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DUAL BRAYTON CYCLE GAS TURBINE PRESSURIZED FLUIDIZED BED COMBUSTION POWER PLANT CONCEPT

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ABSTRACT

High generating efficiency has compelling economic and environmental benefits for electric power plants. There are particular incentives to develop more efficient and cleaner coal-fired power plants, to permit use of the world's most abundant and secure energy source. This paper presents a newly-conceived power plant design, the Dual Brayton Cycle Gas Turbine PFBC, that yields 45% net generating efficiency and fires on a wide range of fuels with minimum pollution, of which coal is a particularly intriguing target for its first application. The DBC-GT design allows power plants based on the state-of-the-art PFBC technology to achieve substantially higher generating efficiencies while simultaneously providing modern gas turbine and related heat exchanger technologies access to the large coal power generation market.

INTRODUCTION

Fluidized bed combustion (FBC) is the basis of most modern coal-fired power systems. FBC is well suited to firing various quality coals or co-firing coals with other fuels, such as biomass and waste, with low emissions of pollutants. This has been demonstrated in conventional atmospheric FBC power plants. However, the conventional plants based on the Rankine steam turbine cycle are relatively inefficient. The efficiency can be slightly improved in the state-of-the-art (1st-generation) pressurized fluidized bed combustion (PFBC) combined cycle power plants that incorporate the more efficient Brayton gas turbine cycle to provide a small share (20-25%) of overall plant power generation.

Proposed advanced (2nd-generation) PFBC combined cycle power plant designs increase the share of power generation from the gas turbine cycle to about 50%, by raising significantly the gas turbine inlet temperature and by using very high excess combustion air (in the range of 100-150%). These advanced designs require a partial coal gasification stage, to produce the gaseous fuel needed to heat flue gas in a second combustor, in order to reach the required turbine inlet temperature. These designs also considerably increase the load and design requirements of the hot gas cleanup system. The quest for higher efficiency in the advanced PFBC designs has resulted in increased system complexity that adversely affects plant economics, operation, and development time. Other advanced designs such as the integrated gasification combined cycle (IGCC) system are similarly complex and offer no advantage of efficiency or cost over the advanced PFBC designs.

Dual Brayton Cycle Gas Turbine (DBC-GT) PFBC is a newly-conceived power plant design that employs an innovative cycle arrangement to achieve clean and efficient power generation at competitive cost (Yan and Lidsky, 1996). The design is based on PFBC for coal combustion in conjunction with both a closed and an open Brayton cycle gas turbine, connected in such fashion as to maximize the system performance while reducing the technological demands on each of the components. The DBC-GT design surpasses the efficiency and environmental goals of other advanced designs, yet is substantially smaller, simpler, and thus less expensive. Furthermore, the DBC-GT provides a practical means to incorporate modern closed-cycle helium turbine into a commercially attractive fossil plant design.

DBC-GT POWER PLANT CONCEPT

A schematic of the baseline DBC-GT power plant design is shown in Fig. 1. The plant consists of three major subsystems, the circulating PFBC system, the open-cycle gas turbine system, and the closed-cycle gas turbine system. At design conditions, approximately 75% of the total plant power output is provided by the closed-cycle gas turbine while the remaining 25% is provided by the open-cycle gas turbine. In addition to power generation, the open-cycle gas turbine supplies compressed combustion air to the CPFBC, which produces hot flue gas for expansion in the open cycle turbine and provides indirect heating to the closed cycle in an external fluidized bed heat exchanger (FBHX). A portion of the combustion air supplied

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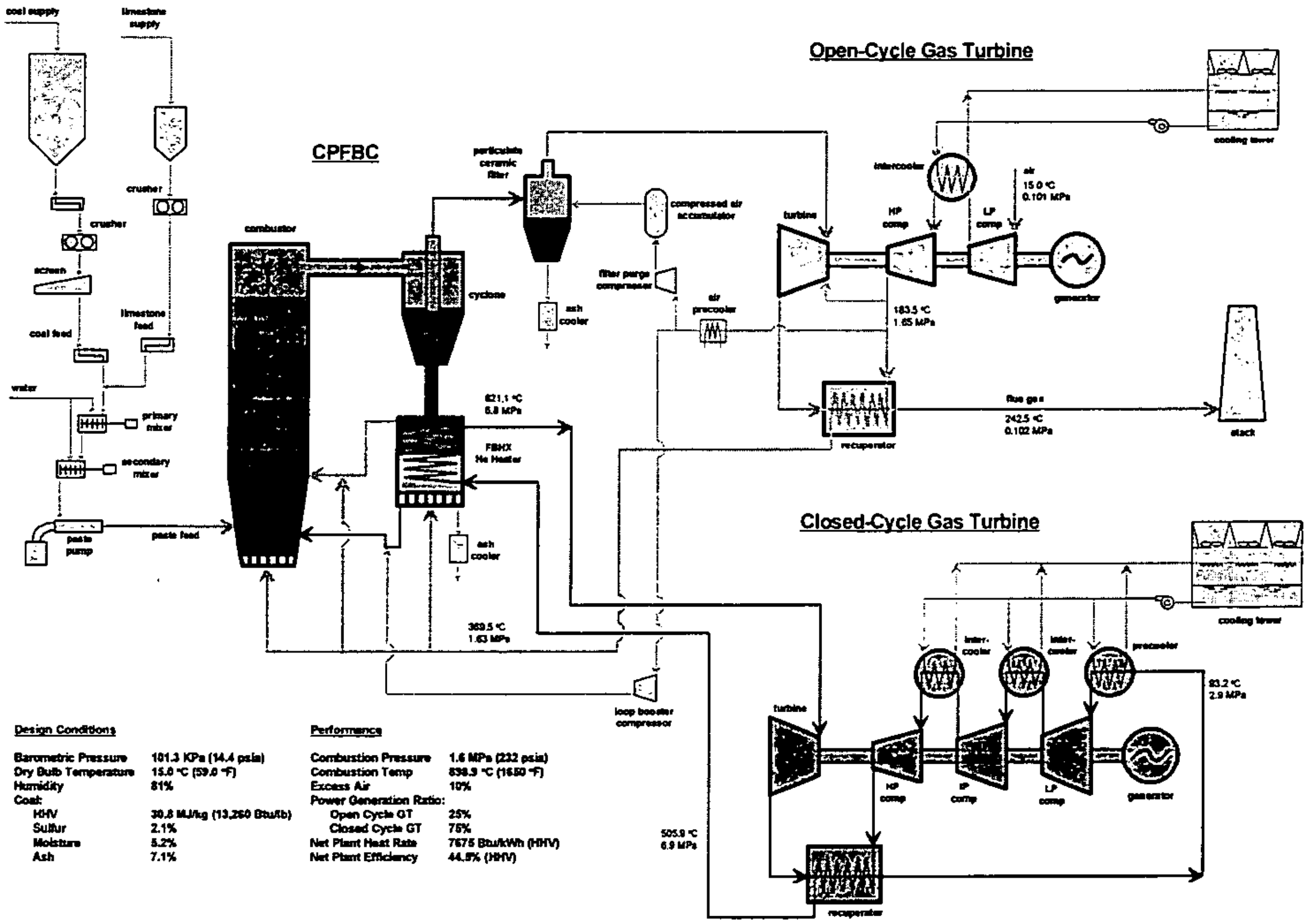


FIGURE 1: SCHEMATIC OF DBC-GT POWER PLANT

by the open cycle is fed into the FBHX heater as fluidizing air before being injected into the combustor as tertiary air.

The CPFBC allows combustion of various quality coals with good atmospheric emission characteristics and extremely high firing capacities. Coal and limestone are mixed with water to form a paste which is then fed by a paste pump into the lower bed of the combustor. Coal is combusted to heat the solid particles contained in the combustor bed and to produce hot flue gas. Most of the thermal energy released from combustion is contained in the bed solids. Combustion takes place in the CPFBC with staged combustion air and at relatively low combustion temperatures to limit NOx emissions, while limestone reacts with the coal bound sulfur.

The hot flue gas with entrained solids leaves the top of the combustor and enters cyclones, where the coarse solid particles are separated from the flue gas. The hot flue gas exiting the cyclones flows into ceramic filters for final filtration of the remaining particulate dust. The cleaned flue gas is then directed into the open-cycle turbine, which extracts work from the sensible heat of the flue gas to drive an electric generator and to drive air compressors to compress combustion air. The compressed combustion air is preheated by the turbine exhaust gas in a recuperator before it is delivered to the combustor. This is an important energy recovery step to attain high thermal efficiency for the high-pressure combustor system. The cooled flue gas from the recuperator is sent directly to stack for emission without further treatment.

The main energy transfer takes place in the FBHX external to the combustion zone of the circulating fluidized bed combustor. The hot solid particles captured in the cyclones contain the bulk of the combustion energy. These solid particles are circulated from the cyclones into the FBHX, wherein the sensible heat of the hot solid particles is transferred at high heat transfer rates to the working fluid (helium) of the closed-cycle gas turbine, which then converts the heat at high efficiency into shaft power to drive a second electric generator.

There are several design features that merit comment here. First, the DBC-GT design is in part aimed at finding a way to incorporate modern closed-cycle helium turbomachinery into a commercially attractive fossil plant design. A major impediment to the use of this very compact, very efficient technology was the inability to design a robust, economic gas heater. Fortunately, the external FBHX has precisely the attributes required for successful heater design:

- High and nearly uniform temperatures
- High and nearly uniform heat transfer coefficients
- Pressurized environment
- Fluidization of fine solids at low velocity
- Essentially combustion-free atmosphere

This combination of properties minimizes tube thermal and mechanical stresses, assures low rates of chemical and mechanical attack on the tubing, and results in very compact (i.e. high volumetric heat transfer) heater design.

Furthermore, the DBC-GT design relies on the highly-efficient, reliable, closed cycle gas turbine for the majority of the plant power generation. The open-cycle gas turbine is used primarily as a heat recovery means rather than as a major contributor to total power output. Thus, it is not necessary to deviate from optimal combustor operating conditions to maximize open cycle output by using high excess air or by raising turbine inlet temperature with resulting deleterious impact on component sizes, filter capacity, and environmental performance.

Finally, and most obviously, the DBC-GT replaces the Rankine cycle in conventional PFBC plants with a higher-performance Brayton cycle. This allows power plants employing PFBC technology to achieve substantially higher efficiencies while simultaneously providing modern gas turbine and related heat exchanger technologies access to the large coal power generation market, which has been traditionally dominated by Rankine cycle steam turbine generators.

CPFBC System

Figs. 2 and 3 depict elevation and plan views of a CPFBC system design for a 400 MWe DBC-GT plant. The CPFBC system employs separate pressure vessels to contain individual components, an modular design approach that is favored by industry to reduce pressure vessel costs and system installation requirements (Robertson and Bonk 1993; Rehwinkel et al. 1993). The major components of the CPFBC include a single combustor with a firing rate of 905 MWt ($3089x10^6$ Btu/hr), four parallel cyclone/filter trains for flue gas cleanup, and a FBHX heater unit for heating the closed cycle. The pressure vessels are fabricated of carbon steels and protected with internal refractory linings (exclusive of the heater vessel) from the abrasive solids and hot gases. Because of its capacity for firing at extremely high power density, the combustor is very compact; the largest outer diameter of the combustor pressure vessel is only 5.0 m (16 ft-5 in). The cyclones and filters are also compact modular units.

The horizontal pressure vessel of the FBHX helium heater encloses a pair of refractory-walled fluidized beds, each containing an identical U-tube bundle. The pressure vessel is cooled on the inside by cold stagnant air. The two tube bundles share common tubular headers for directing helium flows into and out of the tubes. The tube bundles have a heat duty of 2x300 MWt (2x1025 10^6 Btu/hr) and include a total heat transfer surface area of 2x6,141 m^2 (2x66,098 ft^2). Each tube bundle is immersed in a series of seven fluidized cells to facilitate heating the helium gas to the required exit temperature of 821.1 °C (1510.0 °F). To augment heat transfer, the bed solids are forced to flow, alternately, under and over the partition weirs from one cell to another to provide an overall cross-counter flow effect between

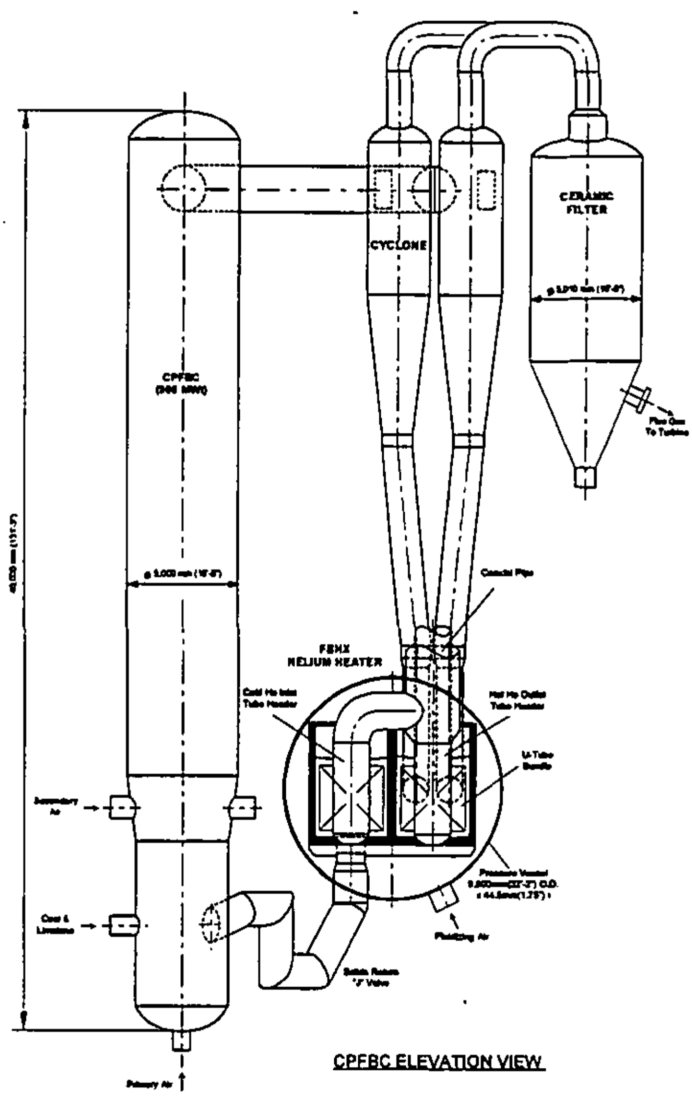


FIGURE 2: CPFBC FOR 400 MWe DBC-GT POWER PLANT

the solids and helium and to avoid solids flow bypass. The distributed temperatures and heating duties among the multiple cells are detailed in Fig. 4.

Combustion-related corrosion on the heater tubes is minimized, since the external heater is essentially free of combustion. Tube erosion is similarly minimized because the particle beds in which the tubes are immersed are fluidized at very low velocity (0.3 m/s or 1 ft/s) with fine solids. These salubrious working conditions allow heater tubes fabricated of suitable high-temperature alloys with reasonable design margins to achieve a design lifetime of 30 years.

The overall dimensions of the heater steel pressure vessel are 9.8 m (32 ft-2 in) O.D., 45.3 m (148 ft-7 in) length, and 44.5 mm (1¾ in) wall thickness. The vessel weighs under 600 metric tons (660 tons). One approach to constructing the heater is to shop assemble it into two subassemblies, each of which contains one tube bundle in a half-length pressure vessel, to ship the two halves to site by barge (and by

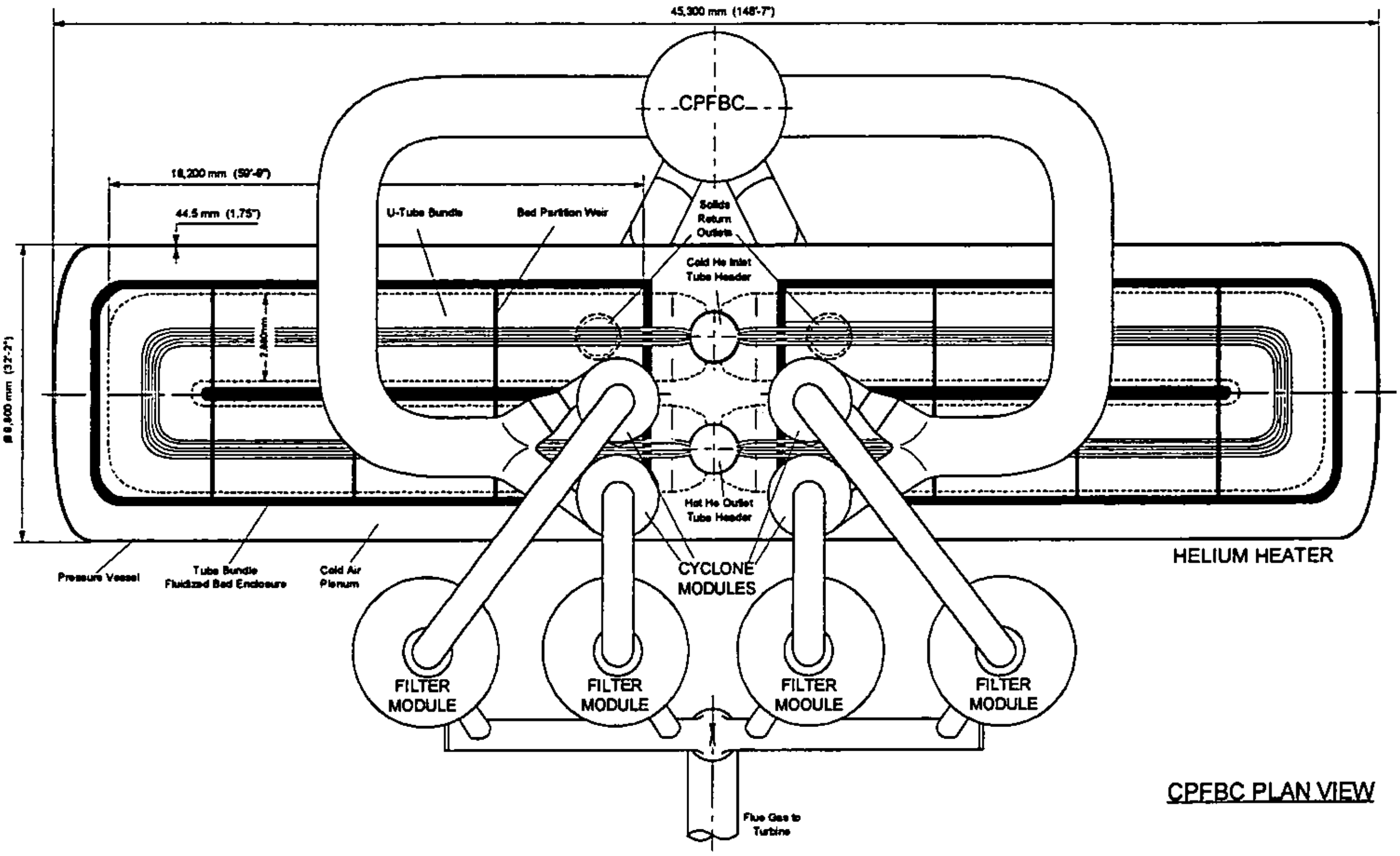


FIGURE 3: PLAN VIEW OF CPFBC FOR 400 MWe DBC-GT POWER PLANT

crawlers from barge to inland location if necessary), and to erect and join them through circumferential welding on the vessel and the tube headers in field. The size and shipping requirements of the heater subassemblies are well within the experience of the power industry. The combustor vessel, cyclone, and filter modules are all smaller than the heater modules. Therefore, they can easily be shop fabricated and shipped to site by barge or rail.

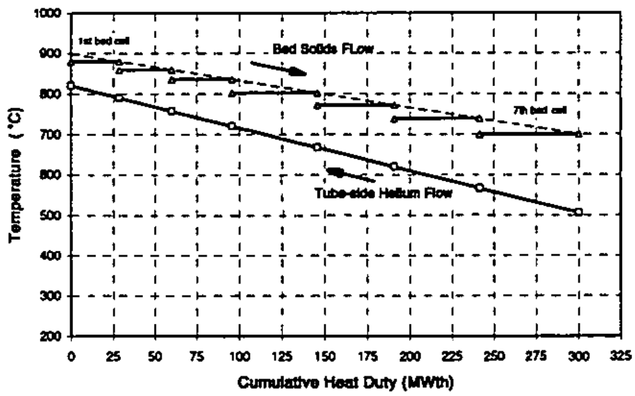


FIGURE 4: FBHX TEMPERATURE AND HEAT DUTY DISTRIBUTION PER TUBE BUNDLE

Open Cycle Gas Turbine System

The open-cycle gas turbine for the 400 MWe DBC-GT plant operates at a turbine inlet temperature of 889.0 °C (1632.2 °F) with a compressor pressure ratio of 16.8. The compressor air flow rate is 339.5 kg/s (748.5 lb/s). Compressor intercooling is used to deliver a cold air stream to enable effective recovery of turbine exhaust heat in the recuperator. It should be noted that intercooled and recuperated gas turbines are a well-established technology in both transportation and power generation.

The gas turbine for the open cycle can be chosen from any number of commercially available gas turbines without major design modification. One such machine is the ABB GT140P gas turbine developed for the 350 MWe P800 PFBC power plant. The GT140P is a twin-shaft gas turbine with compressor intercooling. Adjustable inlet guide vanes are used to control air flow rates to the combustor for part load operation. The operating conditions of the GT140P closely resemble the working conditions required by the open cycle of the 400 MWe DBC-GT plant. For smaller plants, a candidate gas turbine is the ABB GT35P, which has been used in a number of commercial PFBC demonstration plants.

Closed Cycle Gas Turbine System

The closed cycle gas turbine system is a compact, reliable, and efficient power conversion unit responsible for 75% of the total plant output. The cycle begins with the working gas being compressed sequentially in three compressor sections. Gas intercooling is provided between the compressor sections to reduce compressor power consumption. The gas discharged from the last compressor stage flows into one side of the recuperator to be heated by the turbine exhaust gas that passes through the other side of the recuperator. The preheated gas leaving the recuperator is then delivered into the FBHX heater, wherein it is heated to a final temperature of 821.1°C (1510.0°F) at a pressure of 6.8 MPa (981.9 psia). The hot gas is then directed into the turbine to drive the compressor and an electric generator. The gas exhausted from the turbine is passed into the recuperator to transfer its residual heat back to the cycle, after which it is cooled by the precooler before being fed into the compressor to start next cycle process.

Fig. 5 illustrates the performance characteristics of the recuperated and intercooled Brayton helium turbine cycle. The design point is set at the optimal cycle pressure ratio of 2.50, where cycle efficiency peaks for the turbine inlet temperature of 821.1°C (1510.0°F). Although the selected turbine inlet temperature, which is limited by the heater, is considerably lower than those encountered in combustion gas turbines, the closed cycle yields 50% generating efficiency. The key to the high efficiency is performance augmentation by cycle intercooling and recuperation, using high-effectiveness and low-pressure-loss heat exchangers. Another factor that contributes significantly to the high performance is the high aerodynamic efficiencies of the turbomachine made possible by the high Reynolds numbers and extremely low Mach numbers characteristic of helium flows. These desired conditions enhance blading efficiency and eliminate the shock losses that commonly exist in air-breathing gas turbines.

The closed cycle system of the 400 MWe DBC-GT plant is rated at 300 MWe and is based on a conventional layout of turbomachinery, recuperator, precooler, and intercooler. The system layout is shown in Fig. 6 with key dimensions to indicate the compactness of the system. The small size is mainly attributable to the closed-cycle's unique abilities to pressurize the system and to use helium rather than air as working fluid. Both the transport capacity and the thermal conductivity of helium are five times larger than those of air. This leads to high power density and small equipment size. It sbould be noted that helium is readily available at a cost negligible compared to the total operating cost of a plant.

The turbomachine is a single-shaft, axial-flow machine made up of three compressor sections and a single turbine section. The compressor has 10, 12 and 14 stages in the low-, intermediate- and high-pressure sections, and the turbine has 11 stages. The maximum tip diameter of the compressor is 1.5 m (4 ft-11 in) and that of the turbine is 1.8 m (5 ft-11 in). Because of the low gas temperatures in the turbine, the vanes and buckets throughout the turbine stages are uncooled and made of conventional alloys. The turbomachine directly drives a synchronous electric generator. Conventional radial and thrust oil bearings are used on the turbomachine and generator rotors.

The recuperator is made up of two identical, modular, units. Each unit contains a plate-fin heat exchanger based on a design widely used in gas turbine power plants. The plate-fin design offers high surface compactness and thus small unit size. The high-pressure helium greatly enhances heat transfer and minimizes pressure drop

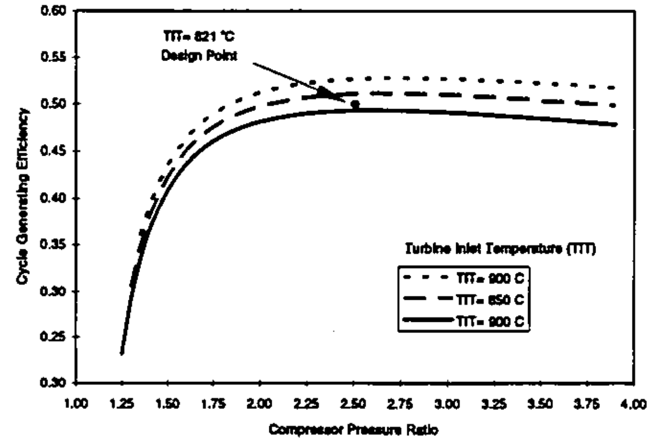


FIGURE 5: HELIUM TURBINE CYCLE CHARACTERISTICS

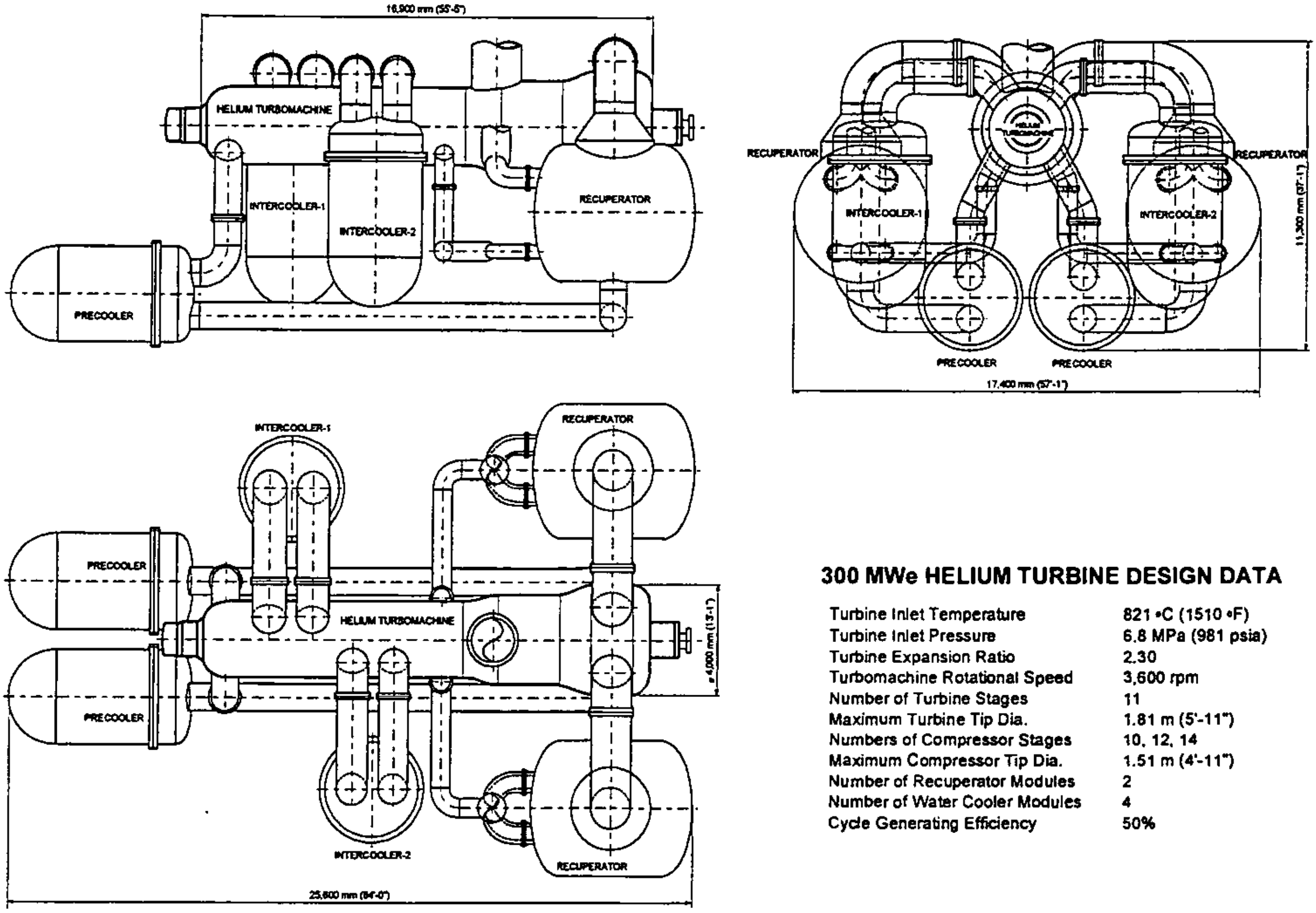
while providing an inert, non-fouling working environment compatible with the compact surface topology. The design effectiveness of the recuperator is 95% with a total pressure drop of 2.0%. The recuperator is easily designed to tolerate the anticipated number of thermal cycles and rapid transients over the plant's lifetime without scheduled maintenance.

The closed cycle system uses four modular coolers of identical design to provide heat rejection. The coolers are helium-to-water heat exchangers of tube-and-shell construction. The helium flows in the tube side in a counter-cross flow arrangement with the shell-side cooling water. Two cooler modules operating in parallel are used as a precooler to cool the inlet gas flow to the low-pressure compressor section, while the remaining two modules are each used as an intercooler to cool the inlet gas flow to the intermediate- and high-pressure compressor sections. The helium leaves the coolers at an exit temperature of 25.0 °C (77.0 °F) under the design basis ambient conditions [17.0 °C (62.6 °F) cooling water inlet temperature, 11.1 °C (52.0 °F) wet bulb ambient temperature, and 5.8 °C (10.6 °F) cooling tower approach temperature].

DBC-GT POWER PLANT PERFORMANCE

Table 1 summarizes the performance data of a 400 MWe DBC-GT power plant burning Pittsburgh No. 8 Bituminous coal with a higher heating value of 30,843 kJ/kg (13,260 Btu/lb) and a sulfur content of 2.1% (a detailed analysis of the coal is provided in Table 3). The coal and limestone are mixed into a paste and fed by paste pumps into the combustor. The coal is burned in the combustor at 898.9 °C (1650.0 °F) and 1.6 MPa (232 psia) with 10% excess air. Limestone is added at a Ca/S molar ratio of 1.3 to achieve a minimum of 90% sulfur removal. The power generated by the open cycle gas turbine is 108.3 MWe, and that by the closed cycle gas turbine is 300.8 MWe. The in-plant power consumption is only 6.4 MWe; the low in-plant power consumption is characteristic of Brayton gas turbine cycle. The net plant heat rate is 7675 Btu/kWh (HHV), equivalent to a net plant efficiency of 44.5% (HHV).

Table 2 compares the performance of the DBC-GT with those of alternative coal power generation technologies of both current and



300 MWe HELIUM TURBINE DESIGN DATA

Turbine Inlet Temperature	821 •C (1510 •F)
Turbine Inlet Pressure	6.8 MPa (981 psia)
Turbine Expansion Ratio	2.30
Turbomachine Rotational Speed	3,600 rpm
Number of Turbine Stages	11
Maximum Turbine Tip Dia.	1.81 m (5'-11")
Numbers of Compressor Stages	10, 12, 14
Maximum Compressor Tip Dia.	1.51 m (4'-11")
Number of Recuperator Modules	2
Number of Water Cooler Modules	4
Cycle Generating Efficiency	50%

FIGURE 6: HELIUM TURBINE SYSTEM FOR 400 MWe DBC-GT POWER PLANT

advanced designs. The potential ranges of efficiencies and economically practical plant sizes are listed for each technology. In contrast to the alternative systems, the DBC-GT allows high efficiency without system complexity and its resulting high costs of construction and operation. Because of simplicity in design and operation and because gas turbine cycles are not sensitive to scale size, the DBC-GT is able to function economically over a wide range of plant sizes. It is possible to further augment the efficiency in the advanced DBC-GT designs by employing a "topping combustor" to raise turbine inlet temperature and by using other design enhancement to permit efficiencies up to 48% (HHV). These advanced designs provide long-term growth potential for the DBC-GT.

PERFORMANCE SENSITIVITY TO ALTERNATE COALS

The base coal for the foregoing DBC-GT performance data is a medium-sulfur, low-moisture Pittsburgh No. 8 bituminous coal. The effects of using alternate coals and feeding methods were studied for a 400 MWe DBC-GT plant. The two alternate coals studied were a high-sulfur, medium-moisture Illinois No. 6 bituminous coal and a low-sulfur, high-moisture Western subbituminous coal. These coals represent a wide spectrum of coals used in commercial power generation. Detailed analyses of these coals are provided in Table 3.

Each coal was studied under four alternate feeding methods:

- Paste feed of coal as-received
- Paste feed of coal, after 50% moisture depletion of coal feedstock
- Pneumatic feed of coal as-received
- Pneumatic feed of coal, after 50% moisture depletion of coal feedstock

In paste feed, water is mixed with coal and limestone to form a paste which is then injected into the combustor by paste pumps. According to the typical requirements of paste pumping systems, the amount of water added for making the paste is assumed to be 18% by weight of the final paste for all three coals. This results in a total water content in the paste of about 22% for the Pittsburgh bituminous coal, 27% for the Illinois bituminous coal, and 43% for the Western

TABLE 1: DBC-GT POWER PLANT PERFORMANCE

Combustor Firing Rate (HHV)	MWt (10^6Btu/hr)	905.6 (3090.1)
Combustion Temperature	°C (°F)	898.9 (1650.0)
Combustion Pressure	MPa (psia)	1.6 (232.0)
Combustion Air	kg/s (lb/s)	327.7 (722.5)
Excess Air	%	10.0
Coal Feed (Pittsburgh No. 8 Bitum.)	kg/hr (lb/hr)	105,706 (233,037)
Limestone Feed	kg/hr (lb/hr)	9,026 (19,898)
Ca/S Molar Ratio		1.3
Minimum Sulfur Retention	%	90.0
Total Ash Discharge	kg/hr (lb/hr)	18,548 (40,891)
Stack Gas Flow	kg/s (lb/s)	373.2 (822.7)
Stack Temperature	°C (°F)	242.5 (468.5)
Open-Cycle Gas Turbine Output	MWe	108.3
Closed-Cycle Gas Turbine Output	MWe	300.8
Gross Plant Output	MWe	409.1
In-Plant Power Consumption	MWe	6.4
Net Plant Output	MWe	402.7
Net Plant Heat Rate (HHV)	Btu/kWh	7675
Net Plant Efficiency (HHV)	%	44.5

subbituminous coal. In pneumatic feed, a transport air compressor and lock hopper system is utilized to feed coal and limestone. For depletion of coal moisture when appropriate, the waste heat of stack flue gas is used to dry the coal feedstock, without need for consuming additional fuel. The stack gas from the DBC-GT still contains sensible heat at a temperature of around 243 °C (469 °F), which could be utilized in many ways, including drying the feedstock, without adverse effect on power generation.

Fig. 7 displays the performance sensitivity of the nominal 400 MWe plant to alternate coals and feeding methods. As seen, the performance is closely affected by the higher heating values, which are largely related to the moisture contents, of the coals and by their sulfur and ash contents. These properties affect solids handling duties for feedstock (coal and limestone) and in ash disposal. For example, the plant using the Illinois coal involves 38% more feedstock flow and 150% greater ash disposal than the one using the Pittsburgh coal. A higher moisture content incurs a larger latent heat loss from water evaporation during combustion and thus lowers the thermal efficiency.

Using pneumatic feed, instead of paste feed, for all three coals leads to a significant improvement of plant efficiency, as it avoids the large heat loss from evaporation of the water added in making paste, and also reduces the mass flow with attendant loss of stack heat.

The incentive for drying coal is greatest for the high-moisture Western subbituminous coal, as seen in Fig. 7. When this coal is depleted of 50% of the coal-bound moisture, the net plant efficiency is increased by approximately 1% for both paste and pneumatic feed cases. The ability of the DBC-GT to achieve efficient power generation with low quality coals is an attractive design feature.

ENVIRONMENTAL IMPACT

The DBC-GT offers outstanding environmental performance. The plant exceeds present emission requirements by large margins. In fact, it is capable of achieving emission levels low enough to permit installation in or near urban areas.

TABLE 2: PERFORMANCE COMPARISON OF COAL POWER GENERATION TECHNOLOGIES

Coal Technologies	Efficiency (% HHV)	Economic Sizes (MWe)
PC&AFBC Steam Cycle		
1800 psia/1000/1000 °F	35-36	100-200
2400 psia/1000/1000 °F	36-38	200-300
3500 psia/1000/1000 °F	38-39	300-500
1st Generation PFBC-CC	38-40	100-400
2nd Generation PFBC-CC	42-45	300-500
IGCC w/ HGCU	41-44	200-400
DBC-GT	**43-45**	**100-400**
Advanced DBC-GT	**46-48**	**400-600**

The first direct benefit of the plant's high efficiency is low specific CO_2 discharge. Second, the clean burning capabilities of the CPFBC ensure low stack emissions of pollutants. Combustion in the CPFBC takes place at low temperature with staged combustion air, which typically limits the total NO_x emissions to less than 50 ppm. To control SO_2 emission, limestone is added during combustion to react with coal-bound sulfur to allow 90-95% sulfur capture at efficient limestone utilization. Finally, the filtration of flue gas by ceramic filters ensures dust concentration in the stack below 10 ppm.

TABLE 3: ANALYSES OF ALTERNATE COALS

		Pittsburgh No. 8 Bitum.	Illinois No.6 Bitum.	Western Subbitum.
Proximate Analysis				
Moisture	%	5.2	12.0	30.4
Ash	%	7.1	16.0	6.4
Volatile	%	36.7	33.0	31.1
Fixed Carbon	%	51.0	39.0	32.1
Higher Heating Value (HHV)	kJ/kg	30,843	23,493	18,655
	Btu/lb	13,260	10,100	8,020
Ultimate Analysis				
C	%	73.8	57.5	47.9
H	%	4.9	3.7	3.4
N	%	1.4	0.9	0.6
S	%	2.1	4.0	0.5
O	%	5.5	5.8	10.8
H2O	%	5.2	12.0	30.4
Ash	%	7.1	16.1	6.4
Coal Ash Analysis (dry)				
Phosphate Pentoxide, P2O5	%	0.4	0.2	0.8
Silica, SiO2	%	55.2	45.0	31.6
Ferric Oxide, Fe2O3	%	9.3	20.0	4.6
Alumina, Al2O3	%	24.8	18.0	15.3
Titanium Oxide, TiO2	%	1.2	1.0	1.1
Calcium Oxide, CaO	%	3.0	7.0	22.8
Magnesia, MgO	%	0.9	1.0	4.7
Sulfur Trioxide, SO3	%	2.3	3.5	16.6
Potassium Oxide, K2O	%	2.1	1.9	0.4
Sodium Oxide, Na2O	%	0.8	0.6	1.3
Undetermined		0.0	1.8	0.8

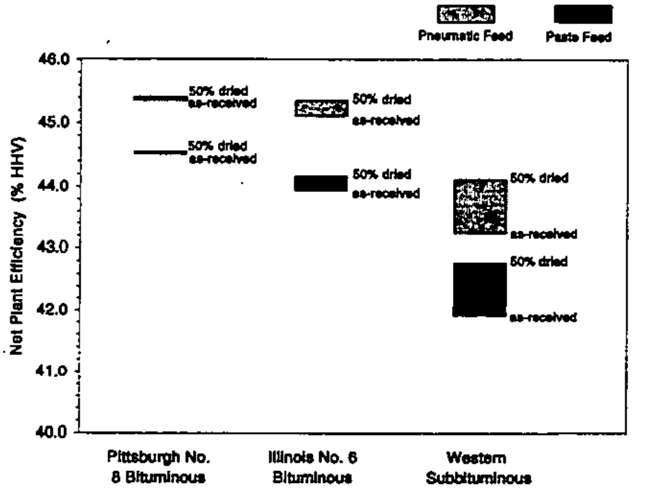


FIGURE 7: PERFORMANCE SENSITIVITY TO ALTERNATE COALS AND FEEDS

TABLE 4: EMISSION PERFORMANCE OF 400 MWe DBC-GT*

Emissions	Pittsburgh No. 8 Bituminous	Illinois No. 6 Bituminous	Western Subbituminous
SO_2			
ppmv	159	361	54
gram/MJ (lb/10^6 Btu)	0.143 (0.331)	0.340 (0.791)	0.054 (0.125)
tonne/year (ton/year)	2645.6 (2916.2)	6315.2 (6961.2)	994.1 (1095.8)
NOx			
ppmv	48	48	48
gram/MJ (lb/10^6 Btu)	0.031 (0.072)	0.033 (0.076)	0.035 (0.081)
tonne/year (ton/year)	577.5 (636.6)	607.5 (669.6)	643.0 (708.7)
CO			
ppmv	24	24	24
gram/MJ (lb/10^6 Btu)	0.009 (0.022)	0.010 (0.023)	0.011 (0.025)
tonne/year (ton/year)	175.8 (193.8)	184.9 (203.8)	195.7 (215.8)
Particulates			
ppmw	10	10	10
gram/MJ (lb/10^6 Btu)	0.004 (0.009)	0.004 (0.010)	0.004 (0.010)
tonne/year (ton/year)	74.1 (81.7)	77.3 (85.2)	80.3 (88.5)

* based on coal HHV and at 65% capacity factor where applicable

Table 4 details the estimated atmospheric emissions from a 400 MWe DBC-GT plant for the three representative coals.

The Dual Brayton Cycle eases the requirements of plant waste heat rejection. The high cycle thermal efficiency minimizes waste heat rejection from the plant. Furthermore, the cycle rejects the waste heat over a broad high temperature range. As a result, the DBC-GT requires about half the circulating cooling water flow needed in a comparable combined-cycle plant, and employs correspondingly smaller circulating circuits and cooling towers. The high temperature heat rejection also makes dry (air) cooling feasible at those sites where cooling water resources are limited.

COMMERCIALIZATION

All of the technologies required by the DBC-GT are accessible for near-term commercialization. The CPFBC is a current-state-of-the-art technology that is being commercially developed and demonstrated by industries and government-sponsored projects throughout the world (Moore 1993). A number of vendors are championing this technology, which is expected to enter the coal power generation market in the near future.

The open-cycle gas turbine required by the DBC-GT can be selected from several existing machines, some of which are already in operation in commercial PFBC power plants. The closed-cycle gas turbine is a proven, although relatively underutilized, technology. More than 20 closed-cycle gas turbine plants have been built and operated worldwide (Bammert 1975; Zenker 1988). Recent technological advances in industrial and aircraft gas turbines, and modern numerical modeling techniques have provided the opportunity to substantially improve existing closed-cycle gas turbine technology. The development of closed-cycle helium turbine technology in recent years has had the benefit of extensive studies by the U.S. Department of Energy, electric utilities and industry (U.S. DOE, 1994).

Development of a prototype plant, in an optimal size range of 100-200 MWe, would be the first step in commercial deployment. The prototype plant will provide the design basis and operational experience necessary for scale-up to larger sizes. In addition, the prototype plant is itself in a size range of commercial interest in many parts of the world.

Nearly 600 GWe of new electrical generating capacity addition is planned worldwide for the 1990s and the same or greater power addition is anticipated for the first decade of the next century. Coal, the most abundant and reliable fossil fuel in the world, is predicted to be the choice of fuel for about 50% of worldwide power plant additions, at an average rate of 70 GWe per year over the next 10 to 20 years. Timely and successful development of the DBC-GT would make the technology well positioned to respond the growing electric power demands worldwide. The simplicity, low cost, high efficiency and sound environmental performance of the DBC-GT should make the technology an attractive option in power generating markets.

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