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# Economics of Co-Firing Waste Materials in an Advanced Pressurized Fluidized-Bed Combustor


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# ECONOMICS OF CO-FIRING WASTE MATERIALS IN AN ADVANCED PRESSURIZED FLUIDIZED-BED COMBUSTOR


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## ABSTRACT

The co-firing of waste materials with coal in utility scale power plants has emerged as an effective approach to produce energy and manage municipal waste. Leading this approach is the atmospheric fluidized bed combustor (AFBC). It has demonstrated its commercial acceptance in the utility market as a reliable source of power by burning a variety of waste and alternative fuels. The fluidized bed, with its stability of combustion, reduces the amount of thermochemical transients and provides for easier process control. The application of pressurized fluidized-bed combustor (PFBC) technology, although relatively new, can provide significant enhancements to the efficient production of electricity while maintaining the waste management benefits of AFBC.

A study was undertaken to investigate the technical and economic feasibility of co-firing a PFBC with coal and municipal and industrial wastes. Focus was placed on the production of electricity and the efficient disposal of wastes for application in central power station and distributed locations. Issues concerning waste material preparation and feed, PFBC operation, plant emissions, and regulations are addressed. The results and conclusions developed are generally applicable to current and advanced PFBC design concepts.

Wastes considered for co-firing include municipal solid waste (MSW), tire derived fuel (TDF), sewage sludge and industrial de-inking sludge. Conceptual designs of three power plants rated at 250 MWe, 150 MWe and 4 MWe were developed. The 4 MWe facility was chosen to represent a distributed power source for a remote location and designated to co-fire coal with MSW, TDF and sewage sludge while producing electricity for a small town. Heat and material balances were completed for each plant and costs determined including capital costs, operating costs and cost of electricity.

With the PFBCs operation at high temperature and pressure, efforts were centered on defining feeding systems capable of operating at these conditions. Since PFBCs have not been tested co-firing wastes, other critical performance factors were addressed and recommendations were provided for resolving potential technical issues. Air emissions and solid wastes were characterized to assess the environmental performance comparing them to state and federal regulations. This paper describes the results of this investigation, presents conclusions on the key issues, and provides recommendations for further evaluation.


## OBJECTIVES

A study has been undertaken to investigate the technical and economic feasibility of co-firing a PFBC with coal and municipal or industrial wastes. Focus was placed on the production of electricity and the efficient disposal of wastes for application in a central power station and distributed locations. Wastes considered for co-firing include municipal solid waste (MSW), municipal sewage sludge, and industrial de-inking sludge. Issues concerning waste material preparation and feed, PFBC operation, plant emissions, and regulations are addressed. This paper describes the results of the performance evaluation and a summary of the economic evaluation.

## BACKGROUND INFORMATION

The Environmental Protection Agency's (EPA) 1990 estimates place the amount of MSW generated in the United States at over 195 million tons per year, up approximately 44 million tons since 1980(1). EPA estimates 4.3 pounds of MSW are generated per person per day. Together with industrial process waste and municipal sewage sludge, the resultant burden on our capacity to dispose of these wastes, in a cost-effective and environmentally acceptable manner, is an enormous management problem.

One method of waste management is through combustion or incineration with energy recovery. This alternative has been plagued with a legacy of inefficient, dirty, and poorly operated incinerators resulting in environmental problems leaving communities searching for solutions. However, advanced power systems that can meet new stringent environmental regulations have been developed and operated successfully. Additionally, electric utilities and non-utility generators have shown significant interest in waste management through waste-to-energy facilities.

Co-firing waste with coal in a utility scale boiler has emerged as an effective approach to produce energy from waste. Fluidized-bed combustors are becoming a primary method of burning wastes. The fluidized-bed, with its stability of combustion and temperature, provides enhanced energy recovery and environmental control while achieving cost-effective waste management.

**Waste Material Characteristics.** The characteristics and analyses of the three waste fuels under consideration were obtained from facilities that presently co-fire these materials. The wastes are municipal solid waste, municipal sewage sludge, and industrial de-inking sludge.

**Municipal Solid Waste.** Waste classified as MSW is extremely variable in composition on a seasonal and location basis. To produce a fuel that can be fed to a PFBC, it must be processed to remove metal, glass, and other non-combustibles to produce what is called refuse derived fuel (RDF). Methods currently used process about 50 percent of MSW to RDF. A typical 3-inch shredded material is prepared by shredding, magnetic separation, and air classification. It can be burned as is, pelletized, or slurried. A representative RDF proximate and ultimate analysis is shown in Table 1.

**Municipal Sewage Sludge.** The incineration of sewage sludge has a long history in the United States. Initially, multiple hearth units were used; now the majority of new installations are FBCs.

Treatment plant sludges generally are less than 7 percent total solids (t.s.). Combinations of processes such as chemical addition, flocculation, thermal conditioning, gravity thickening, and centrifugation are used to thicken sludge prior to burning. Feed sludges range from 20 percent to 40 percent t.s., but 25 percent t.s. is a reasonable average.

Sludge analyses vary from plant to plant and from season to season in the same plant. The fibrous nature of sewage sludge greatly affects the fluidity. A 7 percent t.s. sludge has the consistency of wet cement. At 25 percent t.s., sludge can be conveyed "dry" on a conveyor belt. Table 2 is an ultimate analysis of a sludge that has 13.85 percent t.s. On a dry basis the Higher Heating Value (HHV) of sludge can be as high as 6,500 Btu/lb.

**De-Inking Sludge.** The amount of de-inking sludge produced is increasing as the use of recycled paper gains popularity. In newsprint manufacturing, repulping generates a large quantity of high ash sludge, which previously was disposed of in lagoons. Now incineration in fluidized-bed combustors is preferred since overall energy costs can be reduced and environmental requirements can be satisfied. The pulping process in a typical size facility produces 250 dry tons of de-inking sludge per day from a feed of 1,600 dry tons per day of old newsprint.

### TABLE 1. REPRESENTATIVE RDF ANALYSIS

| Proximate Analysis As Received | | Ultimate Analysis As Received | |
|---|---|---|---|
| Moisture | 30.73 % | Moisture | 30.73 % |
| Ash | 11.59 | Ash | 11.59 |
| Volatile | 48.93 | Sulfur | 0.32 |
| Fixed C | 8.75 | Nitrogen | 0.61 |
| | 100.00 % | Carbon | 28.30 |
| | | Hydrogen | 4.20 |
| Btu/lb, HHV | 4,801 | Oxygen | 24.25 |
| | | Total | 100.00 % |

### TABLE 2. MUNICIPAL SEWAGE SLUDGE ULTIMATE ANALYSIS

| | |
|---|---|
| Carbon | 3.08 % |
| Hydrogen | 0.46 |
| Nitrogen | 0.37 |
| Sulfur | 0.07 |
| Ash | 6.80 |
| Oxygen | 3.07 |
| Moisture | 86.15 |
| Total | 100.00 % |
| Btu/lb, HHV | 464 |

The sludge is concentrated from a 2 percent t.s. stream to 7 percent and is further de-watered to 45 percent t.s. using screw presses. The character of 45 percent sludge is such that storage bins are not used. The sludge is processed and conveyed directly to the boiler on conveyor belts. Table 3 shows a representative sludge analysis.

**Design and Operation Issues.** Although there is considerable data on the operation of PFBCs when feeding coal dry and as a slurry, wastes have not been co-fired with coal. There is, however, considerable information on co-firing wastes in AFBCs that is relevant. Except for pressure, AFBCs have similar operational requirements. Feeding the wastes into the combustors has been the most common problem. This prompted an investigation as to what equipment is available to feed RDF and sludges into a PFBC.

Recently, there has been activity in developing pressurized feeders for biomass waste materials and dry and slurry feeders have been tested. Dry feed systems include double lockhoppers, rotary valve feeders, piston feeders, screw feeders, and pneumatic systems. Slurry feeders include progressive cavity pumps, piston pumps, and rotary feeders. However, these options have not had substantial operating experience at PFBC conditions, but it is assumed that eventually a reliable system will be available.

## PROJECT DESCRIPTION

Economic and performance results were developed for PFBC advanced generation plant configurations with nominal ratings of 110 MWe and 250 MWe. Performance considerations were given

## TABLE 3. DE-INKING SLUDGE ANALYSIS

| Proximate | | Ultimate | |
|---|---|---|---|
| Moisture | 55.00 % | Moisture | 55.00 % |
| Ash | 9.76 | Ash | 9.76 |
| Volatile | 28.74 | Sulfur | 0.11 |
| Fixed C | 6.50 | Nitrogen | 0.35 |
| | 100.00 % | Carbon | 19.58 |
| | | Hydrogen | 2.40 |
| Btu/lb, HHV | 3,562 | Oxygen | 12.80 |
| | | Total | 100.00 % |

to fuel handling, emission control, and residual solids handling. Thermal performance for all cases was calculated by using an Aspen/SP™ modular computer program. The program modeled the PFBC, gas turbine, heat recovery and steam generator, and the steam turbine cycle in a single, integrated calculation process. Plant material and energy balances were developed along with the net plant power, thermal efficiency, and net heat rate.

The capital costs, operating costs and expenses were established consistent with EPRI Technical Assessment Guide (TAG)[2] methods and are expressed in 1992 dollars. An assumed 65 percent capacity factor is used. Comparisons were made to firing with and without waste materials to define the effects on plant performance and costs from waste co-firing.

## RESULTS

The performance and economic analyses for the PFBC power plant co-fired with RDF and/or sludge waste followed two application scenarios. The first assumed a utility base load application with electrical production in the 100 to 120 MWe range, and the second assumed a capacity of 240 to 250 MWe. Application specifics were then based on these scenarios including the definition of site and ambient conditions -- fuel, waste, and sorbent feedstock -- and method of fuel/waste handling. The PFBC 1.5-Generation plant configuration as presented in Figure 1 was the basis for this study and is used to establish the baseline performance. The study utilized defined plant boundary conditions including ISO ambient conditions, Pittsburgh 8 coal, Plum Run dolomite, and waste feedstock for each PFBC application analysis.

The heart of the 1.5-Generation PFBC power plant is a coal-burning PFBC that generates heat to make steam and hot gas for the gas turbine. The PFBC uses compressed air from the gas turbine compressor to fluidize and provide combustion air to the bed. Vitiated air from the PFBC exhaust is used as the oxidant in a natural-gas-fired gas turbine-generator. Energy in the gas turbine exhaust is used to heat feedwater in an exhaust heat recovering steam generator (HRSG), and heat from the PFBC is used to evaporate, superheat, and reheat the steam in a fluid bed heat exchanger (FBHE). Finally, a steam turbine-generator in a Rankine cycle generates power using the PFBC and HRSG as its heat sources.

The ratio of coal-to-waste fuel was established on the following criteria: (1) an 80:20 coal-to-waste ratio on an as-received weight basis was used to define the maximum amount of co-fired waste products, and (2) co-fired amounts for municipal sewage sludge were based on the volume produced from a typical population center of 250,000, employing a typical sludge treatment process.

**Design Review.** Major subsystems specifically influenced by the waste material feedstock are fuel handling, emission control, and residual solids handling. Of particular concern to this study is the

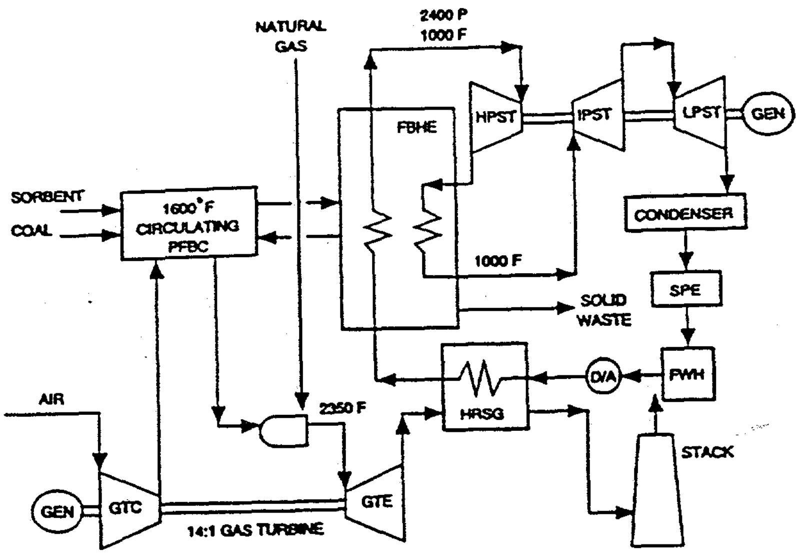


FIGURE 1. 1.5-GENERATION PFBC CYCLE

the impact on system performance from variations in the fuel/waste handling process.

Fuel Handling Options. The analyses investigated slurry processing of the coal and sorbent in either: (1) separate combustor feed of the coal/sorbent and waste streams, or (2) combined coal/sorbent and waste fired in a slurry media. As an alternative approach to slurry feeding, a sensitivity study of dry feeding of coal, sorbent, and the co-fired RDF was completed at the 250 MWe level. The analysis compared overall plant efficiency and cost-of-electricity to determine if an advantage exists in dry versus slurry feed. In the slurry feed approach, the coal and sorbent are transported via a water media at 75 percent total solids.

Waste Material Handling. For the 250 MWe system, RDF is fed to the PFBC as a slurry or pneumatically to determine which method proved higher system efficiency and lower economics of operation. For the slurry feed analysis, RDF is combined with coal and sorbent and slurried with water to 75 percent t.s. The slurry is then pumped into the PFBC. The inherent moisture of RDF was not considered to be used as part of the slurry water content.

In the case of dry feed, the RDF is fed to the PFBC via a screw conveyor. In this case, coal and sorbent are pneumatically conveyed to PFBC. Separate feed systems allow different fuel injection points in the combustor. In this manner the relatively light RDF material can be fed to the PFBC at a point to assure complete combustion.

For municipal sludge, it was assumed to be dewatered to 24 percent t.s. and fed in a separate flow stream to the combustor. A value of 24 percent t.s. corresponds to the industry achievable de-watering capability with conventional belt filter or screw press.

Based on a population value of 250,000 supplying the municipal sludge, a feed rate of 35,000 lb/day was assumed in the 250 MWe and 110 MWe performance analysis. At this input rate, the coal-to-waste feed ratio, on an as received weight basis, is 95:5 and 91:9, respectively.

An additional case analysis examined the potential use of as-received municipal sludge at 6 percent t.s. as the slurry media for the PFBC fuel and sorbent. The limiting factor for this analysis was the requirement to maintain a 75 percent t.s. in the fuel and sorbent feed.

For the analysis of de-inking sludge, it was assumed that a 40 percent t.s. is fed to the PFBC via piston feeder. At this percent solids, de-inking sludge can not be pumped in a conventional fluid pump. A sludge total solids value of 40 percent was chosen to represent the industry standard in recycled newsprint facility operation. Separate feed systems for the coal/sorbent slurry and de-inking sludge allow for different fuel injection points. In this manner, the relatively light sludge material can be fed to the PFBC at a point that will inhibit rapid ascension of the sludge material assuring complete combustion. The coal-to-waste firing ratio of 80:20 was assumed, on a weight basis, and is based on as-received coal and "bone-dry" de-inking sludge.

**Performance Analysis Assumptions.** The design and performance analyses for a PFBC power plant co-firing RDF and/or sludge waste followed similar application scenarios. Operational conditions were established assuming a utility base load application located in the United States mid-Atlantic region.

The 250 MWe application includes the use of a Westinghouse 501D5 gas turbine with an 1800/1000/1000 steam turbine bottoming cycle. The performance for the 110 MWe is based on using a Westinghouse W251B12 gas turbine with a 1450/1000/ 1000 steam turbine bottoming cycle. Turbine inlet conditions are adjusted to maintain constant volumetric flow.

The PFBC combustor design parameters were assumed to follow the design assumptions defined in Gilbert/Commonwealth Report No. 2985(3). The PFBC is a circulating bed with an operating temperature in the 1600°F range. A 99.3 percent carbon conversion efficiency was assumed for performance modeling along with a 93.3 sulfur removal.

The performance analysis for the various PFBC power plants co-fired with waste feedstocks were developed according to the application and waste material used.

The case profiles used to define the performance assumptions are as follows:

**250 MWe Application**

250 MWe with Pittsburgh 8 coal and municipal solid waste as RDF in a combined slurry feed at the 80:20 coal-to-waste ratio.

250 MWe Pittsburgh 8 coal and municipal solid waste as RDF as-received in separate dry feeds at the 80:20 coal-to-waste ratio.

250 MWe Pittsburgh 8 coal and municipal sewage sludge de-watered to 24 percent t.s. with separate feed at a waste feed volume based on a 250,000 population.

250 MWe Pittsburgh 8 coal and de-inking sludge de-watered to 40 percent t.s. with separate feed at the 80:20 coal-to-waste ratio.

**110 MWe Application**

110 MWe with Pittsburgh 8 coal and municipal solid waste as RDF in a combined slurry feed at the 80:20 coal-to-waste ratio.

110 MWe with Pittsburgh 8 coal and municipal sewage sludge de-watered to 24 percent t.s. with separate feed at a waste feed volume based on a 250,000 population.

110 MWe Pittsburgh 8 coal at 6 percent t.s. municipal sewage sludge to provide a combined slurry feed (coal, sorbent, and waste) at 75 percent t.s. with the slurry media supplied by the waste stream.

110 MWe Pittsburgh 8 coal and de-inking sludge de-watered to 40 percent total solids with separate feed at the 80:20 coal-to-waste ratio.

**Performance Analysis Results.** To further enhance the results of this study, performance comparisons were developed for the 1.5-Generation PFBC with and without co-firing of waste. The PFBC plant, as presented in Reference 2, is the basis for this study and was used to establish nominal performance without co-firing waste.

**250 MWe Results.** The performance for the 250 MWe PFBC plant without co-firing is shown in Table 4. Also shown are performance values for the same facility co-firing RDF as a slurry and in a dry form, co-firing municipal sewage sludge, and co-firing industrial de-inking sludge.

As indicated, an overall conversion efficiency of 41.38 percent was defined for the facility without co-firing of waste materials. With waste co-firing, conversion efficiencies decreased in the range of 1.0 percent to 2.7 percent depending on the waste co-fired and method of fuel handling.

**110 MWe Results.** The performance for the 110 MWe PFBC plant without co-firing is shown in Table 5. Performance values for the same facility co-firing RDF as a slurry, co-firing municipal sewage sludge, and co-firing industrial de-inking sludge are also presented for comparison.

As indicated, the overall conversion efficiency of 40.22 percent was defined for the facility without co-firing waste materials. With the additional waste co-firing, conversion efficiencies decreased in the range of 1.3 percent to 2.6 percent depending on the waste co-fired and method of fuel handling. As in the previous analysis, the lowest efficiency is attributable to the co-firing of industrial de-inking sludge.

The RDF co-fired analysis is based on a combined slurry feed system. As indicated, the overall conversion efficiency for the case of co-firing RDF was determined to be 39.29 percent, which represents a 2.3 percent decrease in thermal efficiency from the base case without co-firing.

Alternatives in co-firing municipal sewage sludge were investigated at the 110 MWe level. In the first analysis the coal was co-fired with municipal sewage sludge de-watered to 24 percent t.s. using a separate feed approach. A second analysis assumed a 6 percent t.s. municipal sewage sludge for use in providing a slurry media to transport the combined sludge, coal, and sorbent mixture at 75 percent t.s. This analysis was performed at the 110 MW nominal plant size to investigate the benefits of using the existing as-received municipal sludge as the transport media for the complete fuel, sorbent, and waste feedstock.

As indicated in Table 5, there is no significant performance difference in the combined slurry approach over separate feed. However, a follow-up economic analysis indicated a savings in capital cost and lower cost-of-electricity with this approach.

## ECONOMIC ANALYSIS RESULTS

The cost evaluations for the various PFBC plants were developed by performing a consistent evaluation of the capital and operating costs for each plant and subsequently performing an economic analysis based on the cost of electricity (COE) as the figure of merit. The conceptual cost estimates for each plant were determined on the basis of previous evaluations of conventional pulverized coal and PFBC 2nd Generation power plants. The detail values from this referenced cost data were adjusted for capacity, design condition changes, and cost base.

The fuel cost was defined on the basis of delivered coat cost of $1.80 per MBtu. Costs for the as-received waste materials were not included in the operating cost analysis. Additionally, economic incentives in the form of tax credits or direct payment to the facility were not included. Significant cost savings can be achieved through the application of credits including tipping fees, state and local tax credits, demand-oriented initiatives, and direct payments from municipalities for waste-to-energy disposal.

Table 6 shows the economic analysis results as unit capital costs defined as Total Plant Cost (TPC) and COE. As a reference, the table includes a comparison to the same size plants without the co-firing of wastes. Capital costs and COEs are within 4.2 percent and 5.2 percent, respectively, of the waste free plants. The estimated TPC in 1992 for the 250 MWe and 110 MWe plants range from $1,101 to $1,167/kWe, and $1,508 to $1,546/kWe. For similar size plants without waste co-firing the TPC is approximately $1,120/kWe for the large plant and $1,554/kWe for the 110 MWe plant. Capital, operating, maintenance, and consumable costs are shown in Tables 7 and 8 for the 250 MWe and 110 MWe plants, respectively.

## TABLE 4. 250 MW PFBC PLANT PERFORMANCE COMPARISON

| | W/O Waste Co-firing | RDF | (DRY) RDF | Municipal Sludge | De-Inking Sludge |
|---|---|---|---|---|---|
| ENERGY INPUT | | | | | |
| Coal Feed, lb/hr | 128,861 | 118,313 | 117, 691 | 128,885 | -111,329 |
| Coal HHV, Btu/lb | 12,450 | 12,450 | 12,450 | 12,450 | 12,450 |
| Natural Gas, lb/hr | 19,257 | 19,635 | 19,251 | 19,553 | 19,710 |
| Natural Gas HHV, Btu/lb | 21,799 | 21,799 | 21,799 | 21,799 | 21,799 |
| Waste Feed, lb/hr | | 29,578 | 28,367 | 6,076 | 69,581 |
| Waste HHV, Btu/lb | | 4,103 | 4,103 | 804 | 3,166 |
| Plant Energy Input, MW | 595.181 | 592.713 | 588.256 | 596.628 | 596.710 |
| ENERGY OUTPUT | | | | | |
| Gas Turbine, MW | 87.501 | 98.882 | 89.139 | 96.908 | 103.182 |
| Steam Turbine, MW | 169.369 | 151.897 | 163.932 | 156.514 | 152.661 |
| Auxiliaries, MW | 10.590 | 11.407 | 12.030 | 10.166 | 10.583 |
| Net Plant Power, MW | 246.272 | 239.373 | 241.041 | 243.256 | 240.271 |
| Thermal Efficiency, % | 41.38 | 40.39 | 40.98 | 40.77 | 40.27 |
| Net Heat Rate, (Btu/kWh) | 8,246 | 8,449 | 8,327 | 8,369 | 8,474 |

## TABLE 5. 110 MW PFBC PLANT PERFORMANCE COMPARISON

| | W/O Waste Co-firing | RDF | Municipal Sludge (24%) | Municipal Sludge (6%) | De-Inking Sludge |
|---|---|---|---|---|---|
| ENERGY INPUT | | | | | |
| Coal Feed, lb/hr | 61,581 | 56,814 | 61,634 | 61,634 | 53,457 |
| Coal HHV, Btu/lb | 12,450 | 12,450 | 12,450 | 12,450 | 12,450 |
| Natural Gas, lb/hr | 7,781 | 7,853 | 7,902 | 7,890 | 7,880 |
| Natural Gas HHV, Btu/lb | 21,799 | 21,799 | 21,799 | 21,789 | 21,799 |
| Waste Feed, lb/hr | | 14,200 | 6,076 | 24,306 | 33,410 |
| Waste HHV, Btu/lb | | 4,103 | 804 | 201 | 3,166 |
| Plant Energy Input, MW | 275.345 | 274.550 | 276.844 | 276.767 | 276.434 |
| ENERGY OUTPUT | | | | | |
| Gas Turbine, MW | 38.107 | 43.760 | 43.491 | 44.025 | 44.735 |
| Steam Turbine, MW | 77.408 | 69.320 | 71.028 | 73.048 | 68.354 |
| Auxiliaries, MW | 4.774 | 5.204 | 4.608 | 7.039 | 4.806 |
| Net Plant Power, MW | 110.741 | 107.875 | 109.911 | 110.035 | 108.284 |
| Thermal Efficiency, % | 40.22 | 39.29 | 39.70 | 39.76 | 39.17 |
| Net Heat Rate, (Btu/kWh) | 8,484 | 8,684 | 8,594 | 8,582 | 8,711 |

## TABLE 6. ECONOMIC ANALYSIS RESULTS

| | Net Power MW | Total Plant Cost $/kW | COE $/MWh |
|---|---|---|---|
| Co-Firing RDF | | | |
| 150 MW (Slurry) | 108 | 1,539 | 112.7 |
| 250 MW (Slurry) | 239 | 1,107 | 85.0 |
| 250 MW (Dry) | 241 | 1,167 | 86.2 |
| Co-Firing Municipal Sewage Sludge | | | |
| 150 MW (24% solids) | 110 | 1,544 | 113.9 |
| 150 MW (6% solids) | 110 | 1,509 | 110.8 |
| 250 MW (24% solids) | 243 | 1,101 | 85.6 |
| Co-Firing De-Inking Sludge | | | |
| 150 MW | 108 | 1,546 | 110.5 |
| 250 MW | 240 | 1,114 | 83.4 |
| Without Co-Firing Wastes | | | |
| 150 MW | 111 | 1,553 | 108.4 |
| 250 MW | 246 | 1,120 | 83.4 |

**250 MWe Results.** The 250 MWe PFBC plants are compared in Table 7. As a point of reference, capital costs ($/kW) and COEs ($/MWh) are within 4.2 percent and 3.2 percent, respectively, of the waste-free plant. These differences are reduced to within 1.7 percent for TPC and 2.5 percent for COE when the dry feed approach is removed from the comparison.

The fuel prep and feed component of the TPC has the greatest variance within the cases. The coal (waste-free) and the RDF (dry) cases are the highest values. This is due to the pneumatic design for fuel feeding. Slurry feed systems are inherently less costly to install than dry feed systems. However, also included in this cost component are the waste preparation and delivery equipment. Dewatering equipment is a major contributor to the variance. The belt filters used for municipal sewage sludge are less costly than the screw presses used with the de-inking sludge. The dry-feed system combined with waste preparation and feed equipment make the RDF (dry) case the most expensive. The plant with slurry feed system combined with the waste preparation and feed equipment is equitable on the TPC $/kW basis with the coal (waste-free case).

The capital costs associated with the waste feedstock preparation and feed ranged from a high of 37 $/kW for the RDF dry feed approach to 15 $/kW for the RDF slurry. Municipal sewage sludge and de-inking sludge preparation and feed costs were defined at 16 $/kW and 28 $/kW, respectively.

The fuel cost component of the COE varies between cases due to the plant efficiency and the percent of the Btu input supplied by the waste fuels. The fixed and variable O&M cost components of the COE are higher for all plants with waste co-firing than for waste-free plant due to the additional equipment train required to process the waste fuel feedstocks.

**110 MWe Results.** The 110 MWe plants are compared in Table 8. The effect of economy of scale is obvious when comparing the TPC and COE values of Tables 7 and 8. The same relationship for the TPC and COE cost components exist in the 110 MWe size

## TABLE 7. 250 MWE PLANT COMPARISON (1992 DOLLARS)

| Case Description | | Base Plant (Waste-free) | RDF (Slurry) | RDF (Dry) | Municipal Sewage Sludge | De-Inking Sludge |
|---|---|---|---|---|---|---|
| Net Power | MW | 246 | 239 | 241 | 243 | 240 |
| Heat Rate | Btu/kWh | 8,247 | 8,449 | 8,327 | 8,369 | 8,474 |
| **Capital Cost** | | | | | | |
| Fuel Prep & Feed | $M | 17.4 | 9.4 | 25.4 | 9.7 | 12.2 |
| PFBC | $M | 38.8 | 37.5 | 38.2 | 38.2 | 37.2 |
| Turbine/Generator | $M | 68.4 | 65.6 | 67.2 | 66.5 | 65.2 |
| PFB HGCU | $M | 16.8 | 17.5 | 16.9 | 17.4 | 17.7 |
| Rest of Plant | $M | 134.4 | 135.1 | 133.7 | 136.0 | 135.3 |
| Total Plant Cost | $M | 275.8 | 265.1 | 281.4 | 267.8 | 267.6 |
| TPC | $/kW | 1119.8 | 1107.4 | 1167.3 | 1101.0 | 1113.9 |
| Change from Base | | - | -1.1% | +4.2% | -1.7% | -0.5% |
| **Cost of Electricity** | | | | | | |
| Capital Chg | $/MWh | 36.5 | 36.7 | 38.0 | 36.5 | 36.9 |
| Fixed O&M | $/MWh | 9.4 | 10.9 | 11.1 | 10.5 | 10.6 |
| Variable O&M | $/MWh | 5.1 | 5.8 | 6.0 | 5.7 | 5.7 |
| Consumables | $/MWh | 5.2 | 5.1 | 5.1 | 5.3 | 4.9 |
| Fuel | $/MWh | 27.3 | 26.4 | 26.1 | 27.6 | 25.3 |
| Levelized COE | $/MWh | 83.5 | 85.0 | 86.2 | 85.6 | 83.4 |
| Change from Base | | - | +1.8% | +3.2% | +2.5% | -0.1% |

## TABLE 8. 110 MWE PLANT COMPARISON (1992 DOLLARS)

| Case Description | Base Plant (Waste-free) | RDF (Slurry) | Municipal Sewage Sludge (24% solids) | Municipal Sewage Sludge (6% solids) | De-Inking Sludge |
|---|---|---|---|---|---|
| Net Power MW | 111 | 108 | 110 | 110 | 108 |
| Heat Rate Btu/kWh | 8,484 | 8,684 | 8,595 | 8,582 | 8,711 |
| **Capital Cost** | | | | | |
| Fuel Prep & Feed $M | 10.8 | 5.9 | 7.6 | 3.8 | 7.5 |
| PFBC $M | 27.9 | 26.9 | 27.3 | 27.4 | 26.7 |
| Turbine/Generator $M | 38.7 | 37.9 | 38.8 | 39.0 | 37.8 |
| PFB HGCU $M | 9.9 | 9.8 | 9.8 | 10.0 | |
| Rest of Plant $M | 85.1 | 85.4 | 86.2 | 86.0 | 85.4 |
| Total Plant Cost $M | 172.0 | 166.0 | 169.7 | 166.0 | 167.4 |
| TPC $/kW | 1553.7 | 1538.6 | 1544.4 | 1508.5 | 1546.0 |
| Change from Base | - | -1.0% | -0.6% | -2.9% | -0.5% |
| **Cost of Electricity** | | | | | |
| Capital Chg $/MWh | 49.8 | 50.9 | 51.1 | 50.0 | 51.1 |
| Fixed O&M $/MWh | 16.4 | 19.2 | 18.9 | 17.8 | 18.6 |
| Variable O&M $/MWh | 8.8 | 10.3 | 10.2 | 9.6 | 10.0 |
| Consumables $/MWh | 5.5 | 5.4 | 5.6 | 5.5 | 5.2 |
| Fuel $/MWh | 27.8 | 26.8 | 28.0 | 28.0 | 25.6 |
| Levelized COE $/MWh | 108.3 | 112.7 | 113.9 | 110.8 | 110.5 |
| Change from Base | - | +4.1% | +5.2% | +2.3% | +2.0% |

plants as for the large plants. Capital costs and COE are within 2.9 percent and 5.2 percent, respectively of the waste-free plant.

The municipal sewage sludge cases exemplify the impact of the preparation and feed system on the COE. The 24 percent case requires dewatering equipment and stakefeeders while the 6 percent case utilizes sludge, as received, as a portion of the coal slurry water.

The capital costs associated with the waste feedstock preparation and feed ranged from a high of 37 $/kW for the de-inking sludge to 21 $/kW for the RDF slurry. Capital costs for municipal sewage sludge preparation and feed were defined at 35 $/kW.

## FUTURE WORK

This study's objective was to investigate co-firing a pressurized fluidized-bed combustor with coal and refuse-derived fuel and/or sludges for the production of electricity and the efficient disposal of waste. Performance evaluation of the PFBC power plant co-fired with RDF and/or sludges showed only slightly lower overall thermal efficiency than similar sized plants without waste co-firing. Capital costs and COEs are within 4.2 percent and 5.2 percent, respectively, of waste-free operation.

The results also indicate there are no technology barriers to the co-firing of waste materials with coal in a PFBC power plant. The potential to produce cost-competitive electrical power and support environmentally acceptable waste disposal exists with this approach. However, as part of technology development, there remain several design and operational areas requiring data and verification before this concept can realize commercial acceptance.

In summary, the key issues for co-firing are feeding waste materials against system pressures (solids handling), materials concerns due to the addition of potentially corrosive constituents, and environmental impact of solid wastes and gaseous emissions. In order to address these issues, pilot-scale testing co-firing waste materials should be performed and the results used to predict commercial-scale performance. The testing should be performed in a facility of adequate size so commercially representative fuel feed sizes and gas residence times can be evaluated.

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