landfill site was becoming full. The practice at the time was to recycle as much waste as possible and compost the organic waste. In 1990, Urbaser proposed that city council develop, construct and maintain a waste-to-energy recovery facility. The EC (under the THERMIE program) sponsored the project with US$1.7 million. In 1992 TIRMadrid was contracted to operate the plant and, in the same year, purchased it for US$125 million.

### *Incineration and Environmental Technology*

The TIRMadrid plant accepted 441 000 t MSW in 1999, of which 62 000 t was recovered for sale, 119 000 t was landfilled or composted, and 260 000 t RDF was fed to the three BFBs. RDF is transported from each of three hoppers (10-13 t/h) by double screws into two shafts operating as the feeding system into the furnace about 3 m above the bed. The BFBs are of the Rowitec twin interchanging fluidization (TIF) design, constructed by Hölter-ABT. The TIF is similar to the Ebara design, in that the floor of the bed (4 x 6 m) slopes down from the centre to the side walls, producing circular mixing patterns in the bed. Larger particles are moved over the bed bottom to the side walls, into the ash/sand removal system. Average residence time in the bed is four minutes. To slow combustion and to keep the bed temperature at 670°C, recirculated flue gas and water (up to 2 500 kg/h) are injected above the bed. In the freeboard, temperatures of 900°C are reached.

The boilers consist of two vertical radiation sections (water-cooled walls), a horizontal convection section (superheater) and a vertical economizer. Each boiler has a nominal output of 41 t/h of steam at 420ºC and 46 bar. Under design conditions, a total of 29 MWe is generated (at 19.4% overall efficiency).

Gas cleaning for each line begins in the fluidized bed, with injection of fine limestone from above via secondary air outlets. This provides partial $SO_2$ and HCl removal and reduces fouling and corrosion in the superheater. Flue gases are then led through the three boiler passes to a pair of hot gas cyclones to remove fly ash; a semi-dry absorber (calcium hydroxide); a high-performance bag filter with dry injection of lime and activated carbon to remove the remaining fly ash, heavy metals and organic components; and an ID fan, which prevents pressure drops in the system and drives the exhaust gases into the stack. Emissions regulations call for: $SO_2$ – 300 mg/$Nm^3$; CO – 100 mg/$Nm^3$; HCl – 50 mg/$Nm^3$; and dioxins – 0.1 ng/$Nm^3$. These limits are easily met by the above system.

***Capital/O&M***

Capital cost of the plant was US$125 million, 80% for the thermal facility and 20% for waste recovery. O&M costs, including ash disposal, are US$13.5 million annually (US$30.60/t MSW).

## DERL Energy-from-Waste Facility, Dundee, Scotland [6]

The Dundee Energy Recycling Ltd. (DERL) energy from waste (EfW) facility, the first in the UK to use BFB technology for waste treatment, was handed over to DERL by Balfour Beatty/Kvaerner EnviroPower in April 2000. It is on the site of the former Baldovie incinerator. The new plant, with a capacity of 120,000 t/a, receives source separated MSW from Dundee & Angus Councils (population 270 000) together with some clinical waste from Greater Glasgow Health Board. The waste is processed into floc RDF, with recovery of ferrous and non-ferrous metals. The clinical waste is handled and treated in isolation.

***Drivers***

The Baldovie incinerator, in operation since 1979, was closed down in 1996. It had a capacity of 73 000 t/a and, in recent years, had had a troubled history with technical and management problems causing unplanned downtime and local objections. The plant as it stood was not able to meet new EC emissions limits introduced in 1992 and which, for existing plants, came into effect in December 1996. The old plant did not recover energy, apart from a small amount of low-grade heat used for in-house needs. This fact, and the considerable investment needed to upgrade the existing plant to comply with the new emissions limits, favoured construction of a new waste-to-energy plant.

### *Incineration and Environmental Technology*

Within the boiler house there are two 17 MW Kvaerner BFB incineration boiler units, each sized at a maximum continuous rating to match the incoming waste stream of 8 t/h at a heating value of 10 MJ/kg (gross). Each boiler comprises a combustion chamber, a back pass including radiation cavity, superheaters, evaporation stages and economizers. The fluidized bed is designed as an integral part of the boiler; surfaces are fabricated from membrane-wall tubing and the steam drum is close-coupled. The bed of hot sand and ash at the base of the boiler is kept in constant motion by fluidizing primary air injected through the bed from the wind box below via the bottom plate. Fuel is gravity fed and spread across the surface by recirculated flue gases via air-swept spouts.

Non-combustible material and bottom ash are continuously removed from the bed which has dolomite added to reduce boiler tube fouling and control emissions of $SO_2$. A mixture of ash and sand is continuously removed from the fluidized bed. Water-cooled screws recover heat from the bed material prior to the sand being separated and returned to the bed via an ash classifier. Typically the remaining carbon content of the bed ash will be <0.5%.

Combustion air for the process is drawn from the waste storage areas to control emissions of dust and odor from the plant. The boilers are fitted with FD fans to supply primary, secondary and tertiary air for the staged combustion process and some flue gas is also recirculated to help control the formation of $NO_x$. Start-up is by gas-oil burner below the bed, which initially heats the primary air and fluidizes the bed of sand. A secondary gas-oil burner above the bed raises the furnace temperature to 850°C, when fuel can be fed into the boiler.

The Kvaerner BFB boiler uses an Advanced Combustion Zone design which the manufacturer claims enables thermal efficiencies of 89% with typical steam conditions (40 bar and 400°C). Corrosion of heat recovery surfaces by chlorine, sulphur and heavy metals can be caused by reducing conditions and this is avoided by the ACZ furnace design. The lower furnace area is refractory lined to achieve uniform temperatures and reduce slagging. Superheater corrosion is avoided by the empty radiation cooling pass which conditions the flue gas prior to its entering the convective cooling surfaces.

A separate flue gas cleaning unit is provided for each boiler. Flue gases leaving the heat recovery sections of the boiler pass through cyclone pre-collectors where about 70% of the particulates are removed. Following this dry lime reacts with acid gases, and activated carbon is injected after the cyclone to trap dioxins/furans and mercury. Fabric filters then trap any remaining particulates together with the lime and activated carbon added previously. After the baghouse, flue gas emissions are continuously monitored, testing each boiler in turn. Flue gases are discharged to atmosphere via a twin flue stack, 70 m high. Achieved emissions are as follows: dioxins – 0.05 ng/$Nm^3$ (limit is 1.0); $SO_2$ – 15 mg/$Nm^3$ (limit is 300); $NO_x$ – 325 mg/$Nm^3$ (limit is 350); and CO – 4 mg/$Nm^3$ (limit is 100). Particulates, HCl, HF and heavy metals are all well below the limits.

### *Electricity Generation/Balance of Plant*

The steam turbine is a single-cylinder condensing machine designed by Austrian Energy & Environment, and the installation includes the option for future steam export for use in nearby industrial processes. The generator (from ABB Sweden) is rated at 10.5 MWe. The in-house demand is an estimated 2.2 MW leaving 8.3 MWe for export. Overall net efficiency is 20.9%

***Capital/O&M***

The plant was constructed (brownfield site) under a turnkey contract for £35 million (about US$56 million). Total O&M (including ash disposal) is expected to be £2.3 million (US$3.7 million), or about US$31/t MSW.

## Valene Waste Recovery Facility, Mantes la Jolie, France [7]

The Valene waste recovery facility is owned and operated by Generis (part of the Vivendi Group), and is one of approximately 80 such plants worldwide controlled by Vivendi.

***Drivers***

The plant was conceived in 1993 because continued use of the regional landfill was considered environmentally unacceptable. An incentive, approximately 35% of the capital cost of the plant, was granted to the project by ADEME (French National Agency for Energy and the Environment). The final driver was the potential for profit to Generis/Vivendi.

***Incineration and Environmental Technology***

The plant consists of three incinerators, each comprising an L4F BFB boiler, designed and patented by CERCHAR, and constructed by Techniques Modernes de Chauffe (TMC). The L4F incinerator is divided vertically into two beds. The bed bottom consists of a 5 x 5 grid of pyramids. Fluidizing air is injected through nozzles at the bottom of the pyramids, causing swirls that move larger particles toward the sides of the bed (to a newly refurbished water-cooled ash removal system). Currently, 3.4 t/h of RDF (<80 mm topsize) is fed about 1 m above each fluidized bed. The small topsize among other problems has led to high maintenance costs and low availability (35% in 1999), and major modifications are scheduled for 2001 that will, in part, allow use of a larger topsize.

Flue gases first pass through a cyclone for particulate removal, then are injected with activated carbon and lime in a spray-dry absorber prior to entering a baghouse filter. Gases exiting the baghouse are next passed through a wet limestone scrubber, heat exchanged and diluted with air (to avoid a visible plume) before exiting the stack. During modifications, the scrubber will be removed, and the absorber will be rebuilt, to reduce operating costs. Environmental performance (with the existing configuration) easily meets regulated values (maximum 1999 emission in mg/Nm$^3$/regulated value): $NO_x$ – 273/300; $SO_2$ – 3.8/50; CO – 5.3/10; HCl – 1.5/10; particulates –2.4/10; heavy metals – 0.2/0.5. Dioxins were 0.08 ngTEQ/Nm$^3$, while the regulated value was 0.1 ngTEQ/Nm$^3$.

***Electricity Generation/Balance of Plant***

High-pressure steam (39 bar, 390°C, 34.5 t/h per boiler) generates 7.4 MW of electricity in a single turbine/generator set. Net electrical generation efficiency is currently 17.7%, but it is expected this will increase to 24.7% (design) after the modifications have been completed, due to considerably lower station service requirements.

***Capital/O&M***

Plant capital costs were approximately US$50 million ($6 760/kW), with US$17 million of the cost provided by ADEME. O&M costs are currently US$10 million annually ($125/t of MSW), but this should be reduced to about $6 million after modifications ($75/t of MSW).

## Conclusions

Due to a number of factors, such as differing capacities, environmental requirements, land values, labour rates, etc., the evaluated plants cannot be meaningfully compared with each other. Rather, economic comparisons of competing technologies would have to be made on a site-specific basis, beyond the scope of the IEA Bioenergy Task 23 mandate. Operational problems we are aware of are related to fuel feeding and ash removal, and do not appear to be FBC technology-specific. Some of the plants are quite new and are still working out the 'bugs'. These plants should be revisited in the future to obtain more typical operating data.

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## References

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**Table 1. Fluidized Bed Waste Incinerator Plant Statistics Summary**

| Plant | FBC Type | Drivers | Input | Output (max.) | Efficiency (%) | Capital US$M/ (US$/kW) | O&M (US$/t MSW) |
|---|---|---|---|---|---|---|---|
| Robbins (RRRF) | 2 x FW CFBs | Community benefits, profits | 1 450 t/d MSW = 1 090 t/d RDF | 50 MWe | 23 (net) | 301<br>(6 000) | 29 |
| Lidköping | 2 x Kvaerner BFBs | District heat supply | 50 000 t/a MSW and ISW + 20 000 t/a wood waste | 34 MWth - 2 MWe (purchased externally) | 88 (gross) | -- | 61 |
| Toshima | 2 x IHI BFBs | Landfill use reduction, heat supply | 400 t/d MSW (source separated) | 7.8 MWe<br>+ 4.3 MWth | 30.5 (gross) | 140<br>(18 000) | 127 |
| TIRMadrid | 3 x Rowitec TIF BFBs | Landfill use reduction, profits | 440 000 t/a MSW = 260 000 t/a RDF | 29 MWe | 19.4 (net) | 125<br>(4 300) | 31 |
| Dundee (DERL) | 2 x Kvaerner BFBs | Meeting emissions limits | 120 000 t/a MSW (source separated, coarse RDF) | 10.5 MWe | 20.9 (net) | 56<br>(5 300) | 31 |
| Valene | 3 x TMC L4F BFBs | Landfill use reduction, profits | 80 000 t/a MSW = 71 000 t/a RDF | 7.4 MWe | 17.7 (net)<br>*24.7 (net) | 50<br>(6 760) | 125<br>*75 |

*Expected after current major modifications