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Gas Turbines for Advanced Pressurized Fluidized Bed Combustion Combined Cycles (APFBC)

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ABSTRACT

This paper describes gas turbines from several manufacturers that, with modification, have potential for repowering existing steam plants with high efficiency advanced circulating pressurized fluidized bed combustion combined cycle (APFBC) technology. The paper discusses the issues that must be addressed by these manufacturers if they are to have units suited for entry into the APFBC market.

APFBC repowering retains the continued use of existing coal-fired capacity with acceptable economy. APFBC repowering significantly improves the energy efficiency of an existing plant, the plant's environmental performance, and reduces operating costs. Coal-fired APFBC is now under test in large scale demonstrations, and will be ready for commercial repowering installations around year 2005, so it is prudent to begin evaluating the types of APFBC-modified units that might be offered from different manufacturers.

APFBC repowering has some important advantages for the power generating company owner. For example, repowering the 106 MWe output Carolina Power & Light Company's (CP&L) L.V. Sutton steam station Unit 2 with APFBC would boost output and improve the energy efficiency. A single Westinghouse W501F combustion turbine modified for APFBC operations would raise the APFBC-repowered Unit 2 output to 226.5 MWe. The present 32.0 percent HHV level energy efficiency improves to 42.4 percent HHV (44.1 percent LHV).

The paper describes concept evaluations that are completed or underway that would use each of four APFBC- modified gas turbines for APFBC repowering:

- Pratt & Whitney Turbo Power, FT8 Twin Pac, which consists of two FT8s, (for a combined output of 51 290 kW on natural gas). This 20.2 **:** 1 overall pressure ratio aeroderivative engine is configured in a 2 x Twin Pac configuration (four FT8s) or a 3 x Twin Pac configuration (six FT8s), for the APFBC repowering of a 105 MWe class output reheat unit.
- Rolls-Royce Trent (51,190 kW on gas), a 35.0 **:** 1 overall pressure ratio aeroderivative engine is evaluated , is evaluated in a 1xTrent or 2xTrent configuration for a unit repowering of a 165 MWe class output reheat unit.
- Siemens Westinghouse V64.3, (63,000 kW on gas), a 16.1 **:** 1 overall pressure ratio unit designed for stationary service, is evaluated in a 1xV64.3 or 2xV64.3 configuration for a

unit repowering application. The Siemens Westinghouse V-3-series have off-board silo combustors expected to be an easier APFBC design; the newer V-3A-series have hybrid ring combustors™.

- A Siemens Westinghouse V84.3 (152,700 kW on gas), a 16.1 **:** 1 overall pressure ratio unit designed for stationary service, is evaluated for a 110 MWe reheat unit repowering application.
- A Siemens Westinghouse W501F (177,100 kW on gas), a 14.0 **:** 1 overall pressure ratio unit designed for stationary service), is evaluated for repowering: one of the steam units at a 105 MWe output class reheat unit; a 150 MWe unit, and both a 105 MWe and 100 MWe unit at the same site.

APFBC repowering concepts were assessed for several different steam units located at steam power stations owned by the following cooperating electric generating companies:

- Carolina Power & Light Company's L.V. Sutton station Unit 2, and Unit 1 plus Unit 2;
- Duke Energy's Dan River station Unit 3;
- New York State Electric & Gas Company's Greenidge station Unit 4; and,
- Nebraska Public Power District's Sheldon station Unit1 and Unit 2.

The paper focuses on the features of these gas turbines for APFBC systems. Specific attention is paid to modifications needed to develop units that can be applied to APFBC plant repowering. Several important modifications that would allow these gas turbines to operate in an APFBC environment are highlighted.

WHAT IS APFBC?

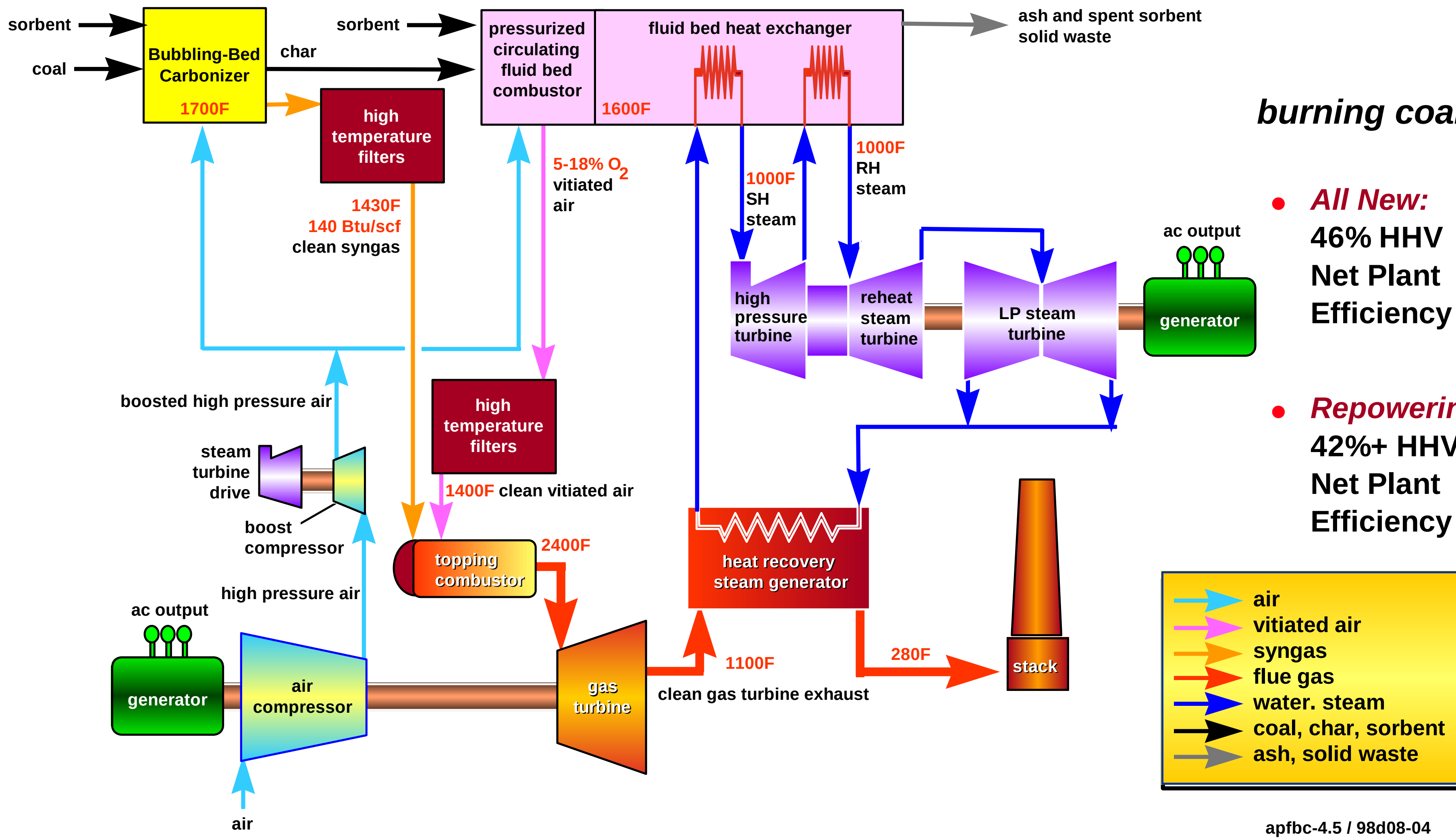
The APFBC system uses the pressurized circulating fluidized bed combustion technologies developed by DOE and industry partners. Exhibit 1 shows the major components of an APFBC power plant.

APFBC uses a circulating pressurized fluidized bed combustor (PFBC) with a fluid bed heat exchanger to develop hot vitiated air for the gas turbine's topping combustor and steam for the steam bottoming cycle, and a carbonizer to produce hot fuel gas for the gas turbine's topping combustor. This provides high combined cycle energy efficiency levels on coal.

Advanced circulating pressurized fluidized bed combustion combined cycle (APFBC) technology uses gas turbine combined cycle technology in combination with coal-fired equipment. APFBC allows the gas turbine to operate free of corrosion and erosion damage.

While a conventional combined cycle uses natural gas, APFBC operates at almost the same high levels of energy efficiency, but on less costly coal. APFBC has a wide tolerance for differing coal types and can use opportunity fuels, so the owner can take advantage of lowest energy price.

Exhibit 1. APFBC Power System Sketch



burning coal:

- ***All New:*** **46% HHV Net Plant Efficiency**
- ***Repowering:*** **42%+ HHV Net Plant Efficiency**

apfbc-4.5 / 98d08-04

This technology is also environmentally clean, which is important to generating companies subject to increasingly stringent air quality regulations. APFBC provides environmental performance superior to NSPS requirements, and DOE estimates *[DOE, 1993]* that APFBC is capable of producing electricity at 42 to greater than 50 percent net plant efficiency (HHV). APFBC is projected to have attractive low production costs.

APFBC is now in the commercial demonstration phase of development. Some key component and integrated system testing by manufacturers and the U.S. Department of Energy (DOE) is underway at the DOE Power Systems Development Facility (PSDF) in Wilsonville, Alabama. Testing of the special gas turbine burners needed was done at the University of Tennessee Space Institute (UTSI). The first full-scale commercial demonstration of APFBC technology is being developed in a DOE-sponsored clean coal technology project at the McIntosh station *[DOE, 1996]* owned by the City of Lakeland, Florida.

Based on earlier DOE evaluations, plant repowering is an attractive way to demonstrate the technology in early commercial applications, add to the base of information on APFBC operability, firmly establish a base of capital and operating costs, and prove APFBC economy, reliability, and availability. A large number of plants of similar size to the L.V. Sutton station *[Weinstein et al. 1999a]*, Dan River station *[Weinstein et al. 1998a]*, Greenidge station *[Weinstein et al. 1999b]*, and Sheldon station *[Weinstein et al. 1999c]* units could benefit from APFBC repowering. There is enough flexibility with APFBC technology that it can be adjusted easily to adapt to any size coal-fired plant. The range of sizes of steam plants that can be repowered depends on the size of the gas turbine selected. Once that gas turbine is selected, relatively inexpensive adaptations in the size of the PFB combustor and fluid bed heat exchanger steam generation surfaces allows adaptation to fit a wide range of steam plant sizes. An APFBC system can even repower two steam turbines at a site, even if those turbines have different steam conditions and configurations.

CP&L production costing evaluations show that APFBC technology can promote a low-use unit from 10 to 20 percent capacity factors to first-dispatched baseload status with projected capacity factors in excess of 80 percent *[Weinstein et al. 1999a]*. With APFBC repowering, energy efficiency improvement is dramatic, so less coal is needed –and less CO_2 emitted—for each kilowatt generated. Exhibit 2 shows the results of the L.V. Sutton Unit 2, and Dan River Unit 3 APFBC repowering evaluations.

Environmental Emissions Expectation. High efficiency and combines with clean operation so that APFBC is expected to have very low environmental emissions per kWh generated. Limestone in the fluid beds removes sulfur, so SO_2 can be 96 percent less than that emitted by the existing station. Combustion temperatures are low and uniform to minimize NOx production. Additionally, the gas turbine topping combustor burners are specifically designed for low NOx production, so NOx can be 67 percent less/kWh than the existing station. The ceramic high temperature filters that protect the gas turbines from dust are extremely effective in reducing particulate emissions. An existing steam unit with well-performing ESPs significantly reduces particulate emissions, but the APFBC filters are so much more effective in particulate reduction that particulate removal is 95 percent less per kWh than a conventional plant with an ESP; hardly any particulate matter escapes from an APFBC plant.

Exhibit 2. Performance Improvements from Two APFBC Repowering Evaluations

	CP&L		Duke Energy	
	Existing L.V. Sutton Unit 2	L.V. Sutton Station Unit 2 Repowered with APFBC	Existing Dan River Unit 3	Dan River Station Unit 3 Repowered with APFBC
Gross output, kWe				
Gas turbine gross	--	138,400 kWe APFBC-modified W501F	--	138,400 kWe APFBC-modified W501F
Unit 3 steam turbine gross	112,500 kWe	105,111 kWe	153,160 kWe	163,069 kWe
Auxiliary losses	-6,500 kWe	-17,020 kWe	-9,420 kWe	-11,060 kWe
Net plant output, kWe	106,000 kWe	226,491 kWe	143,740 kWe	290,409 kWe
Net plant HHV efficiency	32.0%	42.4%	36.4%	43.2%
Net plant LHV efficiency	33.3%	44.1%	37.9%	45.1%
Net plant HHV heat rate	10,660 Btu/kWh	8,041 Btu/kWh	9,370 Btu/kWh	7,891 Btu/kWh

While not a pollutant, some segments of the public have concerns about carbon dioxide as a "greenhouse" gas. The high energy efficiency of APFBC means that there is 25 percent less CO_2 per kWh.

Depending on repowering design choices made, water use and steam condenser thermal discharge can remain unaffected, so existing water use permits often can remain unchanged. However since feedwater heaters are taken out of service, in some repowering applications where the back-end of the steam turbine has adequate capacity for higher flow, there can be advantages in increased output that could result in a modest increase in condenser duty.

MODIFICATIONS NEEDED FOR APFBC OPERATIONS

The applicability of different combustion turbine systems requires consideration of several important criteria needed as unit modifications that would allow the combustion turbines to operate in an APFBC environment *[Weinstein et al. 1998b]*. These include the following, and are discussed below:

- **Export of High Compressor Air**. The easier it is to modify the casing for the export of large quantities of high compressor discharge air, the more suited the engine is for APFBC applications.
- **Ability to Burn Low Btu Syngas**. Manufacturers who already have low Btu combustor designs proven to have low NOx production will have an easier transition to APFBC operations.
- **Ability to Burn Using Low Oxygen Vitiated Air**. Are there features to the combustor design that make it easier to make modifications for the differing combustor conditions in the burner cans imposed by low oxygen content vitiated combustion air?
- **Topping Combustor Capable of Import of 1400 F or Higher Syngas and Vitiated Air**. The easier it is to modify the casing for the import of large quantities of high temperature (1400 EF+) syngas and vitiated air, the more suited the engine is for APFBC applications.
- **Single/Multi Unit Concerns**. Advantages/disadvantages of single unit implementations versus multi-unit implementations.
- **Aeroderivative vs. Large Frame**. Cycle pressure ratios for aeroderivative combustion turbines are higher than for large-frame stationary turbines. This has a number of implications for operations and energy efficiency.
- **Other Issues**. There are other issues that might influence the gas turbine applicability. Does it employ intercooling or other features that enhance or discourage modification for use in an APFBC application? Are there test programs underway that relate to APFBC operations?

Exhibit 3. V64.3 Offboard Combustor Mounting

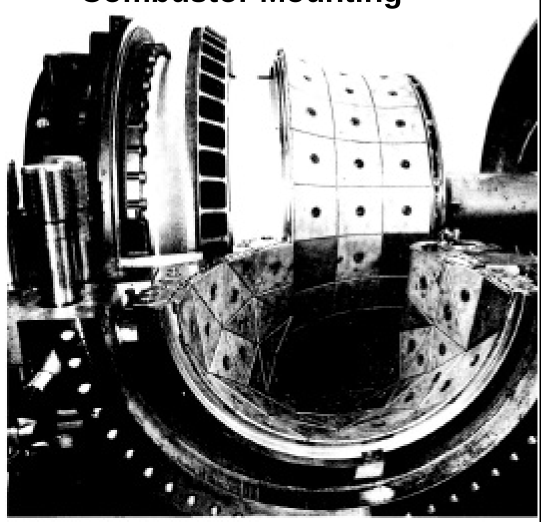


photo courtesy of Siemens

Export of High Compressor Air

Transition sections are needed to export high compressor air, and import hot vitiated air and syngas. Designs like the V64.3, Exhibit 3, which have transition sections in place to take air offboard of the engine case are likely to have an easier conversion interface to APFBC. The easier it is to modify the casing for the export of large quantities of high compressor discharge air, the less costly it would be to modify the engine for APFBC applications. The combustion turbine needs to have sufficient length or design arrangement to be able to collect and discharge the high pressure discharge air at low pressure loss.

The APFBC hardware has pressure drops that are larger than those of the very short path in natural gas combined cycle turbines. To minimize the need for specially designed equipment it is prudent to make design choices where direct use should be made of the standard design for the flow cross sections as well as the external airfoil blade geometry. This is eased by the decision to employ a boost compression system to restore the volumetric flow levels at the turbine face to about the same conditions that exist in the existing design.

Ability to Burn Hot Low Btu Syngas

Manufacturers who already have low Btu combustor designs proven to have low NOx production will have an easier transition to APFBC operations. The topping combustor and burners needed for APFBC service are significantly different than a natural gas combustor.

- The topping combustor must accept hot (1400 °F or higher) low Btu content (130 Btu/scf) syngas.
- The burners must be capable of the stable combustion of syngas and vitiated air over the unit's load range.
- The burner must be capable of sustaining stable combustion and low-NOx operations throughout the load range on syngas.
- Burners must be capable of starting and operating on natural gas, and capable of smooth transition to full syngas/vitiated air firing.
- The nozzles and connectors to the APFBC system fuel gas and vitiated air piping must be capable of handling the thermal growth loads imposed on them at the high delivery temperatures of these gases.
- Internal hoses interconnecting individual burners from the manifolds must be capable of conveying the high temperature gases.

Ability to Burn Hot Vitiated Air With Low Oxygen Concentration

The topping combustor must accept hot (1450 °F or higher) vitiated air. The burners need design features that provide stable combustion with the vitiated air, even though this is partly depleted in oxygen (in some configurations as low as 8 up to about 17 mole percent oxygen).

Single- / Multi-Unit Concerns

There is a great deal of flexibility in an APFBC repowering to match a wide range of steam turbines from one gas turbine. This matching to steam demand is possible because of the easy adaptability of the PFBC fluid bed heat exchanger if supplemental coal is added to the char from the carbonizer in the PFBC combustor. However, if the gas turbine is just too small to completely supply the needs of the selected steam plant even with coal supplement to the PFBC, then combustion turbines can be applied in multi-unit configurations.

When multi-unit configurations are chosen, either multi-independent APFBC trains are used, or a single common APFBC train is used. A single train is likely less costly. If multi-combustion turbines feed a single APFBC train, there is the added control complication of matching the gas turbine discharge conditions, and metering the returned syngas and vitiated air between the gas turbines.

Aeroderivative vs. Large Frame.

Cycle pressure ratios for aeroderivative combustion turbines are higher than for large-frame stationary turbines. This has a number of implications for operations and energy efficiency.

Low exhaust temperature. Usually, aeroderivative engines have high pressure ratios than large stationary combustion turbines. This is a necessary consequence of their heritage: flight propulsion. In aircraft propulsion, the gas turbine needs high simple cycle efficiency. For a given firing temperature, simple cycle gas turbine efficiency peaks at a much higher pressure ratio than does a stationary combined cycle optimized for combined cycle operations. This high pressure ratio of the aeroderivative means more compression stages, and more turbine expansion stages. The result is a lower exhaust gas temperature than lower pressure ratio large-frame units.

This low exhaust gas temperature of the aeroderivative is a penalty when such units are considered for use as combined cycles. In combined cycles, heat recovered from the gas turbine exhaust is used to raise steam. When the exhaust gas temperature is low (say below 900 °F), there is insufficient temperature to raise quantities of superheat or reheat steam, and the steam system suffers. Because the steam heat recovery is tightly constrained by the temperature approach to the turbine exhaust conditions, part load steam cycle performance suffers as the turbine drops in load. Thus, using natural gas fueled aeroderivative gas turbines to fully repower existing steam turbines usually more difficult. Efficient repowering generally means scrapping the existing steam turbine, because it is hard to get an exact match to the superheat and reheat steam flow needs of existing equipment. Another way to overcome low exhaust gas temperature, or to match an existing turbines steam requirement for a repowering application is to provide supplemental firing in the ducts leading to the heat recovery steam generator. This is inefficient and costly. Yet another choice, that is quite acceptable, and frequently done, is to use the heat recovery unit as economizer surface, replacing feedwater heaters. In this type of feedwater heater repowering; the existing boiler is then fired (at reduced fuel flow) to raise superheat and reheat steam, but since the gas turbine only supplies some of the heat, the heat rate improvement from this type of repowering is smaller than other schemes.

APFBC Does Not Suffer if an Aeroderivative Has Low Exhaust Temperature. Since the fluid bed heat exchanger in an APFBC repowering raises the superheat and reheat steam, unlike with natural gas firing, an aeroderivative combustion turbine used in an APFBC application can provide a good match to the existing steam turbine, without compromising steam plant performance, or requiring supplemental firing.

Higher Pressure. Because aeroderivative engines often have higher pressure ratios, the operating pressure of the APFBC system is higher. This means thicker walled pipes and pressure vessels that tend to add costs, but the higher pressure also reduces volumetric flows, which in many components tends to reduce costs. The pressure also changes process chemistry and heat transfer characteristics. A detailed design trade-off is needed to judge the effects.

Fuel Control and Protection Valves

The valves and control system are different with APFBC than operations with natural gas.

- High temperature valves are needed with actuators sized to close with sufficient margin to provide the required overspeed and safety protection.
- gas turbine syngas control valve
- gas turbine emergency vitiated air bypass valve
- gas turbine emergency syngas bypass valve
- gas turbine emergency fuel trip valve

Control valve must be capable of load control modulation with minimum pressure drop, and be capable of transition from natural gas firing at start-up through syngas operations at full load. The APFBC has large gas volumes and substantial thermal "inertia. " Syngas and vitiated air flow rates are linked; adjusting fuel-air ratio takes combined action of the gas turbine fuel control with the APFBC system controls.

Control and Interaction With The Boost Compression System

The boost compression system restores the normal pressure balance of the natural-gas fueled combustion turbine. However, a boost compression system has its own independent driver. This means that the flow/pressure output of the booster must be balanced to the normal and emergency needs of the gas turbine during normal operations and any conceivable upset. This requires active control interaction, and fail-safe protection for key parameters. The combustion turbine/boost compressor system controls must provide control and safety during normal operations and upset conditions.

Anti-Surge Protection. Either the gas turbine's compressor or the boost compressor can surge if incorrect speed-flow conditions develop. Both possibilities need to be considered, and design and control strategies established so there is adequate anti-surge protection of these systems and their piping during normal operations, and any emergency situation.

Turbine and Seal Cooling Pressure Differential. The cooling air and seal air system for the gas turbine also needs review. With a boost compression system, care must be taken that the pressure differentials needed to feed the cooling air for airfoil and seal cooling for all normal and abnormal conditions is maintained at a sufficient margin above the highest that might ever be delivered from the boost system, even under system upset conditions.

Pressure Balance. The boost compression system restores the normal pressure balance of the gas turbine. This prevents different axial forces on the gas turbine generator than was initially designed into the unit. However, protection is needed to prevent out-of-range pressure differentials during system upset conditions. The possibility of reverse axial forces at abnormal operations or low load have to be considered. It may be necessary to check whether this is covered by the existing equipment mechanical design, or if automatic control system protection is needed if emergency conditions are detected.

THE CANDIDATE UNITS

DOE is preparing a preliminary evaluation of the characteristics for several combustion turbines, and is working with the manufacturers to assess the merits of these units for APFBC service. The units being evaluated are listed in Exhibit 4. Exhibit 5 shows the several combinations of these combustion turbine units evaluated at the various power stations.

CONCLUSIONS

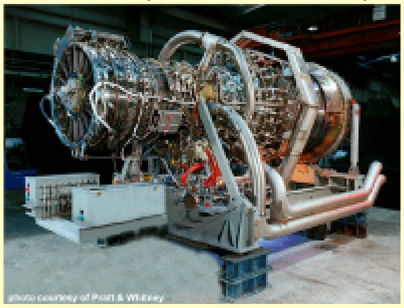
APFBC is a high energy efficiency power generation technology that uses modern high efficiency gas turbines to advantage. APFBC can operate on coal or opportunity fuels, or operate in modes that use a mix of coal and natural gas if desired. It has proven particularly adaptable for repowering a wide range of existing steam units.

With APFBC, a single gas turbine unit can repower a wide range of steam plant sizes, and exactly match the existing steam conditions. This is because with APFBC, superheat and reheat steam generation does not depend on gas turbine exhaust conditions for finishing superheat and reheat, as does a conventional natural gas combined cycle. The APFBC system PFBC combustor uses char from the syngas-producing carbonizer to raise superheat and reheat steam in the fluid bed heat exchanger. This char can be supplemented with added coal to make more steam if needed to exactly match steam turbine flow and temperature demands.

Preliminary assessment shows that a number of gas turbine units from various manufacturers are feasible candidates for APFBC operations. Natural gas-fired units from these manufacturers need modification and testing for APFBC operations to accommodate the export of air, and to import hot syngas and vitiated air. Each unit evaluated could be so modified, should the manufacturer choose to do so when they perceive a market for APFBC repowering sales is emerging.

Exhibit 4. Listing of Some Gas Turbines Being Evaluated for APFBC Service

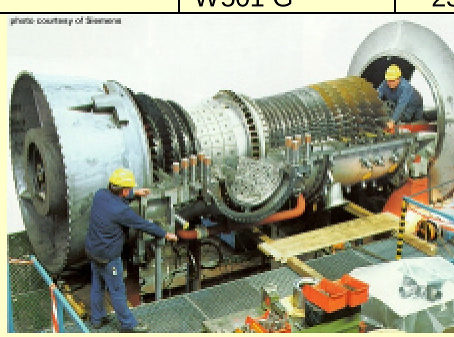
Manufacturer	Model	natural gas ISO Rating	natural gas LHV Heat Rate	OPR	EGT
Pratt & Whitney	FT8 Twin Pac	51 290 kW	8 885 Btu/kWh	20.2 : 1	851 °F
Turbo Power	FT8 Power Pac	24 465 kW	8 950 Btu/kWh	20.0 : 1	851 °F



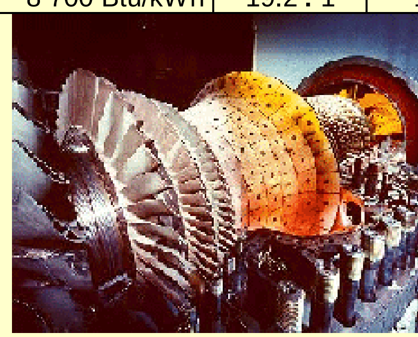
Pratt & Whitney FT8

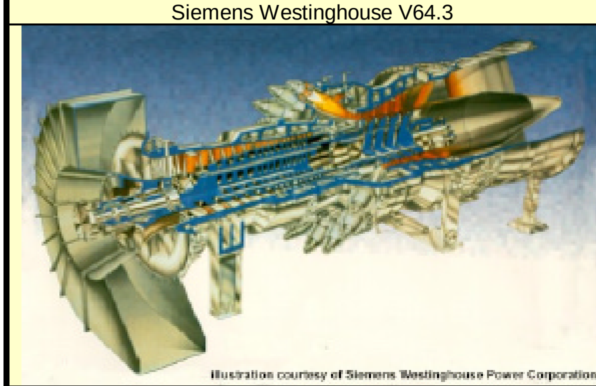

Industrial Trent

Manufacturer	Model	natural gas ISO Rating	natural gas LHV Heat Rate	OPR	EGT
Rolls-Royce	Trent	51 190 kW	8 210 Btu/kWh	35.0 : 1	800 °F
	WR-21	25 200 kW		16.2 : 1	671 °F
Siemens Westinghouse Power Corporation	V64.3	63 000 kW	9 348 Btu/kWh	16.1 : 1	988 °F
	V64.3A	70 000 kW	9 348 Btu/kWh	16.2 : 1	1060 °F
	V84.2	109 000 kW	10 036 Btu/kWh	11.0 : 1	1011 °F
	V84.3	152,700 kW	9,450 Btu/kWh	16.1 : 1	1024 °F
	V84.3A	180 000 kW	8 863 Btu/kWh	17.0 : 1	1071 °F
	W401	85 900 kW	9 330 Btu/kWh	19.0 : 1	1063 °F
	W501 F	177 100 kW	9 230 Btu/kWh	14.0 : 1	1111 °F
	W501 G	235 780 kW	8 700 Btu/kWh	19.2 : 1	1107 °F



Siemens Westinghouse V64.3


Siemens Westinghouse V84.3



Siemens Westinghouse W501F

OPR = overall pressure ratio EGT=exhaust gas temperature ISO=International Standards Organization LHV=lower heating value

Exhibit 5 Combustion Turbines Under Evaluation for APFBC Repowering at Various Power Stations

Owner / Station	Unmodified Nameplate Rating Steam Conditions	Gas Turbines Evaluated for APFBC Repowering
Carolina Power & Light Company	Unit 1 + Unit 2 *97+106 MW=* 203,000 kW	**1 x W501F**
L.V. Sutton station Wilmington, NC	Unit 2 106,000 kW *Non-RH Unit 1: 1450 psia / 1000°F* *RH Unit 2: 1815 psia / 1000°F / 1000°F*	**1 x W501F** **2 x Twin Pacs (4xFT8)** **3 x Twin Pacs (6xFT8)** **1 x V64.3** **2 x V64.3** **1 x V84.2** **1 x V84.3** **1 x V84.3, derated**
Duke Energy Dan River station Eden, NC	Unit 3 150,000 kW *RH Unit 3: 1815 psia / 1000°F / 1000°F*	**1 x W501F**
New York State Electric & Gas	Unit 3 + Unit 4 *55+108 MW=* 163,000 kW	**2 x Trent** **3 x Trent**
Greenidge station Dresden, NY	Unit 4 108,000 kW *Non-RH Unit 3: 865 psia / 900°F* *RH Unit 4: 1490 psia / 960°F /1000°F*	**2 x Trent**
Nebraska Public Power District	Unit 1 + Unit 2 *106+123 MW=* 229,250 kW	**1 x V84.3**
Sheldon station	Unit 1 106,000 kW	**2 x V64.3** **1 x V84.3**
Hallam, NE	Unit 2 123,250 kW *RH Unit 1: 1450 psia / 1000°F / 1000°F* *RH Unit 2: 1800 psia / 1000°F / 1000°F*	**2 x V64.3** **1 x V84.3**

RH = reheat steam turbine Non-RH = non-reheat steam turbine

APFBC repowering is projected to be economically competitive when coal-fired generation additions are needed. APFBC repowering offers the owners added output, with significant improvements in energy efficiency, reduced environmental emissions, and low operating costs. Right now, large scale commercial APFBC demonstrations are underway or planned, so APFBC repowering should be ready for commercial installations around year 2005. If an electric generating company owner anticipates need for new coal-fired generation capacity in the upcoming decade, it is now time to begin assessing the feasibility of APFBC repowering.

ACKNOWLEDGMENTS

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98FT40404. Much of the material was drawn from three of the DOE reports produced under this and predecessor tasks, as cited in the references and related technical papers *[Tonnemacher et al. 1997, Weinstein et al. 1997, 1998c, Wolfmeyer et. al. 1997]*. This work could not have been prepared without the support of Pratt & Whitney, Rolls-Royce, Siemens Westinghouse Power Corporation. Photos are supplied through the courtesy of these manufacturers, and are greatly appreciated.

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