Advanced Circulating Pressurized Fluidized Bed Combustion (APFBC) Repowering Concept Assessment at Duke Energy's Dan River Station

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ABSTRACT

As the power industry moves toward increased competition, low operating costs become increasingly important for continued profitability. This paper provides an overview of the plant concept evaluation of using an emerging coal-fired technology for repowering one of Duke Energy's steam generating stations. The paper describes the results of a U.S. Department of Energy (DOE) conceptual design evaluation of an early commercial repowering application of advanced circulating pressurized fluidized bed combustion combined cycle technology (APFBC). The paper provides a review of the DOE study and summarizes preliminary results. It shows the prospects for APFBC repowering, and discusses how this might be an attractive option for a wide range of existing power plants, when added baseload coal-fired generation is needed.

APFBC repowering is worth considering because: an APFBC system integrates well with the existing steam power cycle; APFBC uses lower cost coal, but has high energy efficiency levels similar to combined cycles; it can use a wide range of fuels, and operates well on low rank coals or opportunity fuels; and it is an environmentally clean technology. Repowering can be considered at a number of sites because of the need for added capacity, the poor condition of plant equipment (particularly the boiler), the need for improved environmental performance, the need for shorter licensing period, and other reasons. Simply put, it is often more economical to keep existing generation capacity in operation than to build new capacity.

An 80 MWe DOE-sponsored Clean Coal Technology (CCT) Tidd project demonstrated pressurized fluidized bed combustion (PFBC) which introduced pressurized fluidized beds with gas turbines as an option for improved heat rate and improved environmental performance.

This paper presents an APFBC concept under development by DOE and equipment manufacturers. This all-coal technology has projected energy efficiency in the 42 to 46 percent HHV (43 to 48 percent LHV) range and

environmental emissions superior to New Source Performance Standards (NSPS). A DOE-sponsored Clean Coal Technology (CCT) demonstration project is being developed to pioneer the first commercial APFBC demonstration, scheduled in year 2002. That 170 MWe APFBC CCT demonstration will use all new equipment, and become the City of Lakeland's C.D. McIntosh, Jr. steam plant Unit 4.

This paper's concept evaluation is for a larger implementation. A single Westinghouse W501F combustion turbine modified for APFBC operation (rated at 138 MWe) is considered for use to produce a 300 MWe class APFBC combined cycle. In a repowering application with a fixed gas turbine size, total output depends on the capability of the existing steam turbine/generator, and the amount of coal added (if any) to supplement the char sent to the PFBC combustor. In this output class, APFBC has a wide application for repowering many existing units in America.

Here, APFBC would repower an existing generation station, the Duke Energy's Dan River steam station. The APFBC concept presented repowers Unit 3. The existing coal-fired Dan River Unit 3 has an output of about 153 MWe and operates at about 36.4% HHV net plant efficiency. When repowered with APFBC in this conceptual configuration, the APFBC-modified W501F gas turbine increases total output to about 287 MWe, with high (41.9% HHV) energy efficiency.

Duke Energy’s Dan River Steam Station Unit 3

- 1955 150 MW unit
- Steam flow 1,080,000 pph
- 1800 psig / 1000 ºF / 1000 ºF
- Present heat rate 9,580 Btu/kWh (35.6 % HHV)
- Capacity factor averaging about 28 %

photo courtesy of Duke Energy DT-96603-06

The DOE team of Parsons Power Group Inc., Foster Wheeler Development Corporation, and the Westinghouse Electric Corporation prepared this repowering conceptual design, using APFBC components and systems under development by Foster Wheeler and Westinghouse.

This team is working with Duke Energy’s engineering and production costing departments to assess the unit dispatch characteristics over the plant life, evaluating year-by-year capacity factor expectation, system production costs, and start-stop cycles expected in dispatch in the grid (or power pool) of the host company. This information, along with the costs, establishes utility industry-based life cycle economics of the repowering expected in actual operation.

DOE'S CBD SOLICITATION: APFBC REPOWERING STUDY CANDIDATES

The Department of Energy solicited companies wishing to participate in this APFBC concept evaluation via the Commerce Business Daily. The response was as follows:

- Four investor-owned electric utility companies responded in time.
- A total of 16 units were submitted as candidates.
- Five units were selected: L.V. Sutton station Unit 1 and Unit 2 from Carolina Power & Light *[Tonnemacher et al., 1997, Weinstein, 1997b, 1997c, Weinstein et al., 1997i]*; Dan River station Unit 3 from Duke Energy, the focus of this evaluation *[Weinstein, 1997d, 1997e]*; and Greenidge station Unit 3 and Unit 4 from New York State Electric & Gas *[Weinstein, 1997f, 1997g]*.

Exhibit 1 lists the stations and unit characteristics of those selected for the DOE repowering evaluation. Eleven other units were considered, but not selected for evaluation.

Exhibit 1. Units Selected for DOE APFBC Repowering Evaluations

attribute	CP&L L.V. Sutton Unit 1[†]	CP&L L.V. Sutton Unit 2[†]	*this paper* Duke Energy Dan River Unit 3[‡]	NYSEG Greenidge Unit 3[§]	NYSEG Greenidge Unit 4[§]
Nameplate MW	**97 MW**	**106 MW**	**150 MW**	**55.0 MW**	**106.3 MW**
Year entered service	1954	1955	1955	1950	1953
Steam flow, pph **Main steam psig** **Main steam ºF** **RH steam ºF**	**950,000** **1450 psig** **1000 ºF** **non-reheat**	**775,000** **1450 psig** **1000 ºF** **1000 ºF**	**1,080,000** **1800 psig** **1000 ºF** **1000 ºF**	**565,000** **850 psig** **900 ºF** **non-reheat**	**665,000** **1450 psig** **1000 ºF** **1000 ºF**
Heat rate, Btu/kWh efficiency (HHV)	11,608 29.4 %	10,660 32.0 %	9,580 35.6 %		9,676 35.3%
Average Capacity Factor	***22.7 %***	***23.9 %***	***28.0 %***	***occasionally used for voltage support as synchronous condenser***	***60.0 %***
Site space	space N or S	space N or S	ample space	space W, and in power house	space W, and in power house

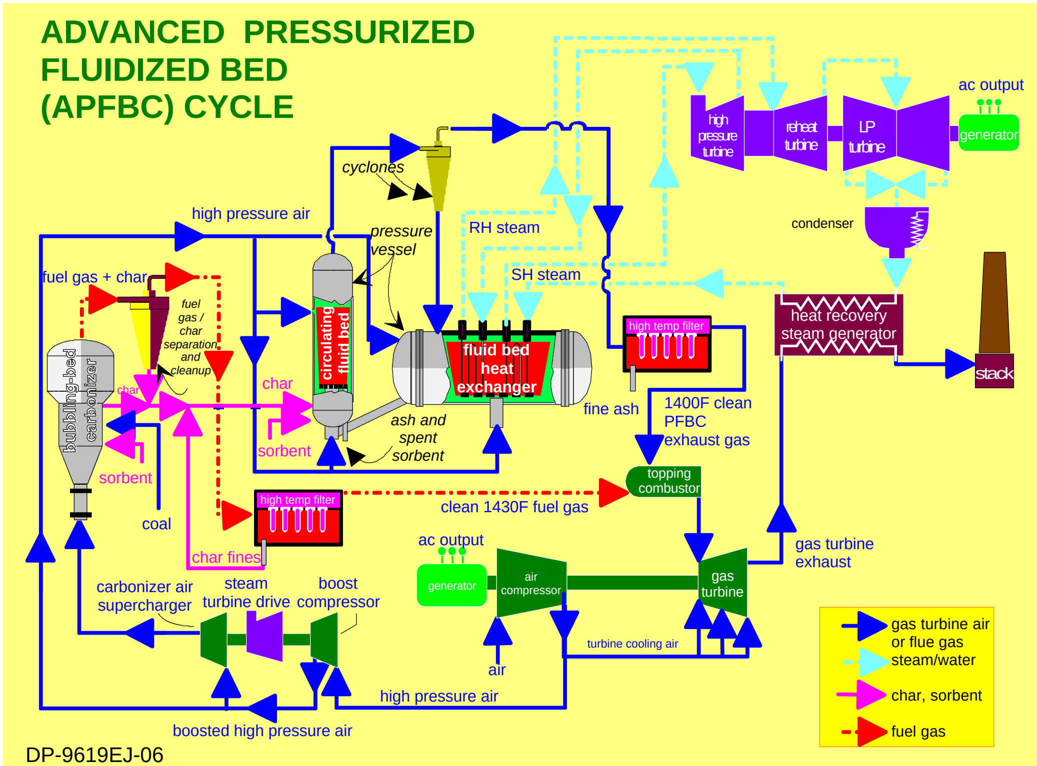
†=*[Tonnemacher et al., 1997, Weinstein, 1997b, 1997c, Weinstein et al., 1997i]*
‡=*[Weinstein, 1997d, 1997e]*
§=*[Weinstein, 1997f, 1997g]*

APFBC DESCRIPTION

An APFBC power plant is a new type of gas turbine combined cycle that is fueled entirely on coal. It provides environmental performance superior to NSPS requirements, and DOE *[DOE, 1993]* 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. Based on earlier DOE evaluations *[De Lallo et al., 1997]*, 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 a large number of plants of similar size to Dan River Unit 3 that could benefit from APFBC repowering.

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 (PFB) combustor with fluid bed heat exchanger to develop hot air for the gas turbine and steam for the steam bottoming cycle, and a carbonizer (a fluidized jetting-bed) to produce fuel gas from coal for the gas turbine topping combustor. This provides high combined cycle energy efficiency levels on coal.

Exhibit 2. Advanced Circulating Pressurized Fluidized Bed (APFBC) Power System Sketch



Boost Compressor. An APFBC system uses combustion turbine compressor discharge air. There is a lot of equipment before the gas is returned to the gas turbine topping combustor. A boost compressor system is employed to overcome the pressure drop of this APFBC equipment, so that an aerodynamic match is made that preserves the use of gas turbine sections designed for natural gas service. The boost system also assists start-up and improves operational flexibility. This boost compressor is driven by a condensing steam turbine in this concept, others use variable speed motor drives.

PFB Combustor. In this implementation, the circulating PFB combustor heat release is recovered by water- and steam-cooled tubes in the fluid bed heat exchanger. The PFB combustor operates at about 16 atmospheres and 1550 °F, and the tubes in the fluid bed heat exchanger recover heat from the circulating solids to develop 1815 psia / 1000 °F primary superheat steam to match existing Unit 3 main steam conditions, and 465 psia / 1000 °F reheat steam conditions. The PFB combustor uses a refractory-lined circulating fluidized bed in combination with a separate carbon-steel fluid bed heat exchanger for steam generation. The exhaust of the PFB combustor is cooled with bypass air to 1400 °F before entering vitiated air candle filters. PFB combustor exhaust gas has high enough oxygen content, about 16 mole percent, and high thermal energy content, so that this vitiated air is used as combustion air in the gas turbine topping combustor.

Topping Combustor. A topping combustor is used in an APFBC to obtain higher energy efficiency levels than are possible with a first-generation PFB combustion plant. This gives thes high combustion temperatures needed by large-frame high efficiency combustion turbines, which shifts more of the energy split from the steam cycle to the combustion turbine, increasing combined cycle efficiency. The topping combustor provides significantly higher gas turbine inlet temperatures without the need for increasing fluid bed temperatures. In this implementation, a fuel supply subsystem generates a low-Btu coal-derived fuel gas that is burned with pressurized 1400 °F vitiated air from the vitiated air candle filters. In this application, internally mounted multi-annular swirl burners (MASB) are used in the APFBC-modified Westinghouse W501F topping combustor.

Gas Turbine. The gas turbine is modified to export high pressure air, accept high temperature air to combustor, and accept low Btu fuel gas. In this application, the Westinghouse W501F used is modified for APFBC operations, and is rated at 138 MWe output whether running on syngas in APFBC application, or on natural gas during start-up. The APFBC modifications case a slight derate in output compared to the unmodified natural-gas-fueled production version of the W501F.

Carbonizer. The fuel gas is generated in a jetting-fluidized-bed coal pyrolysis unit/carbonizer that operates at 1700 °F and 19 atmospheres pressure in parallel to the PFB combustor. A jetting bed is used to minimize agglomeration in the carbonizer. The fuel gas from the carbonizer supplies the topping combustor, and the char supplies the PFB combustor. The hot syngas is a low Btu gas, with an HHV heating value of about 136 Btu/scf. This fuel gas is quenched to 1400 °F before it reaches the fuel gas candle filters.

Limestone Sorbent. The char residue from the carbonizer is blended with additional coal (when needed) and burned in the PFB combustor. Limestone is supplied as sorbent to both the carbonizer and the PFB combustor to desulfurize the gases from both units and to minimize carbonizer tar.

Ceramic Candle Filters. The fuel gas from the carbonizer and the vitiated air from the PFB combustor are laden with char residue, sorbent, coal, and fly ash. These solids could erode and foul downstream equipment, so a hot gas cleanup system assisted by hot cyclones is used. The fuel gas and the vitiated air are each quenched to about 1400 °F after the cyclones. The fuel gas is spray-quenched, and the vitiated air is air-quenched. Ceramic candle filters operating at 1400 °F remove the particulates to solids loading levels below 20 ppm, before the gases enter the topping combustor and gas turbine.

HRSG. Gas turbine exhaust heat energy is recovered in a heat recovery steam generator (HRSG). This provides economizing or added steam generation to support the steam bottoming cycle.

APFBC Repowering Considerations

In the repowering concept *[Weinstein, 1997d and 1997e]*, the steam conditions developed in the HRSG and the fluid bed heat exchanger would be matched to the demands of the existing turbine generator, whose added output results in high combined cycle efficiency levels. The repowering system described here is located adjacent to existing structures, and replaces the existing boiler, which at this site would be abandoned in place. In other locations, the APFBC equipment could use the space formerly occupied by the existing boiler as well as added space close by.

There are a number of significant differences in considering APFBC for repowering applications than exist in new site applications. The main considerations involved in repowering include the following:

- Combustion turbine type and size affect thermal and economic performance.
- A close match to existing steam conditions is desirable, unless the choice is to abandon steam turbine.
- High temperature piping runs should be short to minimize material costs.
- Three to four acres of adjacent space to locate the CPFBC, the combustion turbine, and heat recovery system are needed. One to two acres of nearby space is needed to locate limestone pile and receiving / handling equipment.
- Wide fuel tolerance means opportunity fuels can be used; coal or other opportunity fuels can be bought for best economy from a range of suppliers.
- Environmental emissions are superior to NSPS requirements.
- Switchyard and transmission need adequate capacity for added output.

High Energy Efficiency Implications. The high efficiency of APFBC, estimated at 41.9 percent HHV net plant efficiency (43.6 percent LHV), 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 all of this to occur using coal as the only fuel for all parts of the process. With APFBC, coal consumption is 30 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. With its high efficiency, the APFBC will have 1/3 lower emissions of CO_2 per kilowatt than the existing unit, and lower emission of pollutants.

Environmental Emissions. The limestone in the fluidized bed has been tested and shown effective for sulfur capture, so 95 percent of the sulfur is removed 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, and only 70 percent reduction is needed at the site. Fluid bed temperatures are uniform and low, so NOx emissions are low. Carbonizer/PFB combustor tests have demonstrated NOx emissions at 0.1 lb/10^6 Btu *[Robertson, 1996]*,below Title I requirements. In pilot plant tests, particulate emissions have consistently measured below 3 ppm (0.003 lb/10^6 Btu), which is an order of magnitude lower than NSPS requirements.

Considerations for APFBC in Repowering Application. Some important considerations include the following *[Weinstein and Travers, 1997]*:

- Choose closest combustion turbine to supply steam needs; cycle will be slightly compromised because exact match to steam turbine is unlikely.

- Since the existing steam turbine is of 1950's vintage, not 1995 technology, the repowering will not be as efficient as an all-new plant.

- Wear and tear issues are important, as the unit likely is not new and clean; what is its condition?

- Refurbishment and upgrade with new improved steam turbine blading may be desirable, and improved unit dispatch might justify upgrades that couldn't be justified when the plant was at low capacity factor before APFBC upgrade.

- Fitting the unit in the space available can cause other compromises.

Market for Replicates. 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.

APFBC Repowering Concept

Several features of the proposed repowering include the following:

- Boiler replacement repowering with coal-fueled APFBC where the owner can choose to:
  - Demolish the existing boiler, or
  - retire the existing boiler in place, or
  - Retain the existing boiler in standby for increased reliability states.

- A modified gas turbine is needed. The modifications allow export of high pressure air, acceptance of high temperature air to the topping combustor, and acceptance low-Btu fuel gas from the carbonizer. In this concpet, an APFBC-modified Westinghouse W501F is used.

- The carbonizer provides fuel gas for combustion turbine and char for the PFBC.

- Char plus additional coal to circulating pressurized fluidized bed provides steam and preheated combustion air for the gas turbine.

- Sulfur is captured by the limestone sorbent in the carbonizer and PFB combustor beds.

- High temperature candle filters remove dust that would damage the combustion turbine.
  - The 1700 ºF fuel gas from the carbonizer is cooled to 1430 ºF, before the fuel gas filters, and
  - The PFBC operates at 1550 ºF and its exhaust air is cooled to 1400 ºF before the filters, so the vitiated air filters after the CPFBC operate at 1400 ºF.

- An APFBC system has combined cycle efficiency levels, but on low-cost coal instead of natural gas.

FITTING THE APFBC ONTO THE DAN RIVER SITE

The development of the Dan River plant site to incorporate the new structures required for this repowering takes place to the southwest of the powerhouse, as shown in Exhibit 3. APFBC structures are aligned next to the powerhouse, south of the rail lines, yet north of the river. The coal preparation and injection facilities are aligned with the existing coal conveyors. The limestone sorbent preparation and injection areas are to the west of the coal conveyors. Limestone receiving and storage facilities are located nearby, southwest of the preparation and feed equipment. A cut-out is required in the hill to the west of the rail line, to accommodate the new limestone sorbent pile.

The APFBC island and the associated building enclosing it are located adjacent to the coal preparation and injection equipment. A plan and elevation of the new equipment is illustrated in Exhibit 4. Ash silos are positioned northwest of the APFBC. The gas turbine and its ancillary equipment are sited at the southwest of the PFBC, in a new turbine building designed expressly for this purpose. A bridge crane is not provided in this conceptual design. The combustion turbine's heat recovery steam generator (HRSG) and stack complete the development to the south west. There are dampers and a bypass stack before the HRSG to accommodate natural gas firing of the combustion turbine as a peaking unit, should the APFBC system be out of service.

The arrangement provides good alignment and positioning for major interfaces, provides for rail delivery of coal and limestone, and rail hauling to remove ash and spent sorbent. Truck access is also feasible with this configuration. The positioning of the HRSG in relation to the gas turbine results in increased lengths of feedwater and condensate pipe, but shortens the runs of expensive refractory-lined gas piping. Transmission line access from the gas turbine step-up transformer to the existing switchyard is somewhat longer than desired, but is still within acceptable parameters.

The arrangement described above permits construction to proceed on the entire APFBC addition with minimal interference to operation of the existing plant. The outage required to make the necessary tie-ins to the existing plant can be very short; the total plant outage may be governed by the time required to refurbish the original steam turbine generator sets, and then startup and test the integrated plant.

Demolition Requirements. In order to accommodate the location of the APFBC structures and equipment at the Dan River, the several miscellaneous, temporary facilities must be demolished and rebuilt at new locations, if they are still required. The area adjacent to the existing powerhouse, the area west of the powerhouse west of the railroad track will need to be excavated. These areas may contain buried piping systems and/or cable. These items must be removed and relocated, if still functionally required.

Exhibit 3. Placement of the APFBC Equipment to the Southwest of the Dan River Site

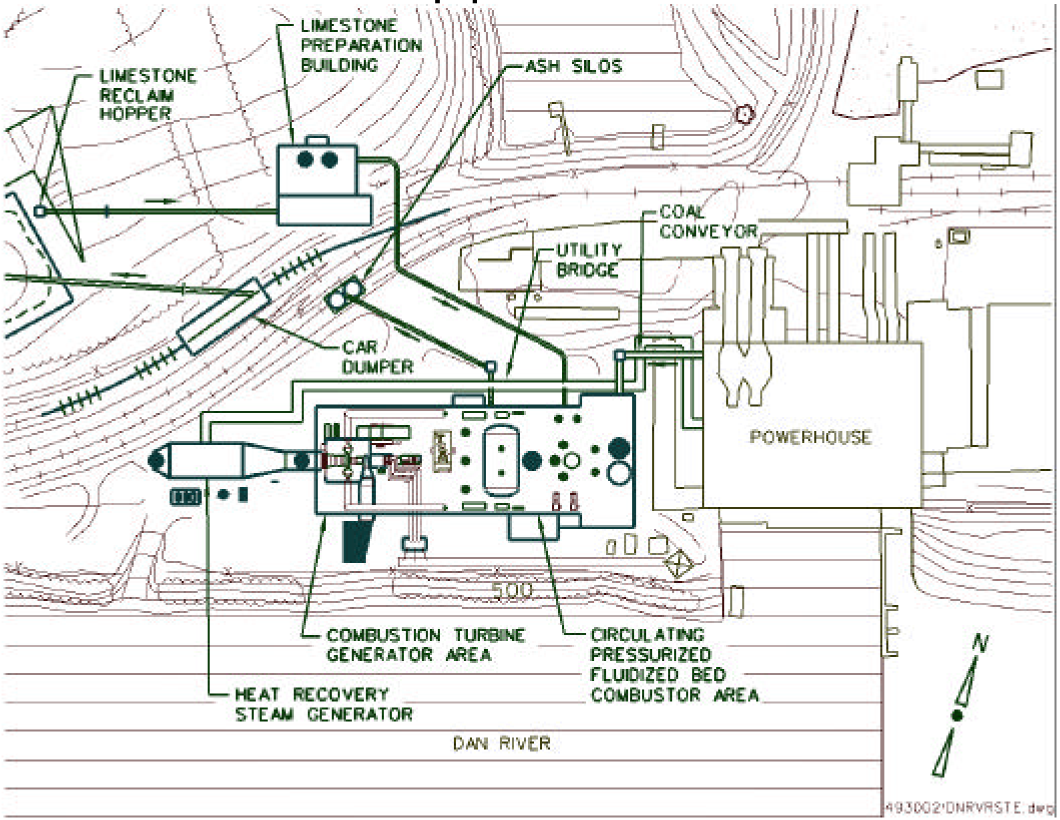


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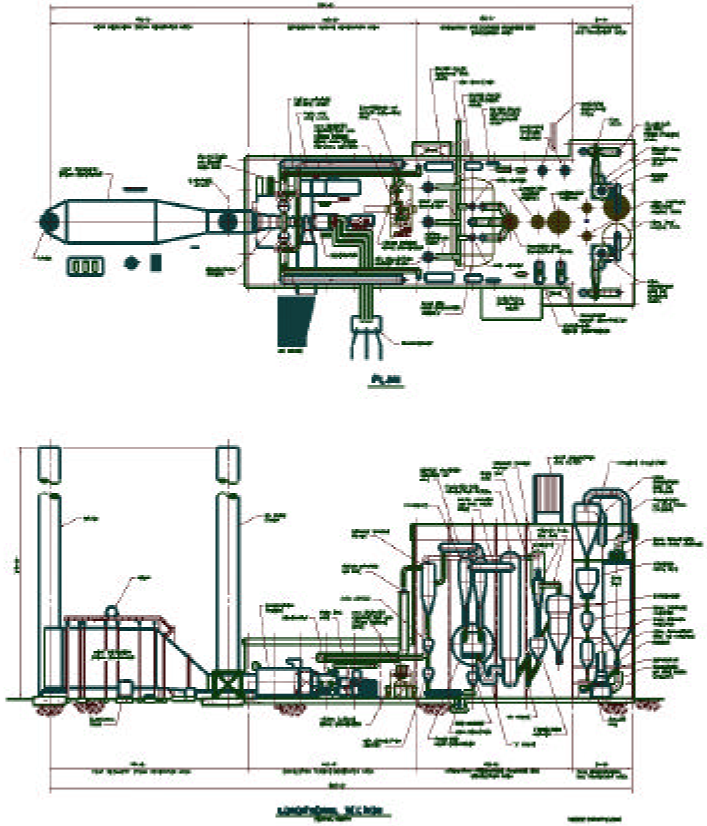
Exhibit 4. APFBC Power Block Plan and Elevation View at the Dan River Site



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DAN RIVER APFBC REPOWERING STUDY CASES

The evaluation included assessment of the following study cases:

- BASE: Unmodified unit.
- Unit upgraded to equivalent environmental emission levels as expected from APFBC repowering using conventional technology:
  - Low NOx burners / overfire air.
  - Wet flue gas desulfurization.
- Unit 3 repowered with APFBC in a configuration felt to have the best potential for lowest life cycle cost. This supplies full steam flow to the existing Unit 3 steam turbine. This choice provides added megawatts of steam output at a relatively low increment in capital cost, but the choice also slightly compromises the highest potential APFBC energy efficiency, since some coal energy is fed to the circulating fluidized bed to add steam output but bypassing the higher efficiency combustion turbine topping cycle.

Main Questions

The evaluation addressed a number of significant questions related to repowering an existing unit with APFBC. These included the following:

- Performance improvements possible in a real unit.
- Capital costs.
- Integration problems.
- Is highest efficiency (44 percent)/modest increase in output preferred over high efficiency (40 percent), but highest output?
- System production costs, capacity factor, system savings.
- How would APFBC-repowered units dispatch? Do they have interesting dispatch features? Are there needs/features that need to be emphasized in a test program?
- Economics for repowering: is this a viable option?
- How would this project look to power industry decision makers?
  - As a first-of-a-kind demonstration, or
  - As a commercial option after a successful demonstration.

Additional Evaluation

The following items are included in the DOE study, and reported in that study's documentation *[Weinstein, 1997e]*.

- Status and technical readiness of APFBC for such a project.
- Site arrangements and alternatives.
- Comparison to conventional technology environmental upgrade of Unit 3.
- Plant configuration details and heating surface arrangements.
- Heat and material balances.
- Detailed performance estimates.
- Plant descriptions and equipment lists.
- Capital and operating cost estimates.
- Assessment of startup, operating, and shutdown features and characteristics.
- Fifteen-year projections of generation production costs and capacity factors for the APFBC plant dispatched against all other CP&L units to meet anticipated CP&L future demand needs.
- Economic assessment of the project.

PRELIMINARY RESULTS

When this paper was submitted for publication in September 1997, preliminary performance assessments were available. These are listed in Exhibit 5.† These are being reviewed with the APFBC and combustion turbine manufacturers, and final estimates will be prepared after incorporating their comments; the final estimates will be presented at the Conference in December. Exhibit 6 shows the APFBC operating conditions used.

Exhibit 5. Preliminary Performance Estimates for the APFBC Repowering of Dan River Unit 3

	Existing Unit 3	Unit 3 with FGD, low NOx Upgrade	Unit 3 Repowered with APFBC†
Gross output, kWe			
Gas turbine gross	--	--	138,400 kWe
Unit 3 steam turbine gross	153,160 kWe	153,160 kWe	173,153 kWe
Auxiliary losses	-9,420 kWe	-10,960 kWe	-24,261 kWe
Net plant output, kWe	143,740 kWe	142,200 kWe	287,292 kWe†
Net plant HHV efficiency	36.4%	36.0%	41.9%†
Net plant HHV heat rate	9,370 Btu/kWh	9,470 Btu/kWh	8,125 Btu/kWh†
Net plant LHV efficiency	37.9%	37.5%	43.6%

† *In September 1997, when this paper was submitted for publication, preliminary performance assessments were available, listed in the table above. In the Conference, revised estimates will be presented. Contact Richard Weinstein for the latest estimate (phone: 610 / 855-2699; eMail: Richard_E_Weinstein@Parsons.COM)*

Exhibit 6. Operating Conditions for Dan River Unit 3 APFBC Repowering

Carbonizer temperature	1700 ºF
Fuel gas temperature to filters	1430 ºF
PFBC temperature	1550 ºF
Vitiated air temperature to filters	1400 ºF
Vitiated air temperature to MASB	1400 ºF
HRSG stack temperature	280 ºF
Feedwater heaters in service?	Only deaerator
Unit 3 steam throttle flow ratio	100%

If instead of the selected design an alternative was considered, with all coal sent to the carbonizer, where no added coal is fed to the circulating PFBC combustor, the cycle would have maximum possible cycle efficiency. This provides the maximum possible fraction of coal energy to the combustion turbine, since only char from the carbonizer is then sent to the PFBC combustor. In "greenfield" APFBC units, this would be the most efficient operating point. For repowering Unit 3, however, this would cause operation of the steam turbine at a low steam flow condition (reduced throttle flow ratio, TFR). The changes in performance for this alternative listed in Exhibit 7.

Exhibit 7. Changes If APFBC Repowering Were Instead Designed for Maximum Energy Efficiency

Steam turbine throttle flow ratio:	APFBC Repowering 100% TFR	Maximum Efficiency 65.8% TFR
Net plant output	base	output reduced by -52,307 kWe
Net plant HHV efficiency	base	efficiency improved by +1.3 points

TFR = steam turbine throttle flow ratio

CONCLUSIONS

This concept study gives focus to APFBC development, which allows a number of conclusions to be tendered by the evaluation team. These include the following:

- Repowering is feasible at the Dan River site, with the APFBC equipment best placed at the west end of the plant, adjacent to existing Unit 3, as shown earlier in Exhibit 3 and Exhibit 4. This orientation necessitates a relatively long steam line connection to the existing unit, but this does not appear to involve any unusual problems.

- APFBC repowering using an APFBC-modified Westinghouse W501F combustion turbine can add about 140 MWe of additional coal-fired output from the site.

- The potential improvement in energy efficiency with APFBC is dramatic; Unit 3 would move from its present 36.4 percent HHV level to 41.9 percent HHV (43.6 percent LHV) with APFBC repowering.

- The operating production cost economy of using coal, with these excellent levels of energy efficiency, would move Unit 3 from low capacity factor today to baseload service, near the top of Duke Energy's unit dispatch order.

- Such an APFBC unit would be an early commercial application, and a decision today involves investment risk for the owner, since at this time not all APFBC components have been proven in full-scale integrated demonstration. Important information is needed on long-duration integrated operation from the Power System Development Facility, the Lakeland CCT project, and other projects. Still, most components are either commercial, or commercially ready. The duration testing of hot gas filters and multi-annular-swirl burner are under demonstration in the PSDF, Clean Coal, and other programs. However, by the time such a plant would be built, perhaps the year 2002, all of these demonstrations would be in operation and would have produced the necessary design base.

- Adding a wet scrubber to Unit 3 to get the equivalent environmental advantage offered by APFBC would be a challenge, and would probably necessitate the construction of a new stack. Should it prove desirable (it is not necessary to meet environmental requirements) to lower sulfur emissions at the site without using APFBC, it might be more cost effective to purchase sulfur allowances than construct a scrubber.

Recommendations

This plant repowering concept assessment provides a good indication of the features and feasibility of APFBC repowering. However, it is not an optimized design. Further evaluation is needed to establish a firm base for the performance and economic trades associated with many of the choices made here.

<u>Decisions Made That Require Trade-Study Evaluation</u>. The design in this report is feasible. However, design position papers on the major choices are needed before a plant configuration recommendation is established. The lists that follow specify some of the areas where design decisions were made, but involve assessment of alternatives before a final choice of approach is established.

The areas chosen in this design, but need more detailed assessment before final selection, include the following:

- Is non-intercooled boost compression system best?
- A condensing steam turbine driver was chosen for powering the boost compressors for this concept. This necessitates an auxiliary boiler to allow cold starts. Is a variable speed motor drive a better choice?
- Is the choice of a mechanical chiller for hot-day combustion turbine operations economical compared to its benefits?
- Is in-duct alkali-getting the better choice?
- Is a spray cooler for fuel gas the better choice?
- Are there more economically optimum arrangements of the heating surface in the fluid bed heat exchanger (FBHE) and combustion turbine heat recovery steam generator (HRSG)?
- Would dropping to 1400 ºF vitiated air temperature improve overall life cycle economy?

Recommendations for More Detailed Future Assessment. This study is a preliminary concept assessment that provides an important guide to many of the issues related to an APFBC repowering. The study answers many questions, but also raises others. Some of the issues recommended for study in future evaluations include the following:

- Evaluate the economic merits of APFBC with "Opportunity Fuels" (petroleum coke, Orimulsion®, culm, etc.), fuel flexibility, sensitivity to fuel cost, initial design features for maximum future fuel flexibility.

- Increase detail of design, involve manufacturers to a greater extent, improve the cost detail.

- Evaluate whether the increase in Unit 3 condenser duty (Btu/h) are within the capability of the present condenser and verify that the condenser back-pressure assumed is consistent. If not within present capability, assess whether condenser surface upgrade is needed.

- Have several combustion turbine manufacturers evaluate boost compression vs. combustion turbine modification for APFBC operations to see if there is a consensus of preferred method. Provide survey of large-frame combustion turbine manufacturers, supported by site visits, to discuss the merits or problems of the boost-compressor approach to overcoming APFBC system pressure drops.

- Evaluate reliability/availability features and expectations.

- Evaluate part-load operation, operating modes, control, dynamics.

- Is the maximum output integration choice made here as the base case (about 41.9% HHV net plant efficiency) is only one choice of integration. It has a lower $/kW capital cost than the higher efficiency (about 44% HHV net plant efficiency) alternative concept. Is this high output choice really better than the maximum efficiency alternative in overall life cycle cost?

- Evaluate operations and operations staffing needs.

- Detail generation production costing to understand operating economics at several electric utility companies.

- Evaluate how APFBC might be sold in the emerging competitive market; assess market size, assess when the market for added capacity will arrive, evaluate which entities (Genco, IPP, vertically integrated energy companies?) will be purchasing generation, and assess what their needs will be for coal-fired baseload generation in that future market.

<u>Recommendations for APFBC Test Program Enhancement</u>. Some additional testing would increase confidence in some of the design decisions made in this concept. These suggestions include the following:

- Provide clear indication of need for alkali-getters. Add a test series at Wilsonville PSDF to establish testing confidence in using in-duct alkali-getting upstream of candle filters in place of downstream packed-bed filters.
- Provide long duration reliability information on combustion turbine operation with multi-swirl annular burners.
- Provide long duration reliability information on ceramic candle filters.
- Test in-duct alkali-getting in place of packed-bed.
- Test the STAMET, Inc. solids feed pump to replace the use of lock hoppers for fuel and limestone feed.
- Test the effectiveness of fuel gas spray cooling.

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