

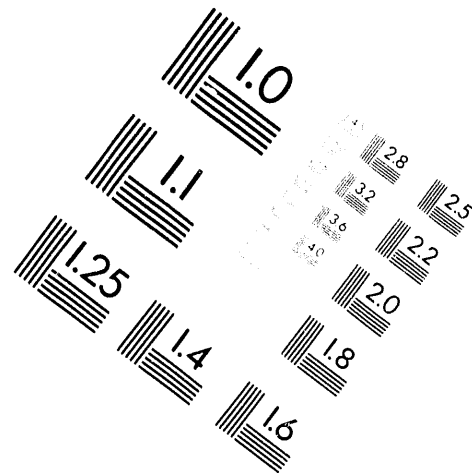
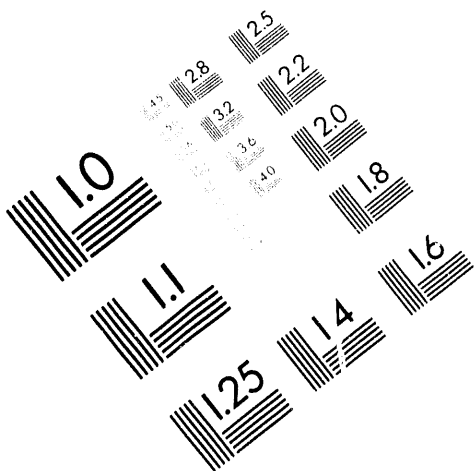


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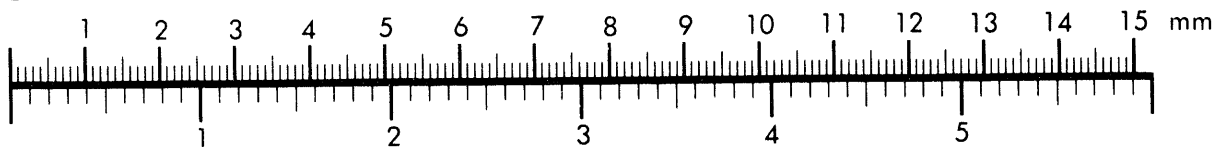
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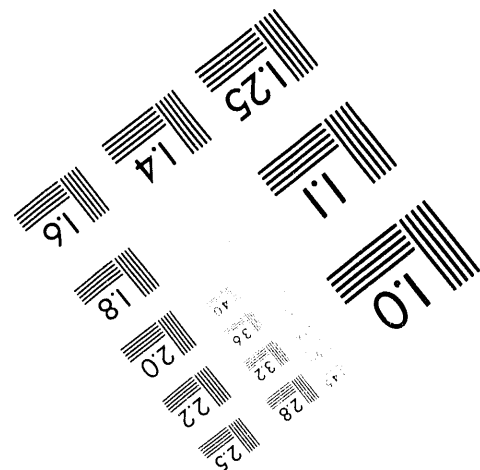
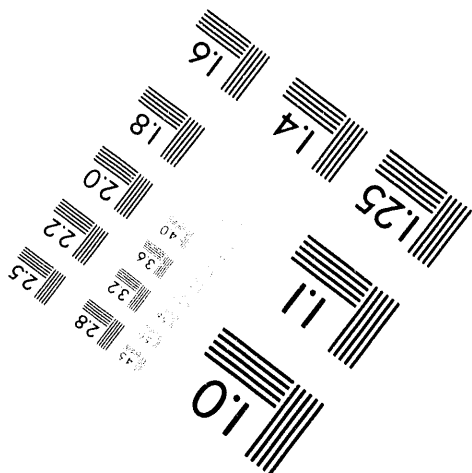
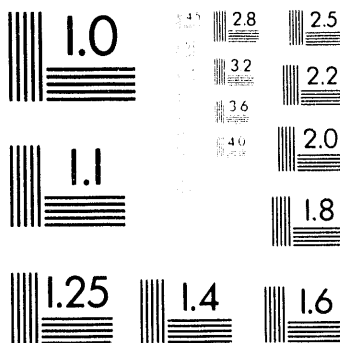
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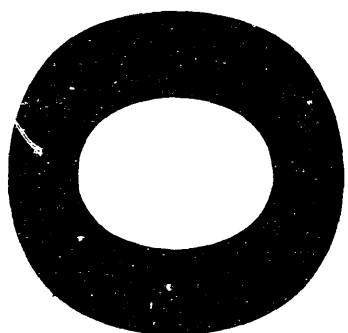
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Conceptual Design and Economics of Coal and Gas Co-Fired PFBC Plants

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CONCEPTUAL DESIGN AND ECONOMICS OF COAL AND GAS CO-FIRED PFBC PLANTS

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Abstract

Advanced 2nd-Generation pressurized fluidized bed (PFBC) cycles are viewed as having increased technological risk related to the pressurized carbonizer systems regardless of their favorable economics and performance. The 1.5-Generation PFBC cycle combines the performance advantages of the 2nd-Generation PFBC plant with the reduced risk of a natural-gas-fired gas turbine. This paper describes the technical and economic evaluation of 246-MW and 111-MW 1.5-Generation PFBC cycles for utility or industrial power generation. Economic evaluation includes sensitivity studies to determine the effects of operating variables and fuel prices on capital cost and COE.

The thermal efficiency, capital cost, and cost of electricity of 1.5-Generation PFBC plants are better than pulverized coal plants, and in between 1st- and 2nd-Generation PFBC plants. Plant capacity turndown is expected to range from full-load (design flows of natural gas and coal) down to 38-percent load (zero natural gas and 50-percent coal flow). The plant can be reduced to 76-percent load by reducing natural gas flow without disturbing the coal feed to the rest of the plant, and other cost-effective variations are also possible.

The 1.5-Generation PFBC plant is the logical repowering alternative to 1st-Generation PFBC, and provides a reasonable bridge to later conversion to a 2nd-Generation PFBC, thus advancing the adoption of 2nd-Generation PFBCs in the future.

Introduction

Over the last 10 years the projected economics and performance of pressurized fluidized bed (PFBC) cycles, especially the 2nd-Generation PFBCs, in utility applications favorable compared to conventional pulverized coal power plants. The 2nd-Generation PFBC concept will utilize the full power producing potential of modern gas and steam turbines in coal-fired combined cycle plants. This is accomplished by topping combustors in 2nd-Generation systems which are designed to

achieve turbine inlet temperatures of 2100 to 2500 °F, consistent with the high power output of modern gas turbines.

However, the improved economics of 2nd-Generation PFBC cycles are accompanied by the perception of increased technological risk. These perceived risks are related to the pressurized carbonizer and its associated gas cleanup systems. In the 2nd-Generation PFBC system, coal is fed to a pressurized fluidized-bed partial gasifier that produces a low-Btu gas and char. Char is then burned in a PFBC, and the flue gas is cleaned of particulate and sent to the topping combustor. Low-Btu fuel gas from the partial gasifier is also cleaned and piped to the topping combustor. In the topping combustor, any air required to complete combustion is mixed with the fuel gas and the flue gases. Steam is produced from heat transfer surfaces located in the PFBC and a heat recovery steam generator (HRSG).

Removing the uncertainties associated with the carbonizer while retaining the high cycle efficiency and low cost should improve the prospects for early commercialization of 2nd-Generation PFBCs.

A PFBC cycle which substitutes the carbonizer and associated equipment with natural gas topping combustion, is referred to as the 1.5-Generation PFBC cycle. The cycle combines the advantages of the 2nd-Generation PFBC plant while reducing the risk associated with the Carbonizer by firing the gas turbine with natural gas. This arrangement has potential for repowering existing plants, while paving the way for the introduction of the complete 2nd-Generation PFBC cycle at some later date. The phased approach to utility size 2nd-Generation PFBC cycles should reduce risk, while providing utilities with time to become comfortable with an emerging technology. In addition the 1.5-Generation PFBC may have operational advantages over other PFBC systems in certain types of service.

This report describes the technical and economic evaluation of 1.5-Generation PFBC cycles for utility or industrial power generation.

Technical Approach

The objective of this project is to develop a reference plant design and cost estimate for a pressurized fluidized bed combustor (PFBC) system that uses oil or natural gas to fire the topping combustor. The project was divided into three main activities: development of plant design; development of cost estimates; and sensitivity studies. The emphasis in this study was on thermal performance, which involved extensive computer modeling, while budgetary costs were estimated using various scaling techniques.

Selected Plant Sizes

Because the 1.5-Generation PFBC concept has the potential to satisfy a wide range of applications, larger and smaller study cases were selected to cover a range of capacities.

- o The larger plant was assumed to be an alternative to conventional gas-fired combined cycles and integrated gasification combined cycles (IGCC), which are nominally sized around 250 MW.
- o The smaller plant is about half the size of the large plant, in the range of 100 to 150 MW was considered for repowering or smaller IPP facilities

In this type of power cycle assuming that coal is the primary fuel about 40 percent of the power is generated by the gas turbine. Gas turbines were selected by a four-step process:

1. Define the approximate sizes of the large, intermediate, and small plants.
2. Refine the criteria for evaluating the candidate combustion turbines.
3. Identify candidate combustion turbines for each size plant.
4. Use the criteria in Step 2 to select a combustion turbine.

The combustion turbine that is best suited to the large 1.5-Generation PFBC system is the 501D5 by Westinghouse. The Westinghouse 251B12 was selected as the gas turbine for the nominal 100-MW plant because it is a turbine that can generate about 50 MW of power without steam injection.

Major Equipment

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 recovery steam generator (HRSG), and heat from the PFBC is used to evaporate, superheat, and reheat the steam in a fluid bed heat exchanger (FBHE) for use in a Rankine steam cycle.

The steam turbine Rankine cycle generates power using the PFBC and HRSG as its heat sources. The larger (246 MW) plant uses a 1800-psig, 1000 °F/1000 °F reheat steam cycle, and the smaller (111 MW) plant uses a 1450-psig, 1000 °F/1000 °F reheat steam cycle.

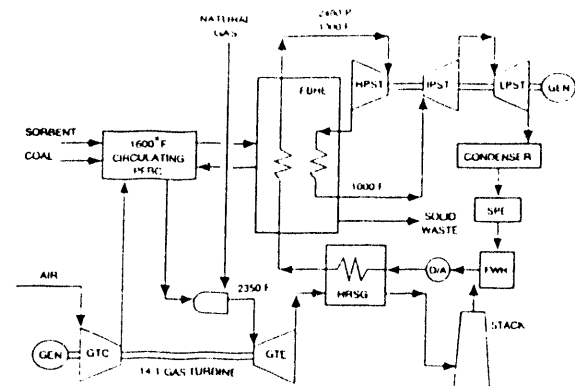


Figure 1 - PFBC-1.5 Cycle

The conceptual flow diagram of the 1.5-Generation PFBC power plant are shown in the schematic Figure 1. The major subsystems are:

- o Coal and limestone Preparation Systems
- o Circulating PFB Combustors (CPFBC)
- o Fluid Bed Heat Exchangers (FBHE)
- o Compressed Air Systems
- o Combustion Turbine-Generator Systems
- o Heat Recovery Steam Generators (HRSG)
- o Steam Turbine-Generator Systems
- o Feedwater Systems
- o Waste Disposal Systems

Conceptual Designs

The conceptual design and performance of large and intermediate 1.5-Generation PFBC combined cycle power plants are compared in Table 1.

Table 1
Thermal Performance Comparison

Size	246	111	MWe
ENERGY INPUT			
Coal	128,861	61,581	lb/h
Coal HHV	12,452	12,452	Btu/lb
Nat. Gas	19,257	7,781	lb/h
Nat HHV	21,799	21,799	Btu/lb
Coal Energy	470.3	227.7	MW
Coal Drying	1.9	0.9	MW
Gas Energy	123.0	49.7	MW
Energy Input	595.2	275.3	MW
ENERGY OUTPUT			
Gas Turbine	87.5	38.1	MW
Steam Turb	169.4	77.4	MW
Auxil	(10.6)	(4.8)	MW
Net Power	246.3	110.7	MW
Efficiency	41.4%	40.2%	HHV

The thermal efficiency of the 1.5-Generation PFBC plant ranks between the 1st- and 2nd-Generation PFBC plants, higher than IGCC but lower than gas-fired combined cycles, as shown in Table 2.

Table 2
Combined Cycle Efficiency Comparison

Plant Type	HHV Efficiency
Gas Turbine	49%
2nd-Generation PFBC	45%
1.5-Generation PFBC	41%
1st-Generation PFBC	39%
Dry-fed oxygen-blown IGCC	39%

A design sensitivity study was performed to determine the effects of PFBC excess air on the design, capital cost, and COE of the 111-MWe, 1.5-Generation PFBC plant. PFBC excess air has only a minor effect on overall efficiency, but a profound effect on plant generating capacity. Using the same gas turbine, plants with lower PFBC excess air have smaller vessels and generate more power.

Plant Operation

The operational concept for the 1.5-Generation PFBC plant is a base-loaded plant with the capability for significant turndown. About 24 percent of the generated power is fueled by natural gas, to which the plant responds quickly,

and the other 76 percent fueled by coal, to which the plant responds more slowly. This combination of fuels allows rapid adjustments between 76 and 100 percent of load by adjusting the natural gas flow to the gas turbine. Assuming that the PFBC/FBHE system is capable of a 50-percent turndown, plant load levels between 38 and 76 percent can be attained by adjusting the coal feed rate. As a result, the effective turndown ratio of a single-train 1.5-Generation PFBC plant is almost 3:1, compared with the 2:1 turndown of a 1st- or 2nd-Generation PFBC plant.

Plant capacity is expected to range from full-load (design flows of natural gas and coal) down to 38-percent load (zero natural gas and 50-percent coal flow). The operation of a 1.5-Generation PFBC plant under various steady-state, start-up, and emergency conditions is feasible.

An operational sensitivity study was performed to determine the effects of load change on the 111-MWe, 1.5-Generation PFBC plant. The plant can be reduced to 76-percent load by reducing natural gas flow without disturbing the coal feed to the rest of the plant. Thermal efficiency over this range is constant to within three percentage points.

Economic Performance

The estimated capital cost (TPC, 12/92 dollars) and cost of electricity (COE) for the 1.5-Generation PFBC plants compare favorably with conventional pulverized-coal steam power plant with flue gas desulfurization, as shown in Table 3. The 1.5-Generation PFBC plant is more efficient than the PC plant (41.9% vs. 35.2%), but much of this advantage when calculating COE is offset by its smaller size (246 MW vs. 560 MW) and the assumed higher price of natural gas compared to coal fuel (\$2.50/MBtu vs. \$1.80/MBtu).

Table 3
Economic Performance

	PC/ FGD Plant	PFBC- 1.5 Plant	PFBC- 1.5 Plant	
Power	559	246	111	MW
Eff.	35.2%	41.4%	40.2%	HHV
Cost	\$1292	\$1120	\$1553	/kW
COE	\$90.3	\$83.4	\$108.4	/MWh

Economic Evaluation Methods

The economics of the 1.5-Generation PFBC plant cost estimates were developed by consistently evaluating 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 utility-sized PC and 2nd-Generation PFBC power plants [1] and smaller industrial sized-power plants [2].

Estimated costs for the major components were established by a variety of methods. In-house cost data and support data from previous PFBC reports were supplemented by vendor budgetary pricing for major items as required.

As a general approximation, the capital costs and COEs of these plants have economies of scale, as shown in Figure 2.

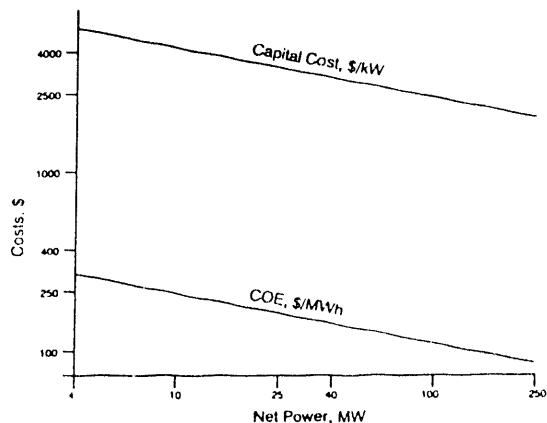


Figure 2 - Economies of Scale

Operation and maintenance (O&M) cost values were determined on a first-year basis and subsequently leveled over the 30 year plant life. Consumables were evaluated on the basis of the quantity required and individual commodity unit prices. Operation cost was determined on the basis of the number of operators, and maintenance was evaluated on the basis of maintenance costs required for each major plant section. These operating costs were then converted to unit values of \$/MWh or mills/kWh. Operating, maintenance, and consumable costs were based on the plant design conditions listed in Table 4.

Additional economic assumptions were a plant book life of 30 years, a 65-percent capacity factor, and a plant in-service date of January 1993.

Table 4
Plant Design Conditions

Size (Output)	246	111 MWe
Heat Rate	8,246	8,484 Btu/kWh
Coal	Pgh. 8	Pgh. 8
Coal HHV	12,450	12,450 Btu/lb
Coal Cost	\$1.80	\$1.80 /MBtu
Gas Cost	\$2.50	\$2.50 /MBtu
Coal	128,861	61,581 lb/h
Nat. Gas	19,257	7,781 lb/h
	7,014	2,834 scfm
Dolomite	51,117	24,428 lb/h
Construction	3.5	2.5 years

The capital and operating costs of the plant are combined with plant performance in the comprehensive evaluation of cost of electricity (COE). Table 5 presents the 30-year leveled costs of electricity for the two 1.5-Generation PFBC cases.

Table 5
Cost of Electricity Comparison
(\$/MWh = mills/kWh)

Size	246	111 MWe
Capital Chgs	36.5	49.8 \$/MWh
Fixed O&M	9.4	16.4 \$/MWh
Variable O&M	5.1	8.8 \$/MWh
Consumables	5.2	5.5 \$/MWh
Fuel	27.3	27.8 \$/MWh
COE	83.4	108.4 \$/MWh

As a comparison, the COE for the 246-MW 1.5-Generation plant is lower than the \$90/MWh for a 560-MW conventional PC/FGD plant, but higher than the \$75/MWh for a 536-MW 2nd-Generation PFBC plant.

Economic Sensitivities

Sensitivity studies were performed to determine the effects of design, operating, and market conditions on capital cost and COE.

- o Topping Combustor Temperature: Even though natural gas is more expensive than coal, the performance penalty for operating at below-design conditions makes it uneconomical to run with greatly reduced amounts of natural gas under base load rate structures.
- o PFBC Excess Air: Plants designed with lower PFBC excess air use more coal, which increases equipment capital costs (in dollars), but the increased generating capacity results in lower costs per kilowatt. Plants designed

with higher PFBC excess air have higher levelized costs of electricity because of their reduced power generating capacity.

- o Fuel Prices: The largest fuel-price influence on COE was coal price (0.201-percent increase in COE for each 1-percent increase in coal price), followed by oil price (0.106 percent per percent increase) and natural gas price (0.063 percent per percent increase).

Conclusions and Recommendations

The conceptual design and analysis of the 1.5-Generation PFBC plant leads to the following conclusions.

- 1 The 1.5-Generation PFBC plant provides a reasonable bridge to the commercialization of 2nd-Generation PFBC technology, and it is the logical alternative to 2nd-Generation PFBC.
- 2 By eliminating the carbonizer and its associated hot-gas cleanup system, the 1.5-Generation PFBC plant has less technological risk than a 2nd-Generation PFBC plant.
- 3 The 1.5-Generation PFBC plant has excellent load-following potential, and is more responsive than a 2nd-Generation PFBC plant. Power output can be reduced 24 percent by adjusting the natural gas, with only a 3-point loss of efficiency (from 40 percent to 37 percent). Plant operation is well within commercial equipment and controls design capability.
- 4 The projected turndown in a 1.5-Generation PFBC plant is about 3:1, since 1/3 of the power supplied by natural gas, and the rest is supplied by coal in a PFBC that can be turned down by 50 percent.
- 5 The gas turbine operating conditions in a 1.5-Generation PFBC cycle are relatively close to

"standard" gas turbine design conditions, allowing fairly "standard" turbines to be considered as candidates.

- 6 The 1.5-Generation gas turbine/steam turbine power split is about 34%/66%, which places it between the 1st-Generation plant (23%/77%) and the 2nd-Generation plant (45%/55%).
- 7 The HHV efficiency of a large 1.5-Generation PFBC plant is about 41%, which also places it between the 1st-Generation plant (38%) and the 2nd-Generation plant (45%).
- 8 The 1.5-Generation PFBC plant follows classical economy of scale over the range of sizes studied -- 111 to 246 MWe.
- 9 The greatest fuel-related COE sensitivity is the sensitivity to coal price (0.201-percent increase in COE for each 1-percent increase in coal price), followed by the sensitivity to oil price (0.106percent per percent increase) and to natural gas price (0.063 percent per percent increase).
- 10 Plants designed with less PFBC excess air have lower capital costs (per kW) and lower COEs than plants designed with more PFBC excess air.

Acknowledgements

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