CLN uprates 501 to 6 MW with under 18 ppm NOx and zero CO

By Victor de Biasi

Converting Rolls-Royce 501-KB7S gas turbines from DLE to CLN combustion has increased unit output to 6MW from 5.2MW and cut emissions to 18 ppm NOx and zero CO.

Earlier this year, a large electric utility in the Midwest released emission test findings of an in-house project to convert five Rolls-Royce 501-KB7S gas turbines in cogeneration service from dry low emissions (DLE) to Cheng low NOx (CLN) combustion. Highlights:

☐ **More power**. Base load rating of CLN units was increased to 6MW from 5.2MW at the 1935°F firing temperature of the original DLE gas turbine.

☐ **Emissions**. At a 5MW test point, CLN reduced emissions to less than 12ppm NOx and 2ppm CO versus 25ppm NOx and 50ppm CO for DLE.

☐ **Efficiency**. At base load output, CLN lowered heat rate to 10,245 Btu/kWh (33.3% efficiency) from 10,850 Btu/kWh (31.5%) for DLE.

☐ **Part-load.** At 3MW part-load power output, CLN lowers NOx to 12ppm while DLE is in excess of the allowable 25ppm site limit.

All five engines were modified for CLN operation during a scheduled year-end gas turbine overhaul period at a total cost of approximately $3 million, averaging around $600,000 per engine.

The CLN units were then tested during commercial cogeneration service by recording gas turbine emissions, firing temperature and fuel consumption at different power levels operating with a fixed 1.65 steam/fuel injection ratio.

For general reference, the original Rolls-Royce DLE 501-KB7S gas turbine is design rated at 5.2MW base load output and 10,850 Btu/kWh heat rate (31.5% efficiency) without losses on natural gas fuel at 59°F ambient and sea level ISO conditions.

The units have been in commercial cogeneration operation since 2002. Each genset installation is equipped with a duct-fired HRSG to produce steam for supply to a nearby chemical processing plant while the electricity generated is supplied to the grid.

The five-unit cogeneration facility is nominally rated at 25MW. Operationally, there are only four gas turbines in service at any one time while one is on standby in case of an emergency shutdown or unplanned outage.

Project scope

The electric utility owner's goals for converting the 501-KB7S from DLE to CLN combustion were to: 1) meet EPA emissions limit of 25ppm NOx with as low CO as possible at part-load operation, 2) increase unit capacity by 15% to 6MW, and 3) improve gas turbine heat rate at part-load and

Nominal CLN design performance for 501-KB7S gas turbine. These ratings apply to converted CLN units operating at different power levels (and days) with a fixed 1.65 steam/fuel ratio. Although the data are specific to different units, they are representative of CLN design performance.

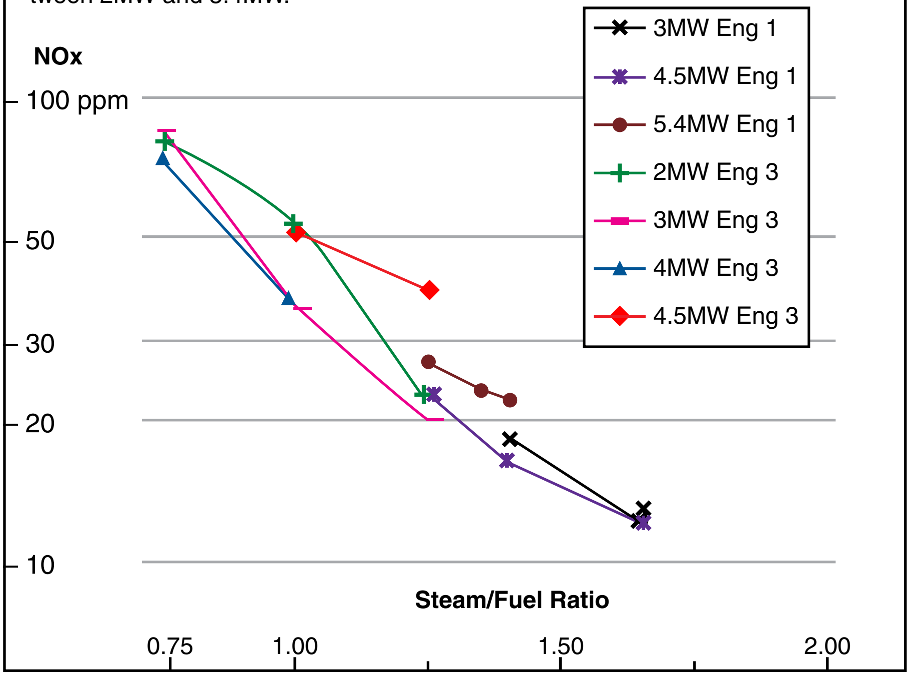
DLE units*	Output	Output	Output	Output
Generator output	5,400 kW	5,100 kW	4,600 kW	3,000 kW
NOx emissions	25 ppm	25 ppm	25 ppm	excessive
CO emissions	50 ppm	50 ppm	50 ppm	excessive
Steam/fuel ratio	N/A	N/A	N/A	N/A
Firing temperature	1935°F	1925°F	1925°F	1527°F

*40°F ambient

CLN units**	Output	Output	Output	Output
Generator output	5,500 kW	5,000 kW	4,400 kW	3,000 kW
NOx emissions	22 ppm	12 ppm	18 ppm	12 ppm
CO emissions	1 ppm	2 ppm	1 ppm	2 ppm
Steam/fuel ratio	1.65	1.65	1.65	1.65
Firing temperature	1848°F	1682°F	1698°F	1501°F

**40 to 44°F ambient

NOx vs steam/fuel ratio. Converted CLN engines 1 and 3 showed a consistent drop in NOx with increasing steam/fuel ratio (up to 1.65) at power levels of between 2MW and 5.4MW.



full load output.

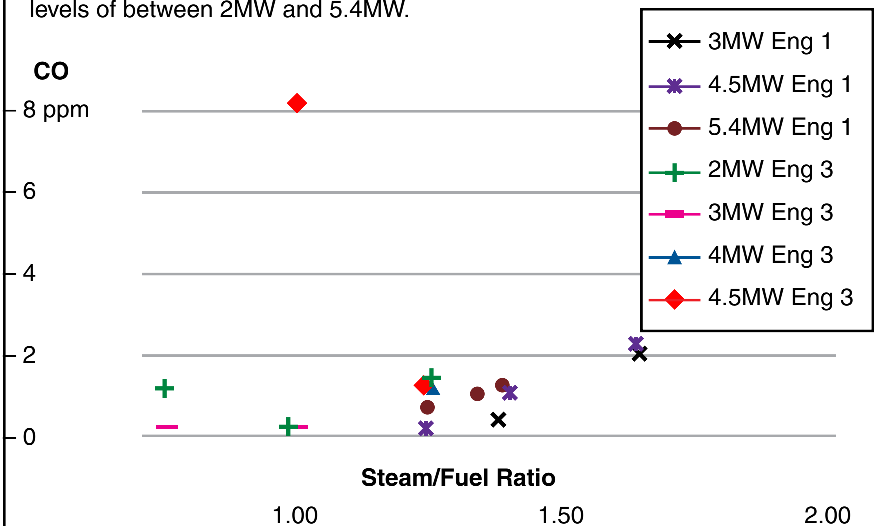
The onsite gas turbine conversion to CLN operation and test was carried out by a team of independent contractors headed by Marsh Creek, LLC as general manager for supervision and coordination of the overall project. Major contractors included:

- **Cheng Power Systems,** responsible for engineering and supply of the CLN steam/fuel manifold equipment, gas turbine operational integration, steam/fuel flow control system design and hardware.

- **Rolls Wood Group,** responsible for replacing the DLE compressor diffuser section with a standard compressor diffuser and for removing the DLE combustors, fuel injectors, associated operating and control equipment. Also, for installing the replacement CLN combustion system package of hardware and controls.

- **Rolls-Royce,** responsible for supervising approved gas turbine modifications. Also, for monitoring performance test and emissions measurement procedures to evaluate and confirm CLN gas turbine performance

CO vs steam/fuel ratio. Converted CLN engines 1 and 3 showed a consistent drop in CO (to near zero) with increasing steam/fuel ratio (up to 1.65) at power levels of between 2MW and 5.4MW.



DLE combustion

The 501-K series gas turbine DLE system design uses premix lean-burn combustion technology to limit the emissions of six axially aligned combustion cans to 25ppm NOx and 50ppm CO at full and part-load output.

Both flame temperature and, consequently, NOx production are lowered by employing air/fuel ratios at least twice as lean as that required for stoichiometric combustion, i.e. where the air and fuel mixture in the combustion zone is chemically balanced.

DLE combustion characteristically propagates elongated flames which sometimes can burn out combustion liners and reach out to overheat and damage first and second-stage turbine blades.

Air-to-fuel ratio

From an engineering point of view, it is always a design challenge to maintain a fixed air/fuel ratio as gas turbine load varies. An overly lean mixture can result in flameout, while richer mixtures would mean higher NOx.

The 501-KB7, for example, requires a 14th-stage compressor air bleed which operates to bypass the combustion system in order to maintain a consistent air/fuel ratio at low fuel flow rates.

Typically, once a 501 engine with DLE is operating at 85% or lower part-load condition, it becomes necessary to bleed air in order to compensate and provide the proper air/fuel ratio.

CLN combustion

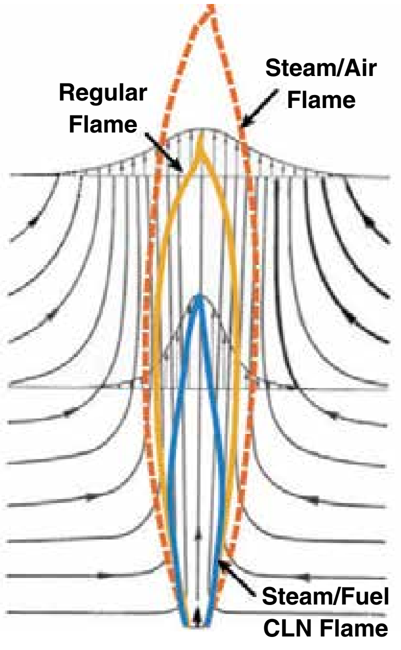
The CLN system was developed by Dr. Dah Yu Cheng, a former rocket scientist with NASA and professor at the University of Santa Clara, now president of Cheng Power Systems.

Steam is commonly used for diluting oxygen concentration or fuel, sometimes both, to control diffusion flame NOx emissions. With CLN, steam is used to dilute the fuel concentration instead of oxygen.

Diluting the fuel rather than oxygen is more effective, Cheng maintains, provided you can also reduce the CO which, in the past, has eluded the industry. Until now, the general belief among gas turbine engineers is that reducing NOx automatically increases CO.

Diluting a fuel stream with steam reduces its specific energy content which has the effect of also reducing flame temperature. It also shrinks the size of the flame envelope. But the rate of heat release going into the turbine is not diminished because the total amount of fuel being burned is the same at any given load point.

Diffusion flame structures. Premixing steam with fuel for CLN combustion reduces flame size and temperature, whereas diluting the air with steam expands and elongates the flame, but in all cases total heat release of the fuel consumed remains the same.



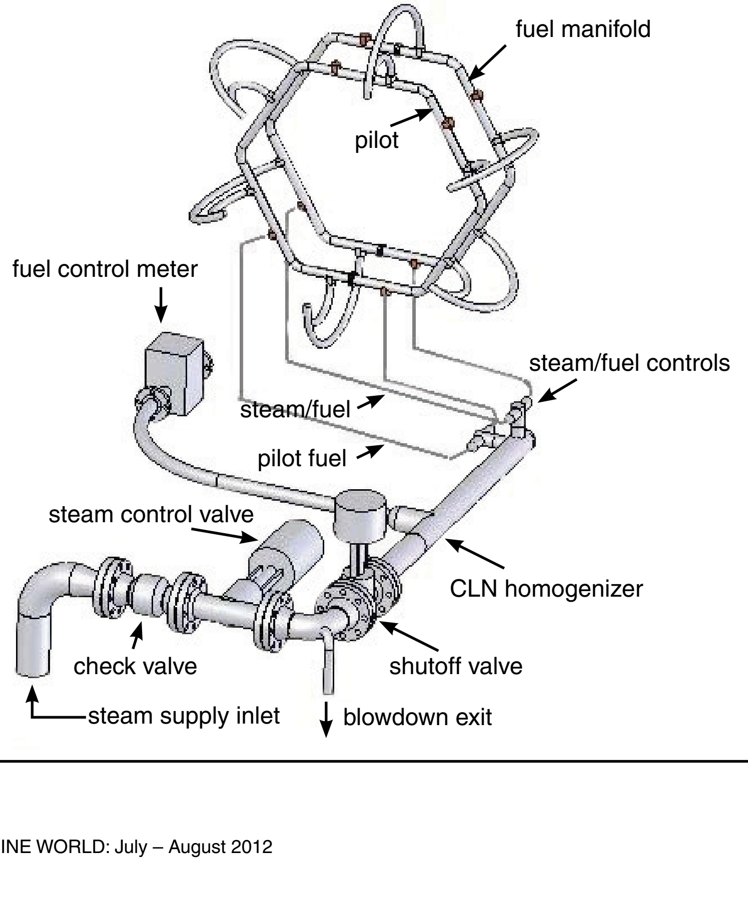
Typically, diffusion flames contain pockets of fuel-rich mixture regions which produce high flame temperature and high NOx emission levels. At the same time, other pockets contain lean fuel mixture regions not able to sustain combustion but which do produce high CO emissions.

Dr. Cheng discovered that the trick to making CO disappear is to achieve the highest possible level of homogeneity in the steam and fuel mixture so as to minimize the deviation between rich and lean mixture regions prior to combustion.

An extensive amount of analytic engineering and testing has been done on the degree of homogeneity and most effective steam/fuel ratios required for reducing both CO and NOx emissions (see emissions charts).

For the 501-KB7 CLN conversion, at its new 6MW base load rating, this works out to a steam/fuel ratio of 1.65 and 5600 lb/hr of steam injection at 650°F 450 psig steam – and over 99.5% homogeneity.

Steam/Fuel manifolds and controls. Ring manifolds and controls automatically maintain fixed 1.65 fuel/steam ratio for CLN system operation.



CLN conversion

Converting the 501-KB7 combustion system over to CLN operation requires removing the DLE combustion liners, fuel injection nozzles, compressor bleed piping and flow controls for all six combustor cans.

Basically, the DLE combustion liner, fuel pre-mix and controls were replaced (for CLN operation) by standard production design LE2 liner set and combustion wraps, and the control system was changed back to standard gas turbine control.

The DLE fuel injection nozzles were replaced by standard production design dual entry low-Btu fuel nozzles adapted for CLN operation.

In addition, the main and pilot fuel manifolds are slightly modified versions of R-R standard hardware with revised mounting brackets and high temperature O-rings to withstand the elevated steam/fuel mix temperatures.

Cheng Power Systems provided hardware for separate "smart" steam and fuel control valves in addition to the homogeneous mixing system that supply the steam/fuel mixture to the Rolls Royce low-Btu fuel distribution manifolds.

The steam supply piping includes a shut-off valve to prevent flameouts during gas turbine startup as required by the enlarged low Btu gas nozzle injection diameters. Once the engine reaches synchronous idle condition, a block valve opens to reduce pressure drop across the nozzle flow passages.

When the engine is up to load, a programmable logic control (PLC) system is used to manage the steam/fuel ratio for NOx control throughout the gas turbine's operating regime.

CLN control system

The smart valve control system compensates for changes in manifold pressure downstream of both steam and fuel valves.

Previously, the fuel control valve assumed a steady supply pressure and relied on valve position as a measure of mass flow. Now, since steam/fuel ratio must be varied, downstream pressure of the valves will change depending on the ratio.

The programmable smart valve inputs mass flow demand (quantity) for both steam and fuel flow. Building flow measurement quantity in those valves enables the programmable control system to send signals to the CLN control as steam/fuel ratio only, independent of load.

When the engine is throttled by adjusting the fuel flow quantities, the steam flow will follow the steam/fuel ratio to set steam flow quantities to maintain the steam/fuel ratio at any load.

An onboard computer adjusts the valve position automatically based on the information of upstream and downstream pressures to maintain a demanded mass flow.

This allows the control system to maintain any fixed steam/fuel ratio up and down the load curve, while maintaining low NOx and low CO conditions.

Steam purity issues

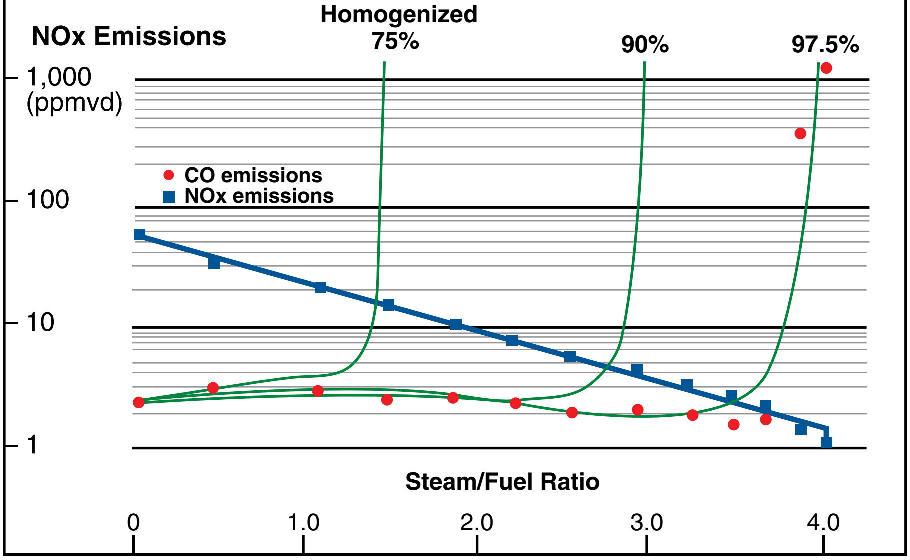
CLN requires an ultra-high degree of purity in the superheated steam used for fuel dilution. Some plant operators mistakenly believe that reverse osmosis (RO) purified water should be good enough to moderate the temperature of the superheated steam.

Reverse osmosis will remove 98% of impurities, but the 2% that gets through creates a drifting problem for the controls. Only deionized water with minimum 18 megohm purity will do the job, says Cheng.

This is based on personal studies backed up by in-service experience at a Chevron facility where a GE Frame 6B gas turbine was modified for CLN combustion and plant operators were adamant about using RO water as pure enough. It wasn't.

Reverse osmosis works for boiler feedwater, thanks to blowdown and systems de-mister treatment that lower the concentration of mineral carryover. But it does not approach the purity that Cheng warns is needed for CLN operation.

Why homogeneity is so important. The more homogenized the steam/fuel flow mix, the more effective CLN becomes in reducing both NOx and CO emissions.



Return on investment

According to Dr. Cheng, the $600,000 unit cost of 501-KB conversion to low emissions CLN combustion is dwarfed by the "free" increase in generating capacity, lower maintenance costs and more flexible power range, Specifically:

- **Capacity.** Base load rating of each unit has been increased to 6MW from 5.2MW (15.4% increase) under the same TIT limit of 1935°F. At an estimated market price of 1,000 $/kW for small cogeneration plants, the extra 800kW on its own is equivalent to an $800,000 increase in asset value.

- **Maintenance.** DLE combustion problems after only 7,000 operating hours (on average) typically require a 1-week shutdown for unscheduled repairs and replacement of combustor liners and hot gas part parts, at a cost of $450,000, versus a projected 25,000-hr hot section life for CLN combustion.

- **Power range.** The owner-operator's self-imposed 75% part-load cutoff point, where DLE combustion was no longer in compliance with EPA emission limits, has been expanded for CLN operation to less than 50% part-load output. ■