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Externally-Fired Combined Cycle: An Effective Coal Fueled Technology for Repowering and New Generation

Authors:

Larry E. Stoddard
Kenneth M. Gray
Mohammad R. Bary
Paul G. LaHaye

Contractor:

Black and Veatch
8400 Ward Parkway
P.O. Box 8405
Kansas City, Missouri 64114

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Larry E. Stoddard
Black & Veatch
P.O. Box 8405
Kansas City, MO 64114
913-339-7225
913-339-2934 fax

Kenneth M. Gray
Pennsylvania Electric Company
1001 Broad Street
Johnstown, PA 15907
814-533-8044
814-533-8108 fax

Mohammad R. Bary
Black & Veatch
P.O. Box 8405
Kansas City, MO 64114
913-339-7842
913-339-2934 fax

Paul G. LaHaye
Hague International
3 Adams Street
South Portland, ME 04106
207-799-7346
207-799-6743 fax

ABSTRACT

The Externally-Fired Combined Cycle (EFCC) is an attractive emerging technology for powering high efficiency combined gas and steam turbine cycles with coal or other ash bearing fuels. In the EFCC, the heat input to a gas turbine is supplied indirectly through a ceramic air heater. The air heater, along with an atmospheric coal combustor and ancillary equipment, replaces the conventional gas turbine combustor. A steam generator located downstream from the ceramic air heater and steam turbine cycle, along with an exhaust cleanup system, completes the combined cycle.

A key element of the EFCC Development Program, the 25 MMBtu/h heat-input Kennebunk Test Facility (KTF), has recently begun operation. The KTF has been operating with natural gas and will begin operating with coal in early 1995.

The US Department of Energy selected an EFCC repowering of the Pennsylvania Electric Company's Warren Station for funding under the Clean Coal Technology Program Round V. The project focuses on repowering an existing 48 MW (gross) steam turbine with an EFCC power island incorporating a 30 MW gas turbine, for a gross power output of 78 MW and a net output of 72 MW. The net plant heat rate will be decreased by approximately 30 percent to below 9700 Btu/kWh. Use of a dry scrubber and fabric filter will reduce sulfur dioxide (SO_2) and particulate emissions to levels under those required by the Clean Air Act Amendments (CAAA) of 1990. Nitrogen oxides (NO_x) emissions are controlled by the use of staged combustion. The demonstration project is currently in the engineering phase, with startup scheduled for 1997.

The anticipated near-term market for the EFCC is repowering of existing coal fueled power generation units. Repowering with an EFCC system offers utilities the ability to match existing steam conditions and improve the efficiency of existing plants by 30 to 50 percent, while reducing NO_x and carbon dioxide on a per megawatt (MW) basis. Furthermore, the EFCC concept does not require complex chemical processes, and is therefore compatible with existing utility operating methods and experience.

The long-term market for EFCC includes new power generation facilities using advanced combustion turbines in combined cycle operation. A conceptual design of a greenfield 300 MW EFCC plant has been developed. The facility has a net plant heat rate on a higher heating value (HHV) basis of less than 7000 Btu/kWh (over 49 percent efficiency), with very low SO_2, NO_x, and particulate emissions. The plant exhibits a highly competitive cost of energy.

EFCC Description

The Externally Fired Combined Cycle (EFCC) is an emerging technology for indirectly firing a gas turbine with coal or other ash bearing fuels. The EFCC concept offers power generators a highly efficient, cost-effective technology for repowering existing plants and for new capacity additions. EFCC plants are relatively simple in concept for design, construction, and operation, compared with other emerging technologies because most components are similar to those used in conventional power plants.

The EFCC Development Program is a cost-shared program between the US Department of Energy (DOE) Morgantown Energy Technology Center and a consortium of US and foreign utilities, industry, and state agencies. The EFCC Consortium is led by Hague International.

In the EFCC concept, shown on Figure 1, fuel is burned in an atmospheric combustor. The hot flue gas flows through a slag screen, which removes ash particles greater than 12 microns in size which might foul the air heater. The flue gas flows into a ceramic air heater, in which air from the gas turbine compressor is heated to turbine inlet temperature. After expansion through the gas turbine, the exhausted air flows to the combustor where it is used as combustion air.

Flue gas exiting the air heater flows to a heat recovery steam generator (HRSG), where steam for the bottoming cycle is generated. In some designs, the HRSG and the combustor are combined into an integrated steam generator (ISG). After flowing through the HRSG, the flue gas passes through flue gas desulfurization (FGD) and particulate removal systems before stack discharge.

The high efficiency of the EFCC concept offers significant potential in both new generation and repowering applications. In near-term new plant applications, this efficiency will exceed 45 percent (with heat rates less than 7,580 Btu/kWh) on an HHV basis. In the long-term, the EFCC has the potential to exceed efficiencies of 49 percent (heat rates less than 7,000 Btu/kWh). Furthermore, unlike other emerging coal fueled combined cycle technologies, the EFCC expands clean air rather than combustion gases through the gas turbine, increasing the service life of the turbine gas path. With existing FGD systems, sulfur emissions are maintained within regulatory requirements.

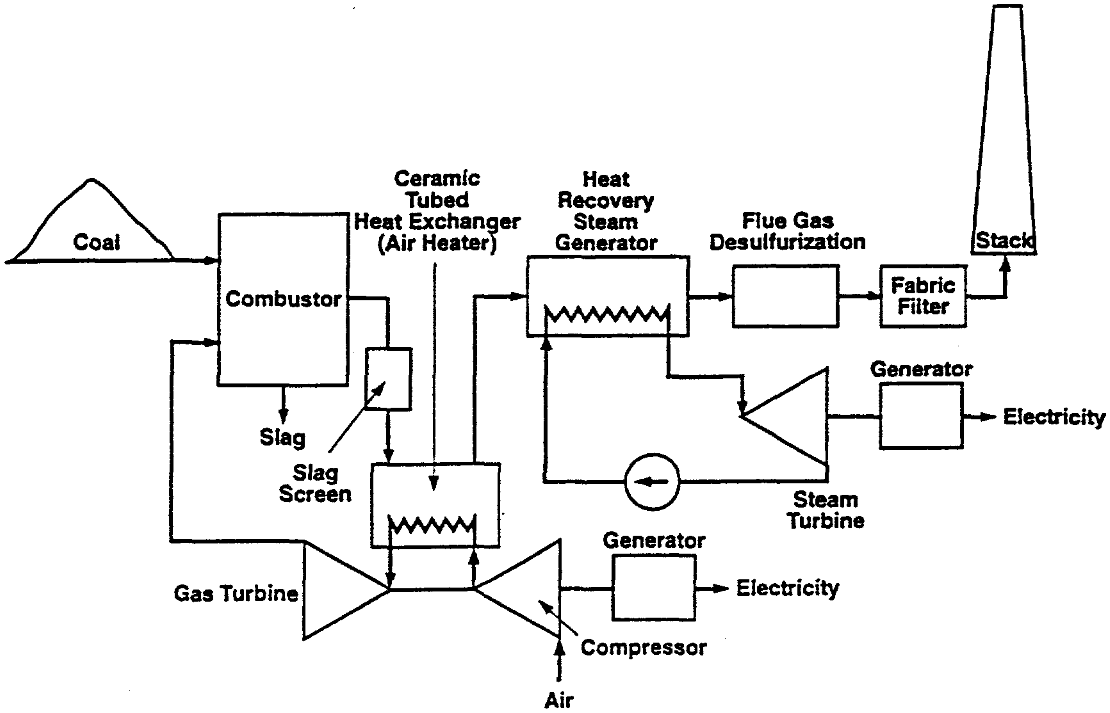

Figure 1. The Externally Fired Combined Cycle Concept

This paper discusses the background of the EFCC, the Kennebunk Test Facility (KTF), the Warren Station EFCC Clean Coal Technology Demonstration Project, the commercial plant concept, and the market potential for the EFCC.

EFCC BACKGROUND

Indirect fired gas turbine power plants have been studied since the 1930s, as summarized by Keller[1] in 1946. Applications of low rank coal and peat fired air heaters were reported by Keller and Gaehler.[2] In the 1950s, a 500 kW closed-cycle gas turbine with a peat fired, metallic air heater was built and successfully operated. This led to the installation of several cogeneration facilities which performed reliably. In 1950, Mordell[3] reported experimental studies at McGill University in Montreal, Canada, which showed promising results for an open cycle, indirect fired gas turbine, the predecessor to the EFCC. However, metallic air heaters used in these earlier versions of the cycle did not allow sufficiently high turbine inlet temperatures for economic power production.

During the 1960s, use of a ceramic air heater in indirect fired combined cycle applications was studied in concept, as summarized by LaHaye.[4] In 1971, Hague began a series of experiments with ceramic materials that culminated in the construction of the first ceramic air heater. Most of the work during this period was on heat recovery equipment (recuperators) for the secondary metals industry. By the early 1980s, about 50 low-pressure Hague units were in operation. These units have accumulated over 3 million hours of successful operation in corrosive, high-temperature, industrial environments.

In the early 1980s, Hague initiated work to increase the pressure capability of the ceramic air heater. In 1987, the USDOE and the EFCC Consortium, a consortium of electric utilities and industrial organizations, began to further pursue the concept.

Phase I of the EFCC development program was summarized by LaHaye and Zabolotny.[5] A low-pressure ceramic air heater was exposed to the products of combustion of a coal/water slurry over intervals of up to 40 hours. Ash buildup occurred on the air heater tubes, indicating the need for an upstream ash collection system. However, the ceramic tubes exhibited good mechanical durability and corrosion-resistance under all test conditions, and a method was devised to alleviate and remove ash deposits on the ceramic air heater heat transfer surface. Phase I was deemed a success by the Consortium members and a decision was made to proceed with Phase II.

Phase II of the EFCC development program, discussed by Vandervort et al.[6,7], began in 1988. This ongoing program has included high temperature and pressure tests of single tube strings, ceramic coupon corrosion and erosion tests, and tube material development. Successful testing of air heater components led to the final activity of Phase II, system testing at the Kennebunk Test Facility.

KENNEBUNK TEST FACILITY

The Kennebunk Test Facility (KTF), located in Kennebunk, Maine, is the first completely integrated system test of the EFCC technology. The KTF, which is shown conceptually on Figure 2, comprises a coal handling system, a 25 MMBtu/h heat input combustor, slag screen, three-pass high pressure air heater, 500 kW gas turbine, and a heat rejection system for waste heat, plus controls and ancillary equipment.

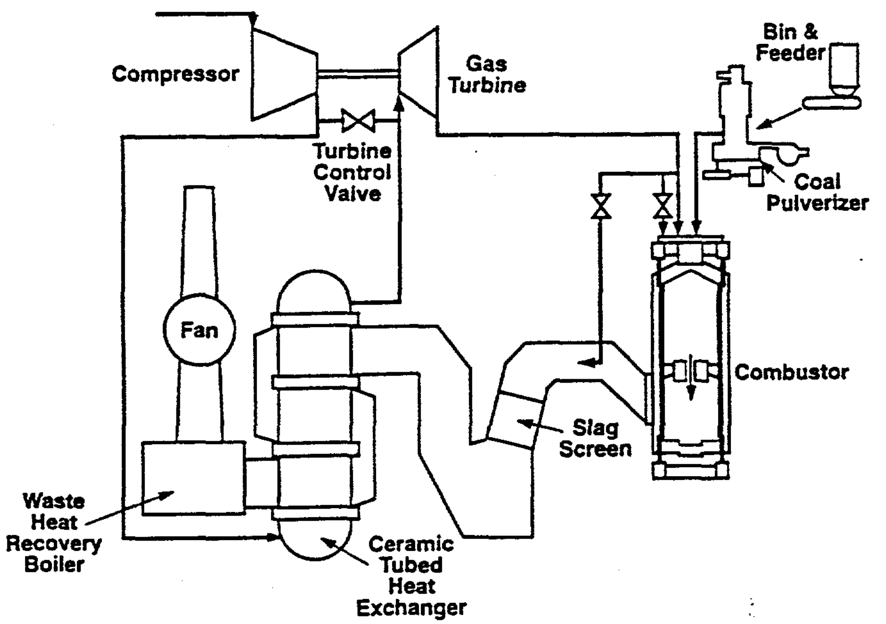

Figure 2. Kennebunk Test Facility

Combustor

The KTF is equipped with a low-pressure drop, air-cooled, staged combustor, shown on Figure 3. Staging is used for NO_x reduction. The combustor unit is down-fired into two cylindrical combustion chambers with the primary stage directly atop the second stage. The total height of the combustor, including the burner, is approximately 40 feet, and the outer diameter of the cylindrical casing is nominally 11 feet. Approximately 2/3 of the total volume is provided for the first stage, with the remaining 1/3 for the second stage. A collar divides the first zone from the second, and also provides convenient ports for the second stage combustor air. A cooling air annulus is built into the furnace insulating refractory. A slag tap is located at the base of the combustor.

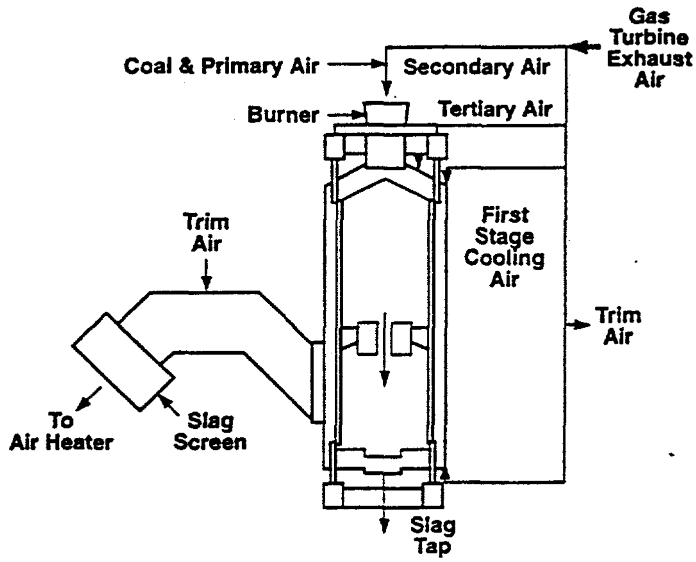

Figure 3. Kennebunk Test Facility Combustor

Screen

The slag screen consists of a staggered array of refractory tubes acting as an impact separator. A slag screen has been built and installed at KTF. Performance of the slag screen will be verified during KTF testing in 1995.

Ceramic Air Heater

The ceramic air heater designed for KTF is a three-pass shell-and-tube heat exchanger. A conceptual illustration of a three pass air heater is shown on Figure 4. The air heater has 72 vertically-oriented tube-strings for a total of 216 tubes. Tubes are supported vertically in compression, with the compressive forces developed by a spring-pack and bellows assembly on the cold end of the tube-string.

Ceramic air heater components being tested at KTF will permit air heater exit temperatures to approximately 1,810° F. However, to meet the goals of this program by the year 2000, a component optimization effort, focused on increasing the temperature capabilities of the ceramic components that comprise the air heater, will be performed as part of the future EFCC development program.

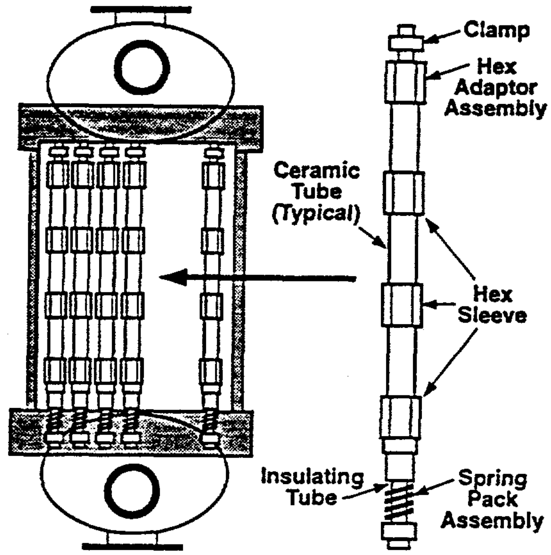

Figure 4. Air Heater Tube String Arrangement

Gas Turbine and High Pressure Piping System

The gas turbine at the KTF is a 500 kW Garrett Model IM831. The KTF air heater has a capacity to power a larger gas turbine; the 500 kW turbine was selected on the basis of availability to the project. As with most gas turbines used for indirect firing, the Garrett machine requires modifications for indirect firing. The conventional gas fueled combustor and associated fuel control system has been removed and replaced by a ceramic air heater fired by an external atmospheric coal combustor. The interface with the air heater requires a double-walled section of piping. The compressor discharge air flows to the air heater in the outer annular area, and the air heated in the air heater returns to the turbine section through the pipe section. The outer piping is fabricated from conventional metal materials and the inner liner from a fiber-reinforced ceramic material.

A turbine control valve system offers a key control of turbine output power. This system allows a portion of the compressor discharge air to bypass the ceramic air heater and mix with the hot discharge air to control the turbine inlet temperature. In this way, the ceramic air heater can be maintained as a nearly constant temperature heat reservoir, and gas turbine load variations are accommodated by control of the bypass flow. As the long-term heat duty of the exchanger varies, the gas inlet temperature can be modulated by regulating the coal firing rate and the combustion air.

Progress at the KTF

The KTF was fired in November 1994 with natural gas and with only metal tubes in the air heater, achieving an output of 300 kW. In February 1995, six metal tubes in the first pass were replaced with ceramic tubes. Firing with a mixture of natural gas and coal is planned for February. Initially, this cofiring will take place with six ceramic tubes in the first pass, and the remaining tubes being metal. The ratio of coal to natural gas will be increased and two full passes of ceramic tubes installed, leading to full firing of the KTF on coal by mid-April. The current goal is to operate KTF for a minimum of 100 hours of continuous operation and to accumulate a total of 300 hours of operation by May 1995. The KTF equipment is extensively instrumented to verify thermal performance, air heater pressure integrity, materials integrity, etc. Fouling or ash buildup will be monitored by video cameras, pressure drop measurements, and post-test evaluations.

WARREN STATION EFCC DEMONSTRATION PROJECT

The Warren Station EFCC Demonstration project, one of five projects selected by the USDOE in May 1993 under Clean Coal Technology Demonstration Program Round V, will repower the Pennsylvania Electric Company's (Penelec's) Warren Station Unit 2 with an EFCC unit. The repowered plant, which is expected to begin operation in 1997, will include a new combustor and HRSG (which are combined in an ISG), slag screen, ceramic air heater, gas turbine, scrubber, baghouse, interconnecting ductwork, and associated auxiliaries. The project team includes Penelec, Black & Veatch (B&V), and Hague International.

The Warren Station, shown on Figure 5, is in northwestern Pennsylvania, 2 miles west of the city of Warren, on the Allegheny River. Warren Station Units 1 and 2 began operation in 1948 and 1949, respectively. The station has four Erie City pulverized coal fueled boilers, each of which produces 225,000 lb/h steam at 875 psig and 885° F. Two Westinghouse steam turbine-generators, each rated at 48 MW, are in service. The units share a common stack, coal handling system, and circulating water system, which will continue to be shared by the repowered unit. The station is in good condition; repowering with EFCC will enable the station to produce energy at a competitive cost while complying with the 1990 CAAA.

The Warren EFCC unit will burn about 26 tons of pulverized bituminous coal per hour in a staged, atmospheric combustor. The combustor, which will be about 85 feet tall and 25 feet in diameter, is designed to reduce NO_x levels to 0.13 lb/MMBtu, well below New Source Performance Standard (NSPS) limits.

Hot flue gases will flow through a slag screen which removes ash particles greater than 12 microns in size. The gas will flow to a four-pass air heater comprising ceramic and metal tubes. The heat exchanger will be approximately 88 feet tall, 27 feet wide, and 8 feet deep. The exit air temperature will be 1,800° F.

Hot air from the air heater will power a 30 MW gas turbine which has been modified for indirect firing. Exhaust air from the gas turbine is used as combustion air in the combustor.

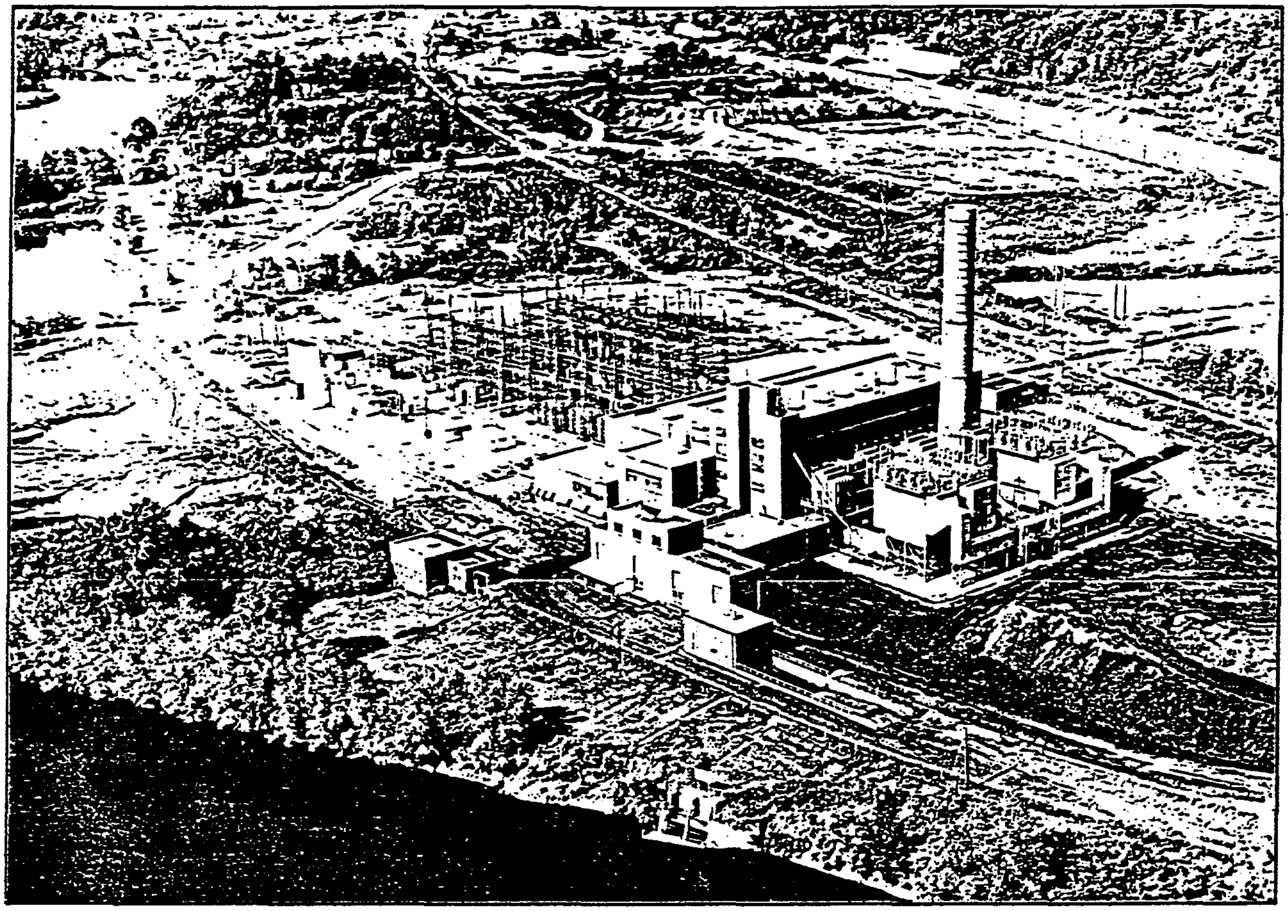

Figure 5. Existing Warren Station

Hot flue gas will exit the air heater and pass through the heat recovery portion of the ISG, which replaces two of the existing pulverized coal boilers. Steam from the ISG powers the existing Unit 2 steam turbine, producing 48 MW (gross). Flue gas exiting the ISG will be cleaned in a dry spray scrubber and baghouse system, reducing SO_2 by 80 percent and particulate to below 0.003 lb/MMBtu.

The projected capacity of the repowered Unit 2 is 78 MW gross (72 MW net), an increase of about 50 percent over that of the existing facility. The Unit 2 heat rate will significantly improve to below 9700 Btu/kWh which, in turn, will increase the dispatchability of the unit. The unit will exhibit very good part-load performance.

Phase I, Project Definition, activities to date include conceptual design, permitting, and work to obtain approvals associated with the National Environmental Policy Act. Detailed design and procurement are scheduled to start in June 1995, with initial construction to begin before the end of 1995.

The Warren EFCC Demonstration Project was reported in more detail in 1994 by Gray, et al.[8]

NEAR-TERM EFCC MARKET

The near-term domestic market for EFCC is likely to be repowering. The US has over 200 coal fueled power units in the range of 30 to 100 MW which are over 30 years old. Efficiencies of these plants range from 23 to 33 percent, with an average of 27 percent. Added to the coal fueled steam plants above 100 MW that are over 30 years old, the total exceeds 500 units. All of these are or will become candidates for repowering using the EFCC technology by 2010. The EFCC technology is particularly well suited to repowering these aging power plants for the following reasons:

- The cycle will boost the efficiency of the existing coal or oil fired units, increasing their dispatchability.
- The topping gas turbine with the steam generator sections can be tailored to match the steam conditions of virtually any of the candidate steam plants.
- Conventional flue gas cleaning systems can be employed, including wet or dry SO_2 scrubbers, fabric filters, or electrostatic precipitators. More advanced stack gas scrubbing and air toxic removal technologies can be used when they become commercially available.
- The dramatic improvement in fuel conversion efficiency reduces CO_2 emissions on a per MW basis.
- The coal currently in use, frequently from area mines, can continue to be used without beneficiation, maintaining a competitive cost with other energy sources.
- The concept remains competitive with other emerging technologies in the 50 to 100 MW range in terms of capital, maintenance, and operating costs.
- The EFCC technology offers an excellent opportunity for existing power generation sites to be used to generate power efficiently, avoiding the requirement of siting new plants.
- The EFCC plant is quite similar in concept to existing power plants and does not add new or complex chemical processes. Operators of existing utility plants can be easily trained for EFCC operation.

LONG-TERM EFCC MARKET

The long-term market for EFCC will include new coal fueled plants, both domestically and internationally. The domestic market for new baseload power generation remains small, with gas fueled generation capturing most of that market. The domestic market is expected to expand in the late 1990s as the current capacity surplus shrinks and existing plants age and retire. With likely increases in gas price, coal fueled plants will capture a larger share of the market with high efficiency, low emissions coal plants having a particular advantage. Because the worldwide growth of power generating capacity is four to five times that of the US, a significant international market potential is available for EFCC.

New EFCC plants will be extremely efficient. In 1992, Vandervort and Orozco[9] reported an EFCC design concept for such a plant. This design was based on the ceramic air heater providing 2,180° F air to a General Electric MS7001F gas turbine, resulting in a net plant efficiency of 44 percent (heat rate of 7,800 Btu/kWh on an HHV basis). The design at 2,180° F turbine inlet temperature is a conservative step in ceramic air heater development from the current KTF tests and the Warren Station design at 1,800° F air heater outlet temperature toward a mid-term goal of 2,300° F operation and a long-term goal of 2,500° F operation.

A conceptual design of an advanced, very high temperature, high efficiency, low emissions EFCC commercial plant was developed in early 1994 by Hague International and B&V, working with Manufacturing and Technology Conversion International (MTCI), Westinghouse, and Environmental Elements Corporation (EEC). This design requires significant developments in ceramic tube technology, beyond that currently available. The design is based on a Westinghouse 501G gas turbine, with an inlet temperature of 2,500° F. Sulfur removal is accomplished by sorbent injection in the combustor coupled with a backend dry scrubber, with the backend scrubber using carryover sorbent from the combustor. In addition to sulfur removal, the scrubber uses injected activated charcoal for mercury adsorption. The scrubber also serves as a conditioner for the electrostatic precipitator. NO_x reduction is accomplished through staged combustion in the combustor and through the use of a selective catalytic reduction unit in the HRSG.

Projected performance for the plant includes a net combined cycle plant capacity of 310 MW. At 100 percent load, the EFCC facility has a net plant efficiency exceeding 49 percent (7,000 Btu/kWh) on a higher heating value (HHV) basis. This is significantly higher than the efficiency of conventional pulverized coal plants (typically about 34 percent). This efficiency is also higher than efficiencies for integrated gasification combined cycle systems, which are typically in the 40 to 43 percent range. The EFCC plant exhibits good part-load characteristics.

Projected plant SO_2 and NO_x emissions are less than a quarter of the levels allowed by today's New Source Performance Standards. Removal of expected trace toxic heavy metals, excluding mercury, will exceed 99 percent. Expected mercury removal, including elemental mercury, will range from 90 to 95 percent.

CONCLUSIONS

The Externally-Fired Combined Cycle is an attractive emerging technology for powering high efficiency combined gas and steam turbine cycles with coal or other ash bearing fuels. Development of the technology continues with the startup of the Kennebunk Test Facility, leading to large scale demonstration at the Penelec Warren Station. Near-term commercialization will most likely focus on repowering applications, with long-term applications being very high efficiency, very clean new plants.

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