ABSTRACT

A long term program was initiated in 1987 to develop an electric utility indirect coal-fired gas turbine combined cycle. This initial program was supported primarily by U.S. electric utility organizations and had as its purpose the experimental assessment of a ceramic heat exchanger concept applied as a high pressure gas turbine air heater developed by Hague International.

The purpose of the initial phase of the development program was to determine if the ceramic materials, then available for use in the air heater, would withstand the high temperature 2200 °F (1204 °C) corrosive environment produced by the combustion of coal. Also, in this initial phase, the program was intended to evaluate means of preventing the fouling of the air heater by fly ash. This experimental work was successful. A second phase of the program to build a 7-MW thermal input prototype was initiated in 1990 under the auspices of a cooperative agreement with the U.S. Department of Energy Morgantown Energy Technology Center (DOE-METC). This work was funded by a consortium of electric utilities, utility organizations, industrial organizations, state agencies, international entities, and the U.S. Department of Energy-METC. New members joined the existing Phase I Consortium to participate in funding the second phase. This second prototype phase is nearing completion and test results are to be available beginning mid-1994.

A third, or demonstration phase, of the indirect-fired gas turbine program was selected under the U.S. Clean Coal Technology Program Round V, in May, 1993. This demonstration phase is currently in the planning and preliminary engineering stage. The objective of this proposed demonstration phase is to repower an existing coal-fired power plant in Pennsylvania Electric Company system at Warren, Pennsylvania (Figure 1). This paper describes the demonstration plant, and the anticipated role of the EFCC cycle in the power generation industry, as well as the performance and economic merits of the Warren repowering concept.

INTRODUCTION

Using the cost of generating power as a basis, the competition for the power generation market during the latter part of this century and early in the Twenty First Century is expected to be between natural gas-fired combined cycles, sub-critical pulverized coal-fired Rankine Cycles, and what could be considered a combination of the two, the externally fired combined cycle or EFCC. Super-critical PC-fired Rankine Cycles are expected to be a major factor as the fuel costs increase to approximately double the present levels in larger plant sizes.

The low first cost and the low O&M costs of natural gas-fired combined cycles are expected to keep this solution the most competitive wherever natural gas is available. This is with the provision that when fuel costs increase, natural gas remains in its current juxtaposition to the other fuels, particularly coal. This would exclude temporary "spikes" in the cost of the natural gas caused by international political events.

To alter the advantages presently enjoyed by gas-fired combined cycles and increase coal's market share in power generation, the first cost of emerging technologies such as integrated gasification combined cycles (IGCC) and pressurized fluidized bed cycles (PFBC) would have to be reduced by over 20 percent. EFCC may be an exception to this, initially as a repowering solution, and eventually for new or "green-field" installations. This paper addresses the initial, or repowering, phase in the evolution of this power plant concept. Repowering is an attractive initial market segment because there are an estimated 500 potential coal-fired steam installations that are candidates for repowering in the United States.
The environmental advantages of one fossil fuel over another should gradually disappear as the scrubbing equipment improves and better waste disposal means are developed for ash. If dramatic improvements are made with hot gas clean-up methods and costs are reduced substantially, the IGCC and PFBC plants would be more competitive and, as a consequence, capture a larger portion of the new...
coal-fired power generation equipment market. For this to happen, a commercially viable hot gas clean-up system is needed that satisfies the stringent demands of high performance gas turbines for a contaminant free fuel. When such a “hot gas” clean-up system will be commercially viable is not known at this time.

The EFCC has the potential of being a lower first cost, lower heat rate solution than either IGCC or PFBC for both “greenfield” and repowering applications. This cycle has been under sustained development for four (4) years and is now in the “proof-of-concept” phase. Current work is being performed by Hague International at its Kennebunk Test Facility (KFF), in Kennebunk, Maine. The Kennebunk prototype facility is scheduled to complete initial coal-fired tests during mid-1994.

A proposal was submitted to the United States Department of Energy in December 1992 under the Clean Coal Technology Program Round V by the Pennsylvania Electric Company, Black & Veatch, and Hague International. The proposal was to repower Penelec’s Warren Station using Hague’s technology. This proposal was one of the four demonstration projects selected for implementation by DOE in May 1993. The repowering would extend the projected life and increase the output of the Unit No. 2 by topping the existing steam cycle with an indirect-fired gas turbine. A preliminary schedule of the proposed project is given in Figure 2.

Warren EFCC Proposed Schedule

| Date       | Event                  |
|------------|------------------------|
| 12/06/92   | Proposal Preparation   |
| 01/03/93   | Proposal Submitted     |
| 04/01/93   | DOE Project Selected   |
| 05/01/94   | Sign DOE Agreement     |
| 11/01/94   | Detailed Engineering   |
| 11/15/95   | Construction           |

Figure 2. Penelec Schedule

When completed, the EFCC cycle at Warren would increase the base rating of the existing installation from 48 to 66 MW. Additional options are being studied which could provide the unit with a peaking capacity to 73 MW. The original integrated heat rate (over the actual operating range) would be decreased from approximately 13,800 Btu/kWh to 9,600 Btu/kWh (HHV). Heat rate improvements are expected as the project evolves, however, to a substantial extent, the heat rate is a function of the steam conditions of the existing Warren plant.

The proposed Warren repowering project is projected to go on line in late 1996 and is expected to operate initially with a load factor near 80 percent, following a 30-month demonstration test phase. Figure 3 shows the Warren plant situated on the Allegheny River in northwest Pennsylvania. Figure 4 is a view of the turbine room at the Warren Plant.

DESCRIPTION OF TECHNOLOGY

The Warren Station EFCC repowering project is an advanced, state-of-the-art, project that will convert the existing pulverized coal-fueled Unit No. 2 at Penelec’s Warren Station to externally fired combined cycle (EFCC) technology. In the EFCC, a heat exchanger (CarHx) with ceramic tubes is fired by pulverized coal, utilizing a staged slugging combustor, replaces the conventional combustor in a gas turbine combined cycle system. The CarHx permits the gas turbine to operate on indirectly heated clean air so that the gas turbine is not exposed to the corrosive or abrasive elements in the fuel. The ceramic tubes allow this clean, filtered and particle-free air from the gas turbine compressor to be heated to the turbine inlet temperature, 1825 °F (996 °C). The EFCC is both economically and environmentally attractive. This is the only clean coal technology that offers the high efficiency of a gas turbine combined cycle fired on conventional unaltered steam plant pulverized coal. The EFCC eliminates the need for a complex fuel preparation of the pulverized coal or a hot-gas clean-up system to protect the gas turbine hot gas path components from deterioration. Figure 5, schematically illustrates an EFCC system.

The EFCC increases design flexibility of the basic combined cycle. The CarHx allows the steam generator to operate at virtually all conventional steam power plant cycle steam conditions, and this is achieved with one combustion system and one fuel, simplifying operation and equipment. This simplicity of operation is essential to meet the needs of today’s utility industry’s need for a flexible reliable means to repower existing coal fueled steam plants.

The proposed Warren repowering project will use the corrosion resistant, toughened ceramic heat exchanger material system technology developed by Hague International. This heat exchanger and associated equipment technology is the result of over two decades of development work by Hague.

Competing technologies include the advanced Rankine Cycle plants, IGCC, and PFBC. The EFCC cycle offers substantially higher thermal efficiencies than these emerging technologies. The “greenfield” EFCC offers overall thermal efficiencies (HHV) ranging from 44 to over 50 percent on coal, depending on the performance of supporting components, such as the gas and steam turbines and coal-burning equipment. The thermal efficiency of Warren, which would be the first repowering installation using EFCC technology, is lower than the optimized “greenfield” installations, which is typical of older plants that are repowered. The Warren steam conditions are 865 psia (59.6 Bars) 875 °F (468 °C) at the turbine. The higher efficiencies “greenfield” plants assume a state-of-the-art reheat steam cycle.

Repowering with EFCC offers a means of improving the heat rate and increasing the power output of the older coal-fired plant. Numerous programs have attempted to direct fire gas turbines with coal. All such attempts to date have resulted in significant ash deposition and corrosion of hot gas path components. Corrosion of the direct coal-fired gas turbine nozzles and blades occurs as a result of the aggressive chemical nature of the products of coal combustion, particularly in the presence of alkali metal and sulfur compounds. The proposed cycle replaces the hot corrosive and erosive combustion products entering the turbine with clean filtered air. This is accomplished with a pressurized, high temperature ceramic heat exchanger or gas turbine air heater. This air heater is currently undergoing
full-scale testing by Hague International at its KTF. The proposed CerHx is orders of magnitude less susceptible to deterioration from ash deposition or corrosion than is the gas path of a state-of-the-art turbine. This is true even if the same ceramic materials were available for turbine blades due to the lower velocities and stresses in the air heated gas path.

Coal gasification (IGCC) removes the corrosive elements in the fuel by refining and converting the fuel to a gaseous state. This gasification process can solve the corrosion problem for high performance gas turbines if the process very effectively removes alkali metals, down to levels below 40 parts per billion, when trace amounts of sulfur are also present. The IGCC erosion problem can be alleviated by totally eliminating the particles above 6 microns in the products of combustion ahead of the turbine. EFCC eliminates the exposure of the turbine to erosion and corrosion.

The IGCC process by requiring gasification adds another step in the conversion of the chemical energy of the fuel to electricity. This step is costly in terms of thermal efficiency, because, at present, to remove the corrosive elements in the fuel gas, the temperature must be lowered to condense or wash out the corrosive constituents. The thermal energy losses in this cleaning process can be substantial. This process is generally referred to as "cold gas cleaning." The energy conversion efficiency of the gasification process is in the range of 76 to 83 percent. Given the efficiency of advanced gas-fired combined cycles at 47-50 percent (HHV), with a gas turbine rotor inlet of 2350 °F (1288 °C), then the best overall IGCC plant efficiency with cold gas clean-up would be 41.5 percent (0.83 x 0.5) from coal pile to transmission line. This corresponds well to the values for the IGCC cycle efficiency of 8,227 Btu/kWh which have been reported (Hertz, Stewart, and Cohn, 1992).
The EFCC, on the other hand, would have a heat rate of 7,500 Btu/kWh, on the same basis, assuming 1.0 percent carbon loss and a 0.5 percent additional radiation loss from the combustor. This heat rate is 15 percent lower than that obtainable using coal gasification combined with a cold clean-up process. Further, the external-firing concept offers one major additional cycle advantage best described by Figure 6. As shown in this figure the cycle provides a means of optimizing the bottoming cycle with one combustion system by adjusting the CerHx gas-side inlet temperature and modifying the effectiveness of the CerHx. This provides an advantage with a pre-existing steam cycle such as in the repowering of existing coal-fired steam plants. By allowing enough energy to pass through the CerHx, the available energy division between the topping gas turbine and the integrated steam generator (ISG) could be set by means of the CerHx effectiveness to obtain the steam conditions and flow required to satisfy the existing steam cycle.

Without a pre-existing steam cycle (greenfield), the most efficient bottoming cycle steam conditions can be selected to obtain optimum EFCC performance. An example of this may be the use of the supercritical steam system. Conventional combined cycles, based on natural gas firing or coal gasification do not have this flexibility because the cycle is limited by the turbine exhaust temperature (950 to 1200 °F [510 to 649 °C]). To obtain higher steam temperatures in an IGCC, it is possible to add a second or supplementary gas-firing system. This addition further complicates the cycle, and because of the poor combustion characteristics of the gas produced by coal gasification, the use of supplementary firing imposes severe restrictions on the operation of the power plant.
Figure 5. Proposed Repowering Cycle: The Externally Fueled Combined Cycle Concept

CerHx - Ceramic Tubed Heat Exchanger
ISG - Integrated Steam Generator Consists of the Combustor and the HRSG
FGD - Flue Gas Desulfurization

Figure 6. Adaptability of EFCC to a Variety of Bottoming Cycles
To avoid the energy losses with cold gas clean-up, an effort was undertaken to perform the gas cleaning at higher temperatures and to recover some of the energy loss in the process with the bottoming or steam cycle. The technical hurdles facing the developers of the high temperature clean-up systems are substantially more challenging than those that were undertaken in the development of a high temperature ceramic air heater. The CerHx is a comparatively simple shell and tube heat exchanger made with ceramic materials. The hot gas clean-up system involves the use of ceramic filters called candle filters. Passing the products of combustion containing aggressive corrosive vapors and solid particulate through a porous ceramic body is a considerably greater technical challenge than simply flowing gas over the surface of a heat transfer tube. The surface of the tubes in the air heater can be more easily protected to prevent corrosion, than can the permeable body of a candle filter.

Due to public concern with CO₂ emissions and potential "global warming," CO₂ emissions have become an international issue. Coal generates over twice as much CO₂ per million Btu than does natural gas due to the lower hydrogen/carbon ratio of coal. The gap in CO₂ emission between these fuels cannot readily be closed at reasonable cost. The sole means presently available of economically reducing this gap is to raise the efficiency of the coal plant. Therefore, in terms of CO₂ emissions, the most efficient power plant is the most attractive emerging technology for the production of electricity from coal. Reference Figure 7 based on DOE-METC evaluation shows this plant to be externally fired, i.e., EFCC.

Figure 8 describes the proposed design fuel to be used at Warren in general terms. Figure 8 is a tabulation comparing current and projected stack emissions. The following summarizes the principal advantages of the Warren EFCC repowering concept:

- Among the emerging coal conversion technologies, EFCC has the highest efficiency.
- All EFCC equipment and components are familiar items except the ceramic component to utility power plants; there are no new "chemical plant" operations introduced by this technology.
- EFCC has the capability of matching or surpassing (within a few percentage points) the atmospheric emissions level of any other coal-fired conversion cycle. This is true with the exception of NOₓ, which is essentially zero for coal gasification cycles and is expected to attain levels below 0.1 lbs./MM Btu (50 gm/KJ Btu) (re: 3 percent O₂) under ideal test conditions in the Warren repowering project.
- EFCC systems can generate power at a lower cost than any other emerging coal conversion power cycle that is projected to be commercially available during the next decade.
- EFCC uses coal without pre-processing or enhancement. The coal is available at a low and stable cost and is plentiful in many parts of the world. The current Western Pennsylvania coal contract price is generally $1.20 per MM Btu. This compares favorably to the contract price of natural gas at $2.258 MM Btu in the U.S. (August/September 1992).

![Comparison of Cost and Efficiencies of Coal Power Generation Products](image-url)
| Tons per Hour | 36 (max) |
|--------------|----------|
| Ash          | 11.8     |
| Sulfur       | 1.82%    |
| HHV          | 12,250 Btu/lb |

Figure 8. Warren EFCC Coal Design Criteria

| Predicted |
|-----------|
| SO₂       | 0.36     |
| NOₓ       | 0.13     |
| PM        | 0.03     |
| VOC       | Negligible|

All Data in Tons MMHait.

Figure 9. Warren EFCC Future Emissions

EFCC is adaptable for repowering of existing small steam plants for increased power production at heat rates that are 25 to 40 percent lower than the existing heat rate. After commercialization, the total capital cost of repowering steam plants in the 50 to 100 MW size range is estimated to be $850 to $1,100/kW.

PROJECT DESCRIPTION

The Warren Station EFCC Demonstration Project is divided into two segments; the EFCC Repowering Island and the Balance-of-Plant. In the interest of brevity this paper is limited to discussion of the Repowering Island, since the new technology is contained primarily in the Repowering Island.

Power Island Description

That island consists of the following major items:

- Coal combustor.
- Slag screen.
- Ceramic gas turbine air heater (CerHₓ).
- Gas turbine.
- Integrated steam generator (ISO).
- Interconnecting high temperature piping and turbine control valve.
- Controls and instrumentation.

These items are shown in Figure 10, the plan view of the Warren Repowering Island.

One of the proposed EFCC plant configurations for Warren uses a 22-MW (gross) combustion turbine with a peaking rating of 33 MW gross. The combustion turbine is indirectly fired through the ceramic air heater. A slag screen is used to protect the ceramic air heater from ash deposition or fouling. Compressed air soot blowers are provided as a redundant means of cleaning the ceramic air heater. Portions of the existing Warren fuel handling system, steam turbine, and plant support system are to be reused in the repowering project.

An important aspect of the project is the high-temperature piping to connect the gas turbine to the air heater shown in Figure 11. Incorporated in this piping are the turbine control valves.

These fast response valves allow a portion of the compressor discharge air to bypass the CerHₓ and mix with the hot discharge air from the CerHₓ to control the turbine inlet temperature. These valves are the primary means of controlling the gas turbine power output. In this way, the CerHₓ can be maintained as a constant temperature heat reservoir. The slower responding portion of load control is obtained by modulating the coal firing rate and the combustion air to the combustor. The combustion air is shunted around the combustor directly to the ISO for fuel air ratio control.
Figure 11. Gas Turbine with High Temperature Piping and Turbine Control Valves
Dual concentric piping is used, the inner pipe carries the hot air to the turbine, and the outer (annular) space carries the compressor discharge air to the CerKix. Allowance is made for regeneration through the turbine air piping and for leakage through the turbine control valves (TCV's).

Energy input is supplied by pulverized coal to the combustor Figure 12 in a (maximum) amount of 896 MMBtu/hr (36 tons per hour). Three new half-capacity pulverizers, each rated at 18 tons per hour are proposed. Staged combustion will be used to maintain NOx levels below the New Performance Standard (NPS) levels that are achievable through reasonably available control technology (RACT). The proposed coal combustor would be a vertically oriented, wet-bottom combustor with air staging for NOx reduction and temperature control.

The first stage of the furnace would be a reducing stage. A studded membrane wall construction would be used with a refractory cover to reduce energy adsorption by the walls. The type and thickness of the refractory will be selected to obtain the needed adsorption of the furnace wall. The water walls would be in a forced circulation loop on the high-pressure evaporator steam drum and recirculated gas is to be used to control the flame temperature and O2 level in the secondary chamber to prevent excessive thermal NOx formation, while maintaining a furnace cavity temperature sufficient to melt the ash for removal. The first and second stage combustion chambers combined shown in Figure 12 would be approximately 85 feet (25.9 m) in height with a cross section of approximately 25 ft (7.6 m) in diameter.

The combustion gases discharge from the secondary chamber into a tertiary chamber where the temperature is trimmed to the level of entry to the slag screen, where ash particles larger than 10 microns are removed. The pressure drop across the slag screen in a new and clean condition would be 5 in wg (0.0125 Bars). The gases then exit the slag screen and enter the turbine air heater (see Figure 13).

Figure 13. Correlation: Warren and Kennebunk

The ceramic heat exchanger (CerKix) in Figures 14 and 15 for this plant is a four-pass, shell and tube design with a total of approximately 700 tube strings. There are four gas passes and one air pass, with each tube-string containing a separate tube for each pass. Each of the four tubes in a string is approximately 16 feet (4.9 m) in length and approximately 4 inches (10 cm) in outside diameter. Tubes would be made of a HI proprietary alumina/silicon carbide ceramic composite toughened material. The height of the heat exchanger (CerKix) would be approximately 86 feet (26.8 m), the face width 27 feet (8.2 m), and the depth 8 feet (2.4 m).

Leakage flows, from the tube-side through the ceramic seals to the shell-side, were determined from numerous single tube-string leakage tests performed by Hague. These tests have demonstrated that leakage rates of less than 0.5 percent of the tube-side flow can be expected. A 1.0 percent radiation heat loss was assumed from the air heater. Pressure drops were determined from classical theory and are to be confirmed by tests on the pilot plant. The maximum shell-side pressure drop has been calculated to be 13 in wg (0.033 Bars), and the tube or pressurized air side pressure drop is 69 in wg (0.173 Bars).
At rated site conditions the combustion gases would exit the CerHx to the ISG at approximately 857 °C (1575 °F) and produce 362,000 lb/hr (164,545 Kg/hr) of steam at 875 °F (468 °C) and 865 psia (59.6 Bars) at the steam turbine. The combustion gas would exit the ISO at a temperature of 280 °F for entry into the flue gas clean-up system. The steam turbine would be one of the two existing steam turbine generators at the Warren Plant. After reconditioning, the power output of the existing steam turbine generator is projected to be 48 MW (gross).

At rated cycle output (66 MW net), a steam injection flow to the gas turbine is approximately 1.0 percent of inlet compressor flow. This steam would enter the ceramic air heater (CerHx) and be heated to turbine inlet temperature along with the compressed air or working fluid. This steam injection was selected to compensate for the absence of fuel in the turbine mass flow.

Additional demineralizer capacity is required to provide water for steam injection, blow downs, and other minor losses through the system. A new deaerating heater is to be installed.

Sulfur removal would be accomplished by a dry scrubber using lime as the sorbent. A new baghouse would be used for particulate removal. The baghouse would be followed by an induced draft fan.

The heat balance was prepared using a general purpose computer code that models, integrates and interconnects the components to balance the cycle. This code was developed specifically for the EFCC program, particularly from codes made available by the Electric Power Research Institute (EPRI) combined with new sub-routines developed by Hague and its subcontractors. The major plant site parameters are given in Figure 16 (Vandervort, Lahaye, Briggs, and Seger, 1991).

The net power output of the combined cycle plant is 66.0 MW, and a breakdown of the power generation and losses is given in Figure 17. These data were prepared using average conditions for the site. Projected part load performance of the Warren Demonstration is illustrated in Figure 18. The heat rate improves slightly up to 60 percent of rated output and then deteriorates gradually to 9,600 Btu/kWh (10,128 KJ/kWh) at the base rating.

The Kennebunk Test Facility (KTF) is shown schematically in the lower portion of Figure 13 and elevation and plan views of Kenebunk are given in...
Ambient Temperatures
Relative Humidity
Plant Altitude
Ambient Pressure

| Units       | Base (Rated) | Peaking (Potential) |
| ---         | ---          | ---                 |
| Net Plant Power Output | MW       | 66                  | 73                  |
| Total Heat Input (HHV) | Million Btu/hr | 633 (667 KJ)       | 774 (816.6 KJ)     |
| Plant Net Heat Rate (HHV) | Btu kWh/hr | 9,600 (10,128 KJ/hr) | 10,600 (11,183 KJ/hr) |
| Steam Injection Flow to CerHx | lb/hr | 8,000 (3,640 Kg/hr) | 80,000 (36,364 Kg/hr) |

Figure 16. Summary of Plant Parameters

Figure 17. Plant Power Generation Base & Peak

The KTF facility is thermally 1/10 the size of Warren and 1/7 of gas turbine air heater face tubes. The gas turbine compressor air flow at KTF is 3.27 kg/sec (7.2 lbs/sec) and at Warren 96.81 kg/sec (213 lbs/sec). The temperatures, pressures and fuel characteristics of the pilot plant (KTF) and the demonstration plant (Warren) are essentially equal.

It is immediately obvious on examining Figure 13 why KTF has and will continue to play an important role in the evaluation of the Warren repowering project and why the data from the pilot is critical.

EVALUATION OF EFCC FOR REPOWERING

When selecting equipment for additional power generation capacity, electric utility planners generally address three broad areas of concern. These are:

1. Environmental and social impact of the proposed power addition.
2. Matching the utility's need with the availability of equipment.
3. The price stability and security of the (energy) fuel supply.
4. Cost of Power (COE), which includes the expected availability and reliability of the equipment.

In the environmental area, the EFCC concept emulates pulverized coal (PC)-fired steam cycles and uses the same technology for stack emissions control that is now used or proposed for existing PC-fired steam plants. There are advantages to the EFCC. The fuel consumption of the EFCC per kWh is 25 to 40 percent lower than existing PC plants. As a consequence, the emissions are proportionally reduced. Additionally, the EFCC cycle provides for more flexibility in designing the combustor. It is possible, for example, to operate with a highly vitiated combustion process due to the nature of a gas turbine cycle. This, combined with air staging, can result in impressive reductions in NOx emissions without compromising the thermal performance of the power cycle.

Figures 19 and 20. Immediately above the schematic of KTF (Figure 13) is shown a photograph of the Warren Repowering Island. Lines drawn between the major equipment serve to illustrate the similarity between the KTF facility and the Warren plant.
The Warren plant would be an ideal demonstration site for this emerging technology. The work force is diverse and positively motivated, highly skilled and has in-depth experience with coal power generation plants. The facility also has the means to be largely self-sufficient in terms of personnel skills and shop facilities to perform modifications and repairs to the existing and new technology equipment. The social impact of the proposed plant modernization would be favorable. Approximately 70 persons are employed currently at the plant. The fuel is purchased principally from small producers in the vicinity of the plant. In brief, the plant has been a "good neighbor" and is accepted by the community.

Improvements in the Warren plant stack emissions are mandated under the Clean Air Act Amendments for 1996. To make such improvements economically viable, it is necessary to increase the plant rating and improve the thermal performance. Repowering using EFCC technology is to accomplish the necessary improvements to make the plant economically viable and environmentally acceptable.

The repowering of Warren is dependent on the KTF pilot schedule and operating results. This pilot plant is to begin the proof of concept tests in April 1994 and continue to operate in a variety of test configurations through 1996 at which time the Warren demonstration plant would go on line. Data obtained from KTF in 1994 is essential for the design and construction of Warren.

Coal is an abundant fuel in western Pennsylvania, whose price has been historically stable. The coal is trucked from a multitude of small largely privately owned mines in the vicinity of Warren. In addition, there is a natural gas pipe line on the premises that can serve as a secondary fuel supply for plant start-up and to provide fuel for a separate peaking gas turbine (unrelated to this project) located on site.

The plant base rating is 66 MW, which is small for a high-performance coal-fired cycle. While the integrated heat rate at 9,600 Btu/kWh (HHV) (10,128 kJ/kWh) is higher than may have been expected for a "greenfield" advanced technology coal-fired power plant, it should be noted that:

- Two-thirds of the power at Warren is to be generated by the existing steam turbine that was designed prior to WWII, i.e., the bottoming cycle is not optimum.
- The proposed repowered plant heat rate will be competitive with other large PC-fired plants now in service. The existing Penelec generating facilities are listed in Figure 21.

The proposed repowering of Warren is to increase the base load capability of the plant by 45 percent and may add a potential peaking capability that would increase the output by 67 percent. Both of these values are referred to the existing gross Unit No. 2 rating of 48 MW.

The cost of repowering an existing PC plant similar to Warren, without subsidies (and without the special requirements imposed by such subsidies) having an existing or original steam power rating in the range of 45 to 80 MW is expected to be $935/kW (1993). This cost would include interests during construction, engineering fees, project and process contingency, start-up and inventory, but would exclude the cost of land, existing equipment, facilities, transmission lines, coal handling and raw water system. The economic attractiveness of such a plant can be defined by comparing the CEQ with a state-of-the-art gas-fired combined cycle. This comparison is given in Figure 22.

The difference between 22(A) & 22(B) is a doubling of fuel prices. As shown at 1993 fuel prices, Figure 22(A), the COE for the EFCC Repowering is essentially equal to the COE for a gas-fired combined cycle. All other factors being equal, the selection of plant type would then be made on the price stability and the security of the fuel supply.

Figure 22(B) shows the same comparison with a change in the fuel cost. Both coal and natural gas were doubled in cost. As shown in Figure 22(B), this increases in fuel cost would bias the differential in favor of a coal-fired solution. With such an increase in fuel cost, the COE of the EFCC repowering solution is 14.6 percent lower than a natural gas-fired combined cycle.

While a variety of fuel escalation possibilities exist in the United States, the long term stability of coal prices is a historical fact; in contrast, natural gas has a history of price instability. With this perspective, all else being equal, the choice would tend to favor coal.

The success of the proposed Warren repowering program was dependent on the development of a gas turbine air heater capable of accepting the products of coal combustion as an energy source and heating turbine compressor discharge air to the normal inlet conditions for expansion through the turbine section. Such a heater has been developed by Hague International using advanced ceramic materials that can tolerate the products of coal combustion at high temperatures.

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### Penelec Owned and Operated Generating Facilities

| Station | Units Type | Owned KW | Operated KW | Total KW |
|---------|------------|----------|-------------|----------|
| A       | PC         | 1,700    | 1,700       | 1,700    |
| B       | PC         | 1,700    | 1,700       | 1,700    |
| C       | PC         | 925      | 925         | 1,850    |
| D       | PC         | 616      | 616         | 616      |
| E       | PC         | 200      | 200         | 200      |
| F       | PC         | 88       | 88          | 88       |
| G       | PS         | 67       | 313         | 380      |
| H       | HYDRD      | 25       | 25          | 25       |
| I       | HYDRD      | 20       | 20          | 20       |
| **TOTALS** | **20** | **1,941** | **4,638** | **6,579** |

NOTE: For proprietary reasons, names of the plants have been coded.

Figure 21. Penelec Generating Facilities

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Figure 22(A) and 22(B)

**COST OF ELECTRICITY COMPARISON (1993)**

| Item | Coal Fired EFCC | Natural Gas-Fired Combined Cycle |
|------|-----------------|---------------------------------|
| Repowering 80 MW | Mills/kWh | % of Total | Mills/kWh | % of Total |
| Cost of Capital | 18.0 | 46.0 | 13.4 | 34.2 |
| O&M; Fixed | 5.2 | 13.3 | 1.5 | 3.8 |
| Fuel | 11.5 | 29.4 | 18.8 | 48.0 |
| Total | 39.1 | 100.0 | 39.2 | 100.0 |

COE = Zero essentially comparable.

(Double 1993 Fuel Costs)

| Item | Mills/kWh | % | Mills/kWh | % |
|------|----------|---|----------|---|
| Cost of Capital | 18.0 | 35.6 | 13.4 | 23.1 |
| O&M Fixed | 5.2 | 10.3 | 1.5 | 2.6 |
| O&M Variable | 4.4 | 8.7 | 5.5 | 9.5 |
| Fuel | 23.0 | 45.4 | 37.6 | 64.8 |
| Total | 50.6 | 100.0 | 59.0 | 100.0 |

COE = 14.6% in favor of 100% Coal Fired EFCC

Small Coal-Fired EFCC for Repowering vs. Natural Gas-Fired Combined Cycle

The comparison of Figure 22 between repowering with EFCC or alternatively, a natural gas-fired combined cycle, makes the following assumptions:

**ASSUMPTIONS: For Figure 22A & B**

| a) Fuel Prices | Coal | $1.20 | $1.20 |
| b) Load Factors | EFCC = 68.2% | Natural Gas | $2.40 | $2.40 |
| c) Plant Size | CC (Gas) = 72.4% | 80 MW |
| d) Average Cost of Capital | 11.5% Simple Interest | $750/kW |
| e) Cost of Greenfield Gas Turbine CC Plant | $935/kW |
| f) Cost of Repowering with EFCC |

*NOTE: These numbers refer to a repowered commercialization plant, in general, and are based on the authors' estimates.*

If the development of an air heater is not technically possible or economically viable, then a compromised solution may be considered. Such a component has been suggested in the form of a hybrid cycle referred to as the HIPPS cycle (Klara, 1994; Ruth, 1992-93). This cycle consists basically of a regenerative gas turbine, similar to those applied to gas pipeline pumping as early as the 1960's with the addition of a coal combustion system (after burner) firing into the gas turbine exhaust upstream from the regenerator. In HIPPS the conventional gas turbine combustor stays in place and is fired on natural gas or distillate oil. In this manner, instead of simply recovering energy from the turbine exhaust with the compressor discharge air, using a regenerator and entering the conventional combustor, at say 900 °F (482 °C), a coal combustor is added to raise the temperature of the turbine exhaust to a level limited only by the ability of the regenerator to accept the products of coal combustion. The combustion of coal may in this manner raise the temperature of the air delivered to the gas turbine combustor from the 900 °F (482 °C) previously mentioned to 1500 °F (815 °C). Natural gas or distillate oil is then used to complete the process of raising the temperature to the normal turbine inlet temperature. The HIPPS solution is more complex and has no economic or environmental advantages over simply providing two separate and commercially available power plants, such as a combined cycle fired on natural gas and independently, and separately, an atmospheric fluidized-bed coal plant.
SUMMARY

The development of the EFCC project has been rapid during the past 5 years. The success of the proposed Warren project depends primarily on the quality of the work done in ceramic material systems, and secondly, on how thoroughly the fundamental engineering in fluid flow, combustion and other basic disciplines was carried out. The concept is fundamentally simple and is more thermally efficient and easier to adapt to the present needs of electric utilities than other known emerging technologies. Because of this, the EFCC is being developed, to the point of commercialization, more rapidly than competing technologies.

The support received from the utility and industrial sector has been one of the most important ingredients in the successful evolution of this project. A listing of the members of the EFCC Consortium is given in Figure 23. This support has manifested itself in both financial and active participation of the members in the development program. This active participation by suppliers of equipment and end users has made it possible to avoid many of the pitfalls normally associated with R&D programs. Also, the support and active cooperation of the DOE Morgantown Energy Technology Center has made it possible for this program to progress rapidly to this point on the path to commercialization.

Competition for the EFCC is now and is expected to remain gas-fired combined cycles, as long as natural gas is available. Repowering of existing steam plants is the only exception, where EFCC concept is expected to have a major impact well into the next century.

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The information contained in this paper represents the authors' interpretations and opinions, and in no way represents the positions of the authors' companies.

Allison Engine Company (formerly Allison Gas Turbine)  Contract
Ansaldo  Contract
American Public Power Association (APPA)  Contract
Black & Veatch  Contract
Mr. Ed Boulos, Jr.  Contract
Du Pont Lanxide Composites  Contract
Empire State Electric Energy Research Corporation (ESERCO)  Contract
EPRI  Contract with DOE
Florida Power Corporation  Contract
Foster-Wheeler  Contract
Hague International  Contract
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N.Y. State Energy Research Development Authority (NYSERDA)  Contract
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