# APFBC Repowering Evaluations at the Sheldon and Greenidge Steam Stations Show the Flexibility of APFBC Technology in Different Applications

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## ABSTRACT

Advanced circulating pressurized fluidized-bed combustion combined cycle (APFBC) technology is a coal-fired technology now under test in large-scale demonstrations. As these tests progress, coal-fired APFBC should become ready for commercial repowering installations around year 2005, making this an appropriate time to begin investigating commercial feasibility. This paper describes a conceptual design evaluation effort that assessed the merits of APFBC repowering at two different coal-fired steam generating stations. The paper shows that APFBC combined cycles have a number of features that make it a more flexible plant repowering option, since unlike natural gas repowering, APFBC combined cycles easily match existing superheat and reheat steam conditions.

The first concept evaluated repowering Unit 1 and Unit 2 of the Nebraska Public Power District's (NPPD) Sheldon electric generation station. This coal-fired station is located near Hallam, Nebraska. Unit 1 is a 109,000 kW net output, 1450 psig/1000 ºF/1000 ºF reheat steam unit with a Siemens Westinghouse Power Generation turbine generator; while Unit 2 is a 125,000 kW net output, 1800 psig/1000 ºF/1000 ºF reheat unit, with a General Electric turbine generator. A single APFBC-modified General Electric Company MS7001EA gas turbine is used in an independent APFBC upgrade of Unit 1, a second MS7001EA in the APFBC upgrade of Unit 2. These evaluations, underway as this

paper is written, should be complete when the paper is delivered. The results are expected to show benefits similar to those from earlier studies: with APFBC, existing plant output doubles, environmental performance is excellent, and energy efficiency increases from 4 to 10 percentage points.

The second station evaluated is Unit 4 of the two units remaining in service at AES Greenidge electric generation station. AES Greenidge is located in Dresden, New York. Unit 4 is a 108,000 kWe reheat unit that sits adjacent to Seneca Lake. For the Unit 4 conceptual assessment, an APFBC-modified aeroderivative gas turbine is evaluated, the Rolls Royce Industrial Trent. The Trent has a significantly higher overall pressure ratio compared to the frame type machines evaluated in the previous studies. The concept evaluation required a 2 x Trent repowering configuration.

The existing Greenidge Unit 4 steam turbine has high flow in its low-pressure section. This proves a particular challenge for an APFBC repowering, which prefers to operate with most of the feedwater heaters out of service for highest energy efficiency. However, the existing Unit 4 has a rather high steam turbine exhaust velocity, about 1,264 feet per second, in the exhaust hood in normal operations, so taking feedwater heaters out of service increases exhaust velocity even higher, which is undesirable. Even with significant steam turbine back-end flow limitations, APFBC repowering boosts Unit 4 output from 106,310 kW to 206,300 kW, and the unit is expected to move from its present 34.6 percent HHV net plant energy efficiency to operate at 39.8 percent HHV energy efficiency with APFBC. Environmental performance is excellent. Different APFBC integration options can overcome the steam turbine limitations, and produce even higher energy efficiency. The paper discusses the actions taken to maintain acceptable exhaust conditions.

These evaluations are part of a series of similar APFBC-repowering concept estimates that DOE is preparing. All of these studies use Foster Wheeler APFBC equipment, but different gas turbine equipment.

In two earlier APFBC repowering concept studies, an APFBC-modified Siemens-Westinghouse W501F combustion turbine was used. At Carolina Power & Light Company's L.V. Sutton steam station, Unit 2 output increased from 106,000 kWe to 226,500 kWe, and the existing 32.0 percent HHV level energy efficiency improved to 42.4 percent HHV (44.1 percent LHV). At Duke Energy's Dan River station, Unit 3 output went from 143,740 kWe to 290,409 kWe with APFBC, and energy efficiency increased from 36.4 percent to 43.2 percent with APFBC. In each case, APFBC environmental performance is excellent, and the cost to repower ranged from about $800 to $1,000 per combined kilowatt. The L.V. Sutton site was also used for APFBC repowering concept evaluations using the Siemens Westinghouse V64.3 and V84.3 gas turbines, and with Pratt & Whitney Turbopower FT8 Twin-Pac gas turbine sets.

A fifth APFBC concept evaluation is also underway, investigating the APFBC repowering of Units 1, 2, and 3 at the Arizona Public Service Company's Four Corners station. The Four Corners station APFBC upgrade is evaluated with phased construction approach to the APFBC upgrades. The Four Corners station uses APFBC-modified Dresser-Rand gas turbomachinery.

## WHAT IS APFBC?

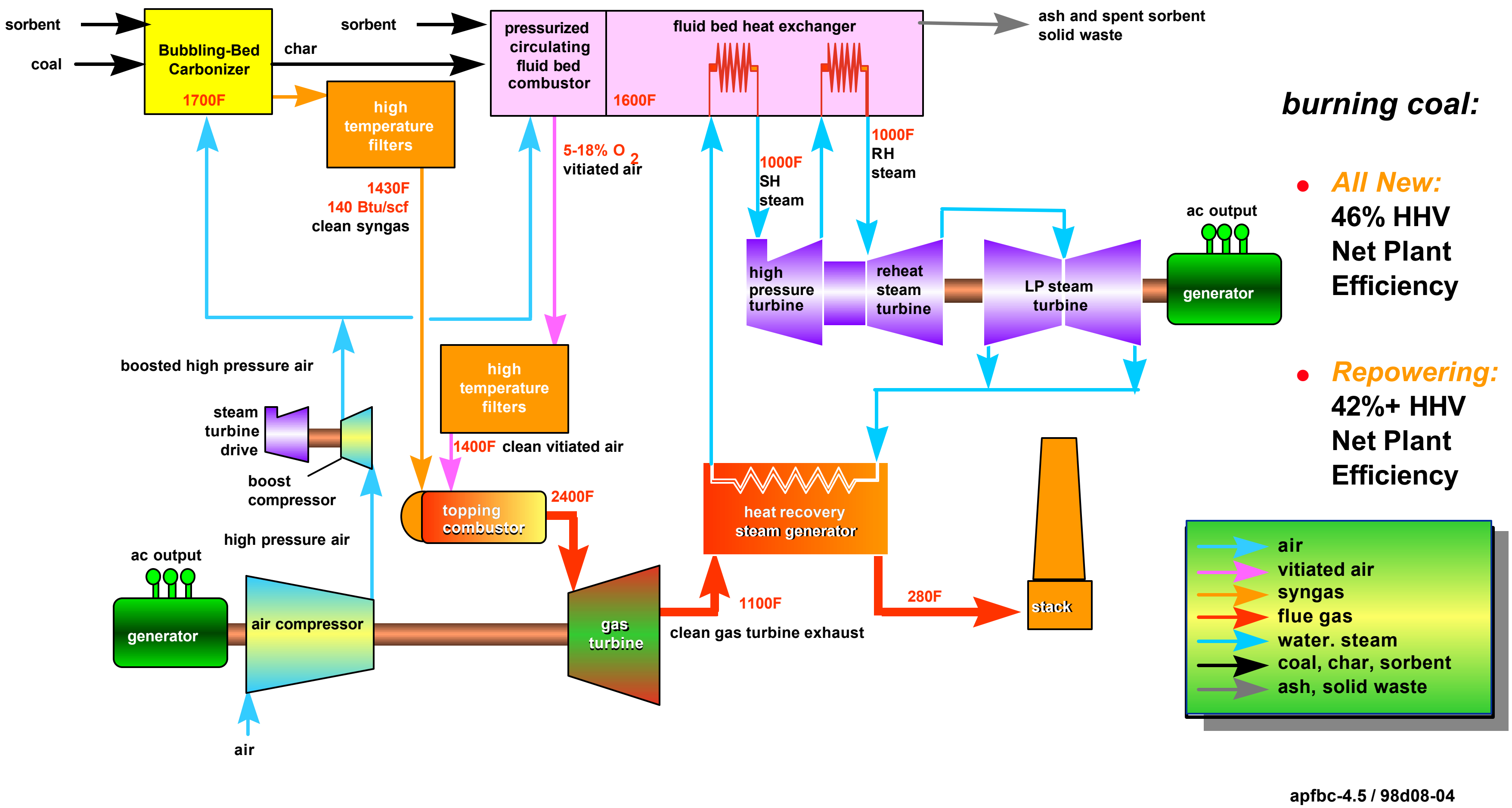
An advanced circulating pressurized fluidized-bed combustion combined cycle (APFBC) power plant is a type of gas turbine combined cycle that is fueled entirely on coal. It provides environmental performance superior to new source performance standards (NSPS) requirements, and the U.S. Department of Energy (DOE)[1] estimates it 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 (fuel cost plus fixed and variable operating and maintenance costs are low). Based on earlier DOE evaluations[2], DOE found that 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. There are potentially many plants similar in size to the Sheldon and Greenidge station units that could benefit from APFBC repowering.

The APFBC system uses 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 (PFB) combustor with fluid-bed heat exchanger to develop hot air for the gas turbine, and steam for the steam bottoming cycle. In addition, APFBC has a carbonizer (a pressurized, fluidized, jetting-bed device) to produce fuel gas from coal for the gas turbine topping combustor. These provide gas turbine firing conditions that allow high combined cycle energy efficiency levels using coal as the unit's fuel.

Exhibit 1 illustrates the major components in an APFBC system, including the following:

- **Boost Compressor** - which is a conventional centrifugal compressor that makes up the added pressure drop experienced by the air flowing through the CPFBC circuit, relative to a typical gas turbine combustor loss. The use of the boost compressor restores the component matching provided by the original gas turbine design, and minimizes the need for redesign.
- **Carbonizer** - a device that partially gasifies the coal, providing a low-Btu syngas for the topping combustor and a char, rich in carbon, which is transferred to the PFBC for complete combustion.
- **CPFBC** - the circulating pressurized fluid bed combustor (CPFBC) burns the remaining char from the carbonizer and heats the main air stream from the gas turbine compressor to the bed temperature (near 1600 ºF in this case). The CPFBC vessel contains the steam generation, and finishing superheat and reheat surfaces. An external steam drum collects the steam.
- **Gas Turbine** - one or more modified machines that are comprised of a compressor and an expander; in this paper, a single APFBC-modified General Electric MS7001EA is used at the Sheldon station and two APFBC-modified Rolls Royce Trent machines are used at the Greenidge station.

## Exhibit 1. APFBC Power System Sketch




*note: Illustrative levels for APFBC only, not those for this particular site or gas turbine*

- **Heat Recovery Unit and Stack** - which recovers thermal energy from the gas turbine exhaust gas for heating of the steam cycle condensate and feedwater. Usually this provides economizer duty. Depending on cycle conditions, steam generation is also possible in the heat recovery unit.
- **Particulate Removal Devices** - including cyclones and ceramic candle barrier filters, which remove more than 99.9 percent of particulate matter. The gas streams from the carbonizer and the CPFBC are cleaned in separate filter assemblies.
- **Steam Turbine(s)** - for repowering, the existing steam turbine from the station is used; in new applications one or more conventional condensing steam turbines are employed.
- **Topping Combustor** - which burns the syngas produced by the carbonizer using the oxygen remaining in the hot vitiated air from the CPFBC as the combustion air. The temperature of the gas exiting the topping combustor is raised to the rated rotor inlet temperature required the APFBC-modified gas turbine used with the system.

**Status**. APFBC is now beginning the commercial demonstration phase of development. Some key component and integrated system testing by manufacturers and the DOE is underway at the DOE Power Systems Development Facility (PSDF) in Wilsonville, Alabama. DOE is also testing the special gas turbine burners needed 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 (CCT) project at the McIntosh station owned by the City of Lakeland, Florida.

**APFBC Implications**. The high efficiency of APFBC is a direct consequence of combined cycle operation. Some of the output comes from a gas turbine, with the balance from the steam cycle. The unique arrangement of APFBC components allows this to occur using coal as the only fuel for all parts of the process. With APFBC, coal consumption can be 25 percent less per kilowatt than the existing unit, and the coal consumption would be significantly lower per kilowatt output than for a new pulverized coal or atmospheric fluidized-bed plant, the current commercial standards for coal-fueled generation.

APFBC has exemplary environmental performance. This technology may be permittable in most areas of the country.

With its high efficiency, the APFBC will have 25 percent lower emissions of $CO_2$ per kilowatt than the existing unit, and lower emission of pollutants. The limestone in the fluidized bed can remove up to 95 percent of the sulfur at a calcium-to-sulfur molar ratio less than 2-to-1. This level of capture exceeds the 90 percent sulfur removal criterion in the NSPS, if needed. Fluid bed temperatures are uniform and low, so NOx emissions are estimated to be below 0.3 $lb/10^6$ Btu. With selective catalytic reduction, NOx emissions below 0.1 $lb/10^6$ Btu are expected. In pilot plant tests, particulate emissions have consistently measured extremely low, below 3 ppm (0.003 $lb/10^6$ Btu), which is an order of magnitude lower than NSPS requirements.

A successful repowering in the size evaluated in this paper would improve the prospects for earlier commercialization of APFBC, and pave the way for the introduction of similarly sized replicate repowering units and all-new stand-alone "greenfield" installations.

## REPOWERING NEBRASKA PUBLIC POWER DISTRICT'S SHELDON UNIT 1 AND UNIT 2 WITH APFBC

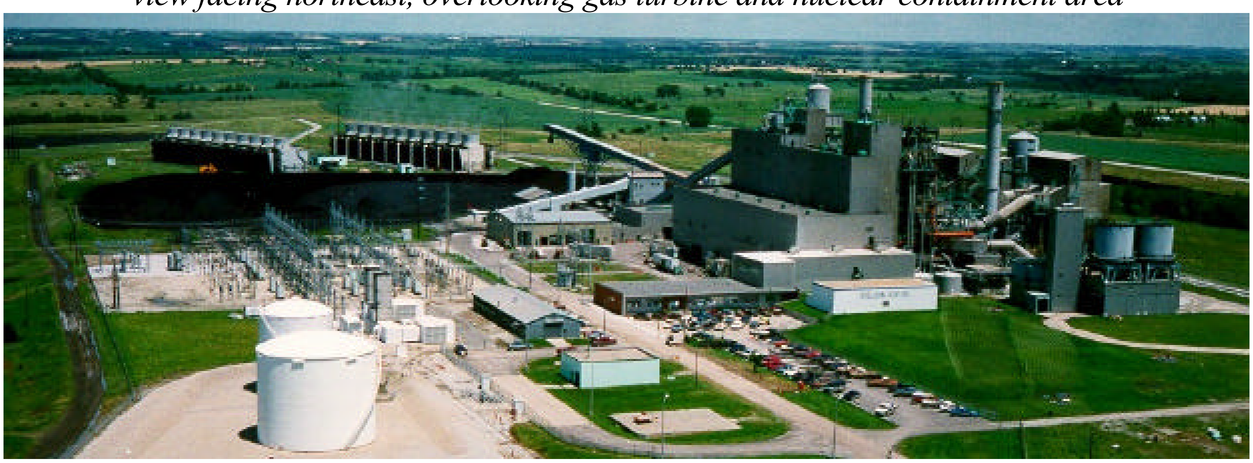
The host site for the first APFBC repowering evaluation described in this paper is the Nebraska Public Power District's (NPPD) coal-fired Sheldon steam generating station. The Sheldon station is located 17 miles south and 5 miles west of Lincoln or 1 mile north of Hallam in Lancaster County, Nebraska. NPPD is interested in APFBC repowering, because:

- APFBC repowering is a coal-fired technology, and NPPD wishes to continue the use of coal at the station.
- While output from the station is adequate today, it appears that APFBC will be commercially ready near the time frame where NPPD projects need of added output.
- APFBC is environmentally clean.

The Exhibit 2 photo is a photograph of the Sheldon station looking toward the northeast. Prominent in the photo, diagonal in the left background, are the plant's two banks of cooling towers. The entire west wall of Unit 1 and Unit 2 faces leftward toward the viewer in right-hand potion of this photo, with Unit 1's south wall closest to the viewer. Both units have Babcock & Wilcox cyclone boilers. Unit 1 was commissioned in 1961. Unit 1 is a 109,000 kW net output, 1450 psig/1000 ºF/1000 ºF reheat steam unit with a Siemens Westinghouse Power Generation turbine generator. Unit 2 is just behind Unit 1 in this photo, in the same structure, where the diagonal coal conveyor enters at the back in this photo, along the hidden north wall. Unit 2, commissioned in 1968, is a 125,000 kW net output, 1800 psig/1000 ºF/1000 ºF reheat unit, with a General Electric (GE) turbine generator.

**Exhibit 2 Nebraska Public Power District's Sheldon Station**

*view facing northeast, overlooking gas turbine and nuclear containment area*



**NPPDsheldon-02b.jpg**

The raised grassy area in the lower right, just past the two lower buildings, contains the tomb for the remains of a test liquid sodium cooled graphite nuclear reactor plant that formerly operated at the site. That area can not be built upon. The proposed site for the APFBC repowering is the area presently occupied by the parking lot left and adjacent to the tomb, and the present location of the long administration building immediately behind the parking lot in the view in the photo. The administration building would be relocated and the present building demolished to make room for the two APFBC power islands.

In this evaluation, two independent APFBC trains will be used – one to repower Unit 1, and another for Unit 2. The operating conditions for APFBC repowering Sheldon Unit 1 and Sheldon Unit 2 are as follows:

- Carbonizer temperature: 1700 ºF.
- Fuel gas temperature to filters: 800 ºF.
- Circulating PFBC bed temperature: 1600 ºF.
- Vitiated air temperature to the filters: 1000 ºF.

**A 1 x GE MS7001EA Configuration Selected**. Each independent APFBC system would use a single APFBC-modified GE MS7001EA gas turbine.

## REPOWERING GREENIDGE UNIT 4 WITH APFBC

The second site considered for APFBC repowering that is described in this paper is the AES Greenidge. AES Greenidge is located near Dresden, New York, on the west shore of Seneca Lake, one of the Finger Lakes. Exhibit 3 shows a view of the station facing northeast. Turbine generator Unit 4, a 108 MWe output reheat unit at the left in the photo, is supplied by Boiler No. 6, which uses the stack to the left. With APFBC repowering, Boiler No. 6 would be replaced by the APFBC equipment, but the turbine/generator and other plant equipment would be retained.

**Exhibit 3**
**The AES Greenidge Steam Station**

Greenidge.JPG
photo courtesy of AES Greenidge

AES Greenidge LLC. is interested in APFBC repowering for the following reasons:

- APFBC repowering affords the opportunity to increase generation capacity and improve heat rate.
- In a competitive business environment, low price wins.
- Coal remains an important fuel for AES Greenidge.
- APFBC is a clean technology, has good cycle efficiency, and has the technology test programs in place to prove its feasibility.
- Should gas prices increase above projections, coal projects could become more favorable.

AES Greenidge wants to understand this technology better to determine the feasibility of APFBC as a possible next coal-fired unit generation expansion option.

While the concept assessment is still underway, some preliminary observations can be made about possible locations for the APFBC equipment at the site:

- The APFBC equipment could be placed at the west of the existing equipment, adjacent to Unit 4, to the left of the powerhouse in the photo.

- There is adequate level space to the west, but several small structures would need to be relocated.
- The high energy steam pipe run lengths would be acceptable.
- Coal delivery could make use of much of the existing coal delivery system.
- The length of transmission wire to get to the switchyard would be acceptable, and the yard has adequate capacity to distribute the added generation to the high lines.
- The west end of the coal yard might be used for limestone delivery.

✔ *West-end arrangement tentatively chosen for APFBC.*

The operating conditions for APFBC repowering Greenidge Unit 4 are as follows:

- Carbonizer temperature:  1700 ºF.
- Fuel gas temperature to filters:  1430 ºF.
- Circulating PFBC bed temperature:  1600 ºF.
- Vitiated air temperature to filters:  1450 ºF.
- Heat recovery steam generator stack temperature:  280 ºF.

### *APFBC Repowered Greenidge Unit 4 Plant Process Decisions*

**A 2 x Trent Configuration Selected**.  The selected repowering option was to use two APFBC-modified Rolls-Royce Trent gas turbines to repower Greenidge Unit 4.

**Other Configurations Rejected**.  A single Trent proved too small to effectively repower Greenidge Unit 4.  A 2 x Trent configuration is feasible, and was selected.  It was felt that this made good use of the existing equipment, and had a configuration with good prospects for being cost effective for AES Greenidge.

A 3 x Trent repowering would also be feasible, and in a more detailed concept assessment would deserve consideration.  It was not chosen because it increased complexity and capital costs.  However, if additional coal-fired power were desired, the 3 x Trent configuration would merit further study.

**Avoiding Too Much Back-End Steam**.  The existing Unit 4 steam turbine has high flow in its low-pressure section.  This proves a particular challenge for an APFBC repowering.

For this repowering case, with a 2 x Trent APFBC, it is preferable for best energy efficiency if all feedwater heaters (excepting perhaps the deaerator) are taken out of service.  This makes best use of the low-temperature recovery of heat from the APFBC island and gas turbine heat recovery system.  However, the exiting Unit 4 has a rather high steam turbine exhaust velocity, about 1,264 fps, in the exhaust hood in normal operations.  If throttle flow were held, and feedwater heaters were taken out of service with APFBC repowering, additional steam would flow through the low-pressure sections, increasing velocity even higher, which is undesirable.

Two actions are taken here to avoid overloading the main Unit 4 low-pressure steam turbine.  These are the following:

- Reduce the total amount of steam passing through the steam turbine by setting the front-end main Unit 4 high-pressure turbine throttle flow ratio to 81 percent.
- Use extraction steam from the IP/LP crossover to drive an auxiliary condensing steam turbine, which drives the APFBC boost compressor.

These two actions, reducing the throttle flow ratio, and diverting steam to the steam turbine boost compressor driver, reduce the back-end steam hood velocity for the Unit 4 low-pressure turbine to an acceptable value of 1,228 feet per second.

As part of this evaluation process, several alternative uses and integration choices for best use of the steam are under investigation.

**Low Vitiated Air Oxygen Percentage Precludes Added Steam Generation**. Often it is possible to generate added steam output by supplying additional coal to the PFB combustor. In this 2 x Trent configuration, however, all of the needs of the PFB combustor are met completely with char from the carbonizer. The oxygen levels in the topping combustor exhaust are already low (4.5 mole percent) in this configuration, so added steam generation capability would not prove practical.

## GAS TURBINES FOR APFBC SERVICE

**Sheldon**. A single APFBC-modified GE MS7001EA gas turbine engine is used in the conceptual design to APFBC-repower Sheldon Unit 1, and another to APFBC-repower Sheldon Unit 2. This gas turbine is a heavy-frame gas turbine designed for power generation service.

**Greenidge**. Two APFBC-modified Rolls-Royce (R-R) industrial Trent engines are used in the DOE conceptual designs to APFBC-repower Greenidge Unit 4. This gas turbine is an industrial electric power generating aeroderivative of the aircraft Trent engine that powers Airbus and Boeing aircraft. The first production industrial Trent was delivered in September 1996. The Trent power generation package is offered by Rolls-Royce as a self-contained electric power generation system which can be used in either simple cycle or heat recovery applications.

**Other DOE APFBC Repowering Studies**. DOE prepared evaluations of APFBC repowering at the Carolina Power & Light L.V. Sutton station, the Duke Energy Dan River station, and the Arizona Public Power District Four Corners station. These concept evaluations use a number of different gas turbines in several configurations, Exhibit 4.

**Modifications Are Needed for a Natural-Gas-Fueled Gas Turbine Design for It to Operate in APFBC Service**. A natural-gas fueled gas turbine design will not work in an APFBC system without modification. Several modifications are needed that include the following:

- Modification is required for collecting and exporting warm compressor discharge air to the APFBC system.
- The materials, valves, and burners must be modified to accept the import hot syngas and hot vitiated air while supporting the stable low-NOx combustion of these gases throughout the load range.
- The topping combustor burners need to be capable of startup on natural gas, with a smooth transition to syngas operations as the APFBC system comes online.

- The system controls must interact reliably and safely with the boost compression system and the APFBC system.
- While not significantly different from natural gas operations, the materials in the unit must tolerate the low dust, sulfur, and alkali loadings from the APFBC during normal and upset conditions.
- Expected Performance and Economy

**Exhibit 4**
**APFBC-Modified Gas Turbines Used in DOE APFBC Concept Screening Studies or APFBC Repowering Concept Studies**

| Station | Units Repowered | Gas Turbine Configuration Investigated | Gas Turbine Overall Pressure Ratio |
|---|---|---|---|
| **Carolina Power & Light Company** | Unit 1** + Unit 2 | *1 x Advanced GT "C17"* | 14.0 : 1 |
| L.V. Sutton station Wilmington, NC | Unit 1** + Unit 2 | 1 x SW W501F | 14.0 : 1 |
| | Unit 2 | *1 x Advanced GT "B17A"* | 14.0 : 1 |
| Non-RH Unit 1: 1450 psia / 1000°F | Unit 2 | 1 x SW W501F | 14.0 : 1 |
| RH Unit 2: 1450 psia / 1000°F / 1000°F | Unit 2 | 2 x P&W Twin Pacs ( 4 x FT8 ) | 20.2 : 1 |
| | Unit 2 | 3 x P&W Twin Pacs ( 6 x FT8 ) | 20.2 : 1 |
| | Unit 2 | 1 x SW V64.3 | 16.2 : 1 |
| | Unit 2 | 2 x SW V64.3 | 16.2 : 1 |
| | Unit 2 | 1 x SW V84.2 | 11.0 : 1 |
| | Unit 2 | 1 x SW V84.3 | 17.0 : 1 |
| | Unit 2 | 1 x SW V84.3, derated | |
| **Duke Energy** | | | |
| Dan River station Eden, NC | | | |
| RH Unit 3: 1815 psia / 1000°F / 1000°F | Unit 3 | 1 x SW W501F | 14.0 : 1 |
| **AES Greenidge** | | | |
| Dresden, NY | | | |
| Non-RH Unit 3: 865 psia / 900°F | Unit 3** + Unit 4 | 2 x R-R Trent | 35.0 : 1 |
| RH Unit 4: 1490 psia / 960°F /1000°F | Unit 4 | 2 x R-R Trent | 35.0 : 1 |
| **Nebraska Public Power District** | | | |
| Sheldon station Hallam, NE | | | |
| RH Unit 1: 1450 psia / 1000°F / 1000°F | Unit 1 | 1 x GE MS7001EA | 12.6 : 1 |
| RH Unit 2: 1800 psia / 1000°F / 1000°F | Unit 2 | 1 x GE MS7001EA | 12.6 : 1 |
| **Arizona Public Service Company** | | | |
| Four Corners Station Fruitland, NM | | | |
| RH Unit 1: 1800 psia / 1000°F / 1000°F | Unit 1 | 2 x Dresser-Rand | |
| RH Unit 2: 2000 psia / 1000°F / 1000°F | Unit 2 | 2 x Dresser-Rand | |
| RH Unit 3: 2000 psia / 1000°F / 1000°F | Unit 3 | 2 x Dresser-Rand | |

** Indicates a non-reheat unit, the rest are reheat units.
GE=General Electric P&W=Pratt & Whitney Turbopower
R-R=Rolls-Royce SW = Siemens Westinghouse

## PERFORMANCE AND COST

**Performance**. Exhibit 6 shows the results of the several APFBC repowering evaluations that DOE completed, and lists those underway. This exhibit lists the expected performance of the APFBC repowering, compared to the unit if no modifications were made.

**Cost**. It is still too early in the Sheldon and Greenidge projects to evaluate the APFBC repowering cost; however, earlier studies[3] at CP&L and Duke Energy give an indication of the magnitude of costs expected for APFBC repowering projects with similar size and scope. Exhibit 6 and Exhibit 5 show the expected total plant cost for these two related APFBC repowering studies.

**Exhibit 5. L.V. Sutton and Dan River APFBC Repowering Estimated Total Plant Cost**

| | Carolina Power & Light | Duke Energy |
|---|---|---|
| | L.V. Sutton Station Unit 2 Repowered with APFBC 1 x Siemens Westinghouse W501-F | Dan River Station Unit 3 Repowered with APFBC 1 x Siemens Westinghouse W501-F |
| Configured as "Utility" plant | $ 243,451,000 | $ 253,346,000 |
| | $ 1,075 / kW | $ 872 / kW |
| Configured as "Merchant" plant | $ 206,751,000 | $ 229,408,000 |
| | $ 913 / kW<br>15.1 % lower | $ 790 / kW<br>9.4 % lower |

**Production Costing Analysis Needed**. The projects described in this paper are not sufficiently advanced for either Nebraska Public Power District or AES Greenidge to evaluate how the APFBC system would dispatch on their electric grid. Both companies await the completion of these studies so they can make that assessment.

Previous APFBC repowering production costing evaluations by CP&L and Duke Energy proved favorable, showing that the APFBC-repowered unit would become the lowest cost coal generation on the system, and would dispatch at over 80 percent capacity factor. Because of high capacity factor, a larger number of betterment projects are economically attractive. Some observations about APFBC can be drawn from earlier investigations by other generating company owners.

## Exhibit 6. Performance Improvements from DOE APFBC Repowering Evaluations

| | CP&L[4] | | Duke Energy[5] | | AES Greenidge[7] | | Nebraska Public Power District[8] | | Arizona Public Service Company[9] | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 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 | Existing Greenidge Unit 4 | Greenidge Station Unit 4 Repowered with APFBC | Existing Sheldon Unit 1 | Sheldon Station Unit 1 Repowered with APFBC | Existing Four Corners Unit 1 | Four Corners Station Unit 1 Repowered with PFBC[§] |
| Gas turbine | -- | 1 x APFBC-modified Siemens Westinghous e W501F | -- | 1 xAPFBC-modified Siemens Westinghous e W501F | -- | 2 x APFBC-modified Rolls-Royce Industrial Trent | -- | 1 x APFBC-modified General Electric MS7001EA | -- | 2 x PFBC[§]-modified Dresser-Rand Industrial Turbo-machinery |
| Syngas temp. to GT | -- | 1400 ºF | -- | 1400 ºF | -- | 1400 ºF | --- | 800 ºF | -- | None[§] |
| Vitiated air temp. to GT | -- | 1400 ºF | -- | 1400 ºF | -- | 1400 ºF | -- | 1000 ºF | -- | 1550ºF[§] |
| Gross output, kWe<br>Gas turbine gross | -- | 138,400 kWe | -- | 138,400 kWe | -- | 110,000 kWe | -- | *tbd* kWe | -- | *tbd* kWe |
| Steam turbine gross | 112,500 kWe | 105,111 kWe | 153,160 kWe | 163,069 kWe | 112,209 kWe | 104,000 kWe | 110,097 kWe | *tbd* kWe | 182,420 kWe | *tbd* kWe |
| Auxiliary losses | -6,500 kWe | -17,020 kWe | -9,420 kWe | -11,060 kWe | -5,899 kWe | - 7,700 kWe | - 4,447 kWe | - *tbd* kWe | -11,191 kWe | - *tbd* kWe |
| Net plant output, kWe | 106,000 kWe | 226,491 kWe | 143,740 kWe | 290,409 kWe | 106,310 kWe | 206,300 kWe | 105,650 kWe[‡] | *tbd* kWe | 171,229 kWe | *tbd* kWe |
| Net plant HHV efficiency | 32.0% | 42.4% | 36.4% | 43.2% | 34.6 % | 39.8 % | 30.9 % | *tbd* % | *tbd* % | *tbd* % |
| Net plant HHV heat rate | 10,660 Btu/kWh | 8,041 Btu/kWh | 9,370 Btu/kWh | 7,891 Btu/kWh | 9,850 Btu/kWh | 8,580 Btu/kWh | 11,040 Btu/kWh | *tbd* Btu/kWh | *tbd* Btu/kWh | *tbd* Btu/kWh |
| Net plant LHV efficiency | 33.3% | 44.1% | 37.9% | 45.1% | 36.0 % | 41.4 % | 32.1 % | *tbd* % | *tbd* % | *tbd* % |
| Total plant cost per combined kilowatt | -- | $ 913 / kW | -- | $ 790/kW | -- | $ *tbd* | -- | $ *tbd* | -- | $ *tbd* |

***tbd*** = *Study still in progress when paper was submitted, results will be presented at conference, contact Dr. Freier for values.*

§ = *Four Corners uses a phased construction approach, initially installing a 1st generation PFBC repowering, with later phases adding carbonizer and gas turbine topping combustor upgrading to 2nd generation APFBC repowering. The conditions for the 1st generation implementation listed above.*

‡ = *The operating point listed here is not at the rated load point of 109,000 kW*

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.[4] With APFBC repowering, energy efficiency improvement is dramatic, so less coal is needed and greater pollution reduction occurs for each kilowatt generated.

Repowering would add an APFBC system to an existing site that retains much of the existing equipment including the steam turbine/generator. The existing boiler is replaced by the new APFBC equipment, however. The gas turbine adds capacity at a site, and the APFBC system improves the environmental emissions. The APFBC-repowered system runs with significantly lower operating costs. Based on earlier DOE evaluation[4,5,6], DOE found that 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.

### *APFBC Repowering Can Create Competitive Advantage*

- Lower cost opportunity fuels can be used, the technology is fuel flexible, and fuel can be easily changed during the plant's life.
- Coal-fired repowering is likely better suited in areas where economical gas delivery might be subject to curtailment or significant price fluctuation during seasonal gas demand peaks; these gas-use peaks are likely to coincide with periods of higher electricity demand in winter peaks, when the competitive spot market price of electricity will command premium electricity rates. Being able to generate during the most profitable operating periods is important to good financial return.
- The superior environmental performance of APFBC means more megawatts can be squeezed out of an existing site. The high efficiency means less $CO_2$ per MW output, should $CO_2$ reductions be mandated.
- Water rights permits are likely avoided even though output increases; the APFBC repowering does not significantly change water use.
- Transmission access exists already; the transmission and switchyards are already strategically near the load centers. The increased capacity from APFBC repowering needs is within the capability of the existing network.
- Using an existing site at higher capacity factor reduces the maintenance and life-reduction costs from damaging start-stop operations.
- Upgrades keep existing plants competitive, retaining the value of an asset.

## THE ADVANTAGES OF APFBC FOR MATCHING EXISTING STEAM TURBINE CONDITIONS

There are potentially a large number of plants of similar size to the L.V. Sutton station[4], Dan River station[5], Greenidge station[7], Sheldon station[8], and Four Corners station[9] units that could benefit from APFBC repowering. There is enough flexibility with APFBC technology that it can be easily adapted to fit the steam demands of any size existing coal-fired plant.

**APFBC Repowering Easily Matches Existing Steam Turbine Steam Conditions**. 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 CPFBC combustor and fluid-bed heat exchanger steam generation surfaces allow 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.

The gas turbine size selection matters: it should be chosen to provide sufficient airflow to support combustion of enough coal to meet the steam demand of the existing steam turbine/generator. However, exact match is not needed, because of the design flexibility of APFBC systems to easily trim the steam demand to meet the existing steam turbine steam demand and temperature conditions. This affords the gas turbine manufacturer an advantage.

The CPFBC bed temperatures are high (about 1600 ºF), so it is easy to match the steam temperature conditions of the existing steam turbine. APFBC repowering does not depend on the exhaust temperature of heat recovery from the gas turbine to meet finishing superheat and reheat temperature. Finishing superheat and reheat steam is generated by the CPFBC in the fluid bed heat exchanger. The gas turbine exhaust heat recovery needs only supply economizing of the feedwater, or if enough energy is left over, to supply a portion of the total evaporation duty or primary steam heating duty.

Matching steam flow demand of the existing steam turbine/generator is also relatively easy for an APFBC system. If the gas turbine heat recovery and the energy from burning the char left over from producing the syngas that fuels the gas turbine do not precisely match the steam generation needed by the steam turbine, the CPFBC combustor can be supplemented with some added coal to make more steam flow. This slightly reduces the APFBC energy efficiency, since the heat from the supplemental coal benefits only the steam cycle, but the added steam generation creates relatively inexpensive coal-fired megawatts, about $300/kW, for any added steam generation capability from any supplementary coal capacity added.

At part load, CPFBC bed temperature is maintained, which means that steam temperature can be held. This means that high steam cycle efficiency can be retained during part-load operation.

**Natural Gas-Fired Repowering Has Greater Difficulty Matching Existing Steam Turbine Conditions**. Attempting to repower existing stations with natural gas-fired combined cycles often involves significant compromise. Because the efficiency of the steam heat recovery is so tightly coupled to the temperature approach to the gas turbine exhaust conditions, using natural gas turbines to repower existing steam turbines is usually not a preferred approach. Efficient repowering with natural gas-fueled gas turbines 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.

Gas turbine exhaust temperature is generally below about 1200 ºF. This means that relatively little temperature differential exists when steam generation is made from exhaust heat recovery. This low exhaust gas temperature is a penalty when natural-gas-fired units are considered for use as repowering combined cycles. In all new combined cycles, heat recovered from the gas turbine exhaust is typically used to generate steam at two or three pressure levels, for powering a multiple admission steam turbine customized for this duty. This arrangement in new combined cycles provides a much better match for the temperature-energy profile of the gas turbine exhaust. This exhaust temperature-energy profile, however, generally does not match that needed to raise the steam conditions required by existing steam turbine systems that were designed for use with a fossil fuel-fired boiler. To overcome low exhaust gas temperature-energy profile often requires such methods as providing supplemental gas firing in the exhaust ducts leading to the heat recovery steam generator, but this can prove inefficient and costly.

## ENVIRONMENTAL & LICENSING ISSUES

Exhibit 7 shows the gaseous emissions comparison for the existing Greenidge Unit 4, and the expected operation with APFBC repowering. The improvements shown for APFBC repowering are representative of those expected from APFBC.

**Exhibit 7. APFBC-Modified Greenidge Emissions Comparison**

*Existing Unit: 106,310 kWe / Unit Repowered with APFBC 206,300 kWe*

| | | | | |
|---|---|---|---|---|
| ***Output*** | Unmodified Unit 4 | ***106,310 kW*** | | |
| | **Repowered with APFBC** | ***206,300 kW*** | | |
| **$SO_2$** | Unmodified Unit 4 | 3.52 lb/$10^6$ Btu | 11,296 tons/yr† | 34.63 lb/MWh |
| | **Repowered with APFBC** | 0.18 lb/$10^6$ Btu | 1,158 tons/yr† | 1.51 lb/MWh |
| **NOx** | Unmodified Unit 4 | 0.33 lb/$10^6$ Btu | 1,060 tons/yr† | 3.25 lb/MWh |
| | **Repowered with APFBC** | 0.30 lb/$10^6$ Btu | 1,628 tons/yr† | 2.57 lb/MWh |
| | ***APFBC with SNCR*** | 0.10 lb/$10^6$ Btu | 543 tons/yr† | 0.86 lb/MWh |
| **Particulate** | Unmodified Unit 4 | 0.04 lb/$10^6$ Btu | 128.5 tons/yr† | 0.394 lb/MWh |
| | **Repowered with APFBC** | 0.002 lb/$10^6$ Btu | 10.9 tons/yr† | 0.017 lb/MWh |
| **$CO_2$** | Unmodified Unit 4 | 202 lb/$10^6$ Btu | 648,647 tons/yr† | 1989 lb/MWh |
| | **Repowered with APFBC** | 202 lb/$10^6$ Btu | 1,095,572 tons/yr† | 1731 lb/MWh |

† Annual emissions are based on an assumed 70 percent capacity factor.

### Solid Waste Characteristics

- The two major solid waste streams from the APFBC combustion plant are the CPFBC combustor spent bed material, and the particulates captured by the fuel gas and vitiated air ceramic candle filters. Coal ash and $CaSO_4$ make up over 77 percent of the solid waste production, with the rest predominantly unspent or calcined limestone.
- APFBC ash is an undifferentiated alkaline mixture.
- APFBC ash is a dry product that is hydrophilic. It sets-up on contact with water, and thus either needs to be transported in dry covered containers, or hydrated before loading for transport.
- APFBC ash is a benign product that is suited for landfill. It has been tested as an agricultural substitute for lime, with positive results, and has good characteristics as a base construction for roadways, and as a portion of conventional concrete/standard concrete masonry construction.

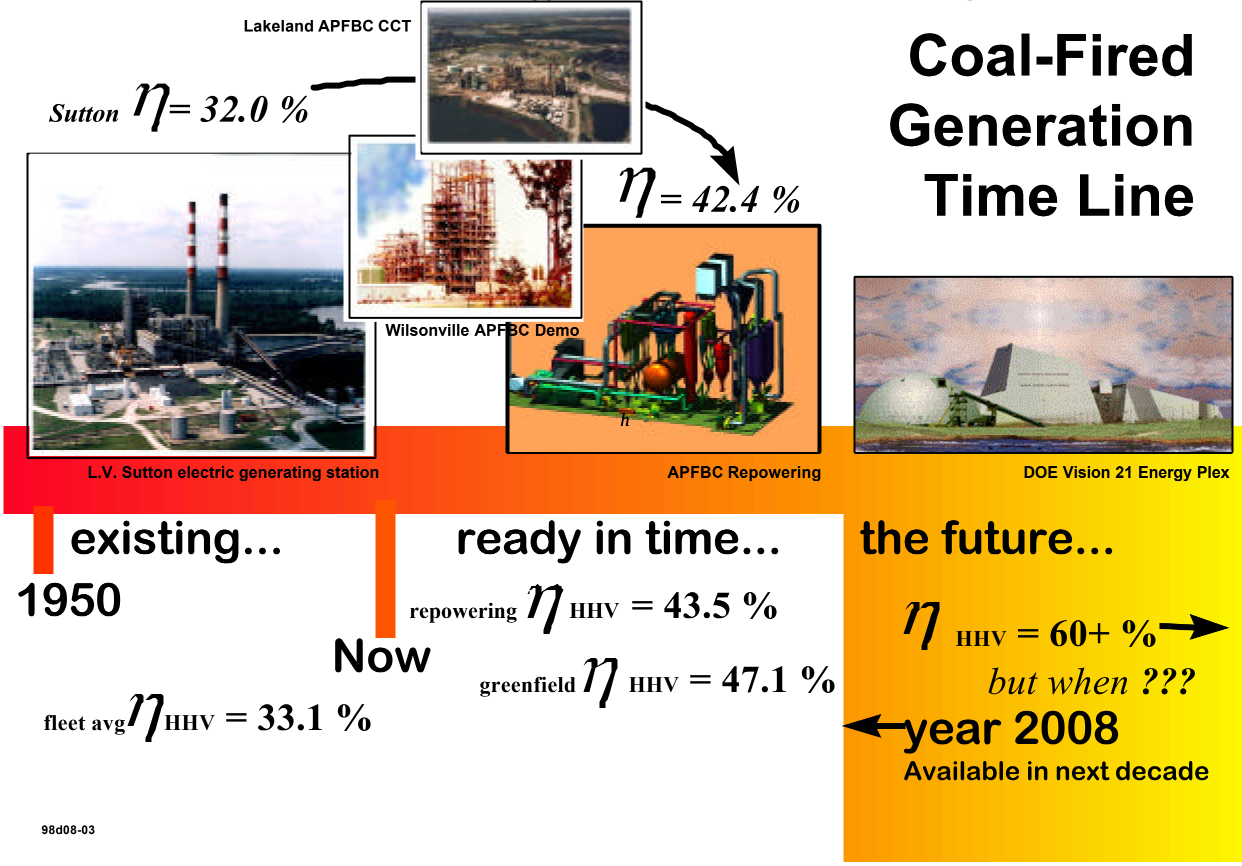
### Water Quality

- Even though plant output approximately doubles with APFBC, the added output comes mostly from the new combustion turbine. The APFBC integration chosen does not significantly alter steam turbine exhaust flow. Therefore, change in the flow or temperature of discharge water is minor, so APFBC repowering is not expected to exceed existing water temperature limits.
- Water use is not expected to change, even though plant output increases by 100 MW.
- Effluent limitations applicable to the repowered or upgraded unit are expected to be similar to those that currently apply to the unit.
- It is not expected that any repowering concept will result in significant water impacts that would require the use of different wastewater treatment systems. Cooling towers, if used, may require an uprating to handle slightly increased duty.

## APFBC DEVELOPMENT TIME-LINE

Successful testing at the DOE Power System Development Facility (PSDF) in Wilsonville Alabama, and at the full-size Clean Coal Technology (CCT) demonstration plant at the McIntosh station owned by the City of Lakeland will pave the way for the initial commercial introduction of APFBC technology. Plant design estimates might be feasible as early as year 2002, when the costs of the CCT demonstration are known. With success at the PSDF and CCT demonstrations, initial APFBC commercial repowering installations as early as year 2005 can be contemplated (see Exhibit 8).

**Exhibit 8**
**The Coal-Fired Technology Choices Need To Be Ready In Time**



## GENERATING COMPANY CONCLUSIONS

NPPD and AES Greenidge are in the midst of these projects, and reviewing the possible value and consequences of APFBC repowering at their stations, and to their respective company's operations. At this stage, these generating company owners have the following perspective on the benefits and risks of APFBC technology for repowering their units:

***APFBC Benefits***

- APFBC uses coal as a fuel, and has flexibility to use a range of low rank coals and opportunity fuels.
- APFBC has good cycle efficiency and good operational economy.
- APFBC is environmentally excellent. It reduces environmental emissions, and should be permittable in most states.
- APFBC technology should be available soon, so long range planning should consider this technology now, and detailed planning for such units can begin as soon as the demonstration projects already underway prove successful.
- APFBC continues the use of existing generation.
- APFBC adapts readily to match a range of existing steam turbine operating conditions; the technology is a reasonable choice for completely coal-fired repowering applications.
- Repowering with APFBC appears possible at lower capital and O&M cost than building a new pulverized coal plant of equivalent capacity.
- Test programs of adequate scale are in place to address all significant APFBC issues.

***Risks Affecting APFBC***

- More stringent future environmental requirements in the future could affect the economics of APFBC economics compared to those of alternatives.
- In some regions, coal projects remain cost competitive. In others, natural-gas-fueled gas turbine combined cycles are an attractive option, because natural gas price remains low even after recent increases. In these regions, gas price would have to increase further before coal technology expansion is justified.
- Ceramic candle filters need more testing time.
- Gas turbines from various manufacturers appear feasible for APFBC applications; however, modification to existing natural gas designs are needed. Some gas turbines appear easier to modify than others. Development and testing are needed before a gas turbine can be commercially offered for APFBC service.
- Gas turbine topping combustors need more testing time.
- Long-term, large-scale integrated testing is needed.
- For the Greenidge station repowering, the extension to high-pressure ratio aeroderivative gas turbines would require development and testing by the APFBC equipment manufacturer; the present experience base is for lower pressure ratio designs.

APFBC technology is being tested in full scale, and has characteristics of great interest for an operating unit that would extend the usefulness of a coal-fired unit as a profitable generator in the increasingly competitive generation market. Both NPPD and AES Greenidge are monitoring the progress of the technology, and including APFBC as a possible coal expansion option for future planning. There is sufficient development progress on the technology to merit planning attention, and the electric generation industry should begin paying attention to its progress. Continued progress at Wilsonville and the City of Lakeland Clean Coal Technology project are important milestones for APFBC, and require continued DOE and manufacturers support of these engineering development efforts.

Right now, natural gas price is low. As long as the current prices stay low, new coal projects will have difficulty competing. However, it is unwise to bet your company on single-fuel generation. Coal generation is still the backbone of U.S. power generation, and remains important to both NPPD and to AES Greenidge. When gas price rises, APFBC technology has good prospects of being ready as a clean, efficient generation repowering option with acceptable initial cost and low operating cost.

The power industry needs to pay attention to the APFBC tests now underway. Success in these development programs means that this technology will become an interesting repowering planning option.

## ACKNOWLEDGMENT

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