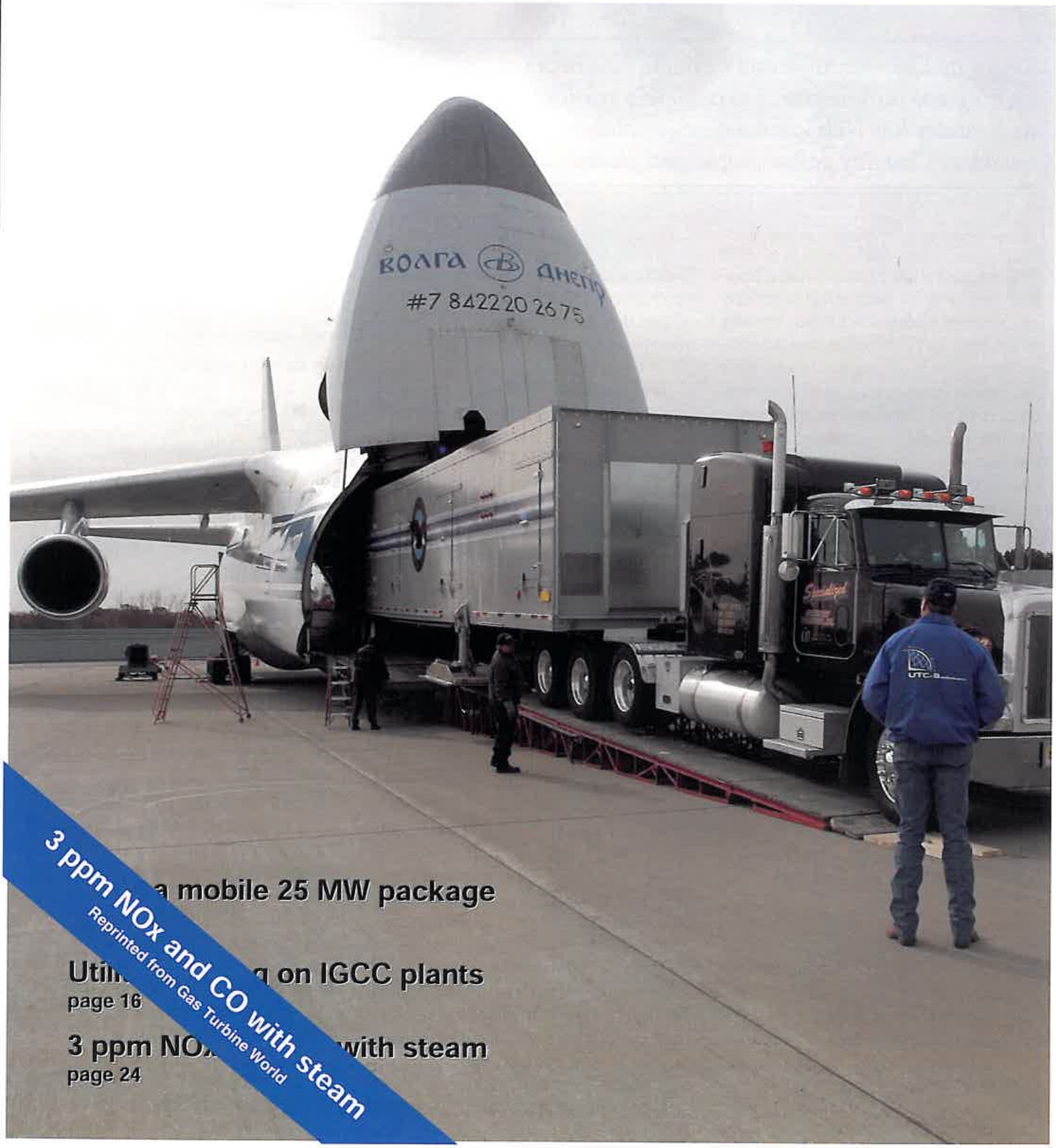
Gas Turbine World

Where Technology Turns Into Power and Profit



a mobile 25 MW package

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3 ppm NOx and CO with steam
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Steam-fuel mix limits NOx and CO below 3 ppm without DLN or SCR

By Victor de Biasi

Steam-fuel pre-mix injection technology is being retrofitted to existing gas turbine plants to achieve ultra-low emission levels, without dry low NOx combustion or catalytic reduction, while enhancing hot day power output and plant heat rate.

Dr. Dah Yu Cheng has found a low-cost way to dramatically reduce gas turbine emissions by pre-mixing steam with fuel prior to its combustion.

The steam is intimately mixed with the fuel in such a way as to suppress the size of the flame and promote combustion efficiency to consume most of the excess oxygen and thereby inhibit NOx and CO formation.

Very low emission levels demonstrated in preliminary lab and engine testing are to be confirmed on a retrofitted gas turbine in commercial service early next year. Operational and economic highlights:

☐ **Emissions.** Below 5 ppm NOx and CO, with around 2.5 steam-to-fuel ratios, and less than 3 ppm when the steam ratio is increased to 3.5 or 4.0 to 1.

☐ **Power.** Steam mass flow typically boosts power output by up to 30% without consuming more fuel, with a 15% reduction in plant heat rate.

☐ **Benefits.** Only emissions control system which reduces CO_2 (greenhouse gas) and generates positive cash flow while cutting fuel costs.

☐ **Revenue.** Power boost is valued at \$3 million a year for a 40 MW-class turbine in base load service to \$10 million for a 100-MW machine.

☐ **Offset Sales.** Revenue can also be generated in the form of NOx and CO offsets that can be banked and subsequently sold on the open market.

☐ **Investment.** Turnkey costs of retrofitting existing installations range from \$500,000 for a small engine to \$3 million for large frame sizes.

International Power Technology (IPT) of California is currently running independent tests on a 6-MW Rolls-Royce Allison 501K combustor under simulated engine conditions to evaluate predicted performance.

During early runs, project engineers reached levels down around 6 ppm NOx and 5 ppm CO with steam-to-fuel ratios of around 2 to 1 using a stock 501-K natural gas fuel nozzle.

In subsequent testing, at higher steam ratios, they have reached close to 5 ppm NOx and 4 ppm CO with a steam-to-fuel ratio of 3 to 1 using different nozzle configurations.

Company president, Randy Turley, reports that the goal is to get below 2 ppm NOx and 2 ppm CO with steam-to-fuel ratios of 4 to 1.

This is to be followed by design development of an optimal fuel nozzle configuration for operational evaluation on a 501K installation in commercial service to confirm projected performance and durability.

On-engine demonstration is scheduled for the first quarter of 2005 at a 501K cogeneration facility operated and managed by IPT.

Key design needs

There are two requirements for achieving ultra-low emissions with CLN technology. One is a 97-98% homogeneous pre-mix of steam and fuel; the other is a fuel nozzle that will operate at high steam-to-fuel ratios up around 4 to 1 without flame out.

Homogeneity is not a problem. Single-unit static mixers can produce a 90% homogeneous mix of steam and fuel; two units in series can deliver over 97% homogeneity.

Basic challenge is to design a fuel nozzle that can operate at 4 to 1 steam ratios without flame instability problems, and without increasing carbon monoxide, hydrocarbon and volatile organic compound emissions.

Nozzle tip design is especially critical as to injected flow momentum and distribution. Each fuel delivery hole in the tip must deliver a well defined, high momentum jet into a targeted location on the combustion liner.

In addition, Turley explains, the nozzle tip holes have to be spaced far enough apart to allow for complete combustion. If holes are too close together, the flames emerging from each hole will combine.

Finally, the swirl angle and diverging angle of each hole has to be optimized to achieve thorough mixing within the combustion liner, and the number and diameter of each hole be determined to keep the pressure drop across the nozzle to a minimum.

Steam NOx control

Dr. Cheng says the idea for mixing steam with fuel to modify the combustion process and reduce NOx came to him as he observed unexpected phenomena during gas turbine steam injection testing.

Previous techniques to modify combustors to control emissions have focused on promoting turbulent mixing as a means of lowering peak flame temperatures. Unfortunately this does not reduce local hot spots which are the source of NOx and flame instability.

The CLN approach is to homogenize steam and fuel to a molecular diffusion level to reduce the flame envelope and modify the diffusion flame combustion process.

Traditionally, steam is injected into combustion air (not pre-mixed with the fuel) for emissions control. The steam quenches the flame to slow combustion, lowers average flame temperatures (but not the hot spots), and reduces the concentration of oxygen in the combustion air.

Reducing the oxygen supply leads to incomplete and less efficient combustion, says Dr. Cheng, and is the cause of high CO and unburned hydrocarbon emissions seen in the exhaust when the steam injection rate is excessively high.

The amount of CO produced is indicative of combustion efficiency. Ideally it should be kept to a minimum or, better still, non-existent. Zero CO is perfect.

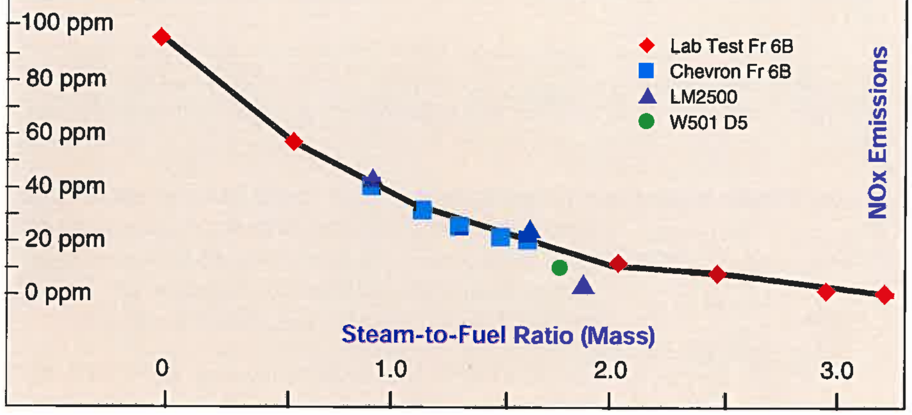
CLN technology

Clean low-NOx technology reverses the traditional approach by using steam as a diluent rather than cooling mechanism.

It uses steam to enhance oxygen supply by increasing the momentum of the fuel jet, thus increasing diffusion rate and accelerating combustion, which allows the oxygen to penetrate deep into the fuel zone and reduce the

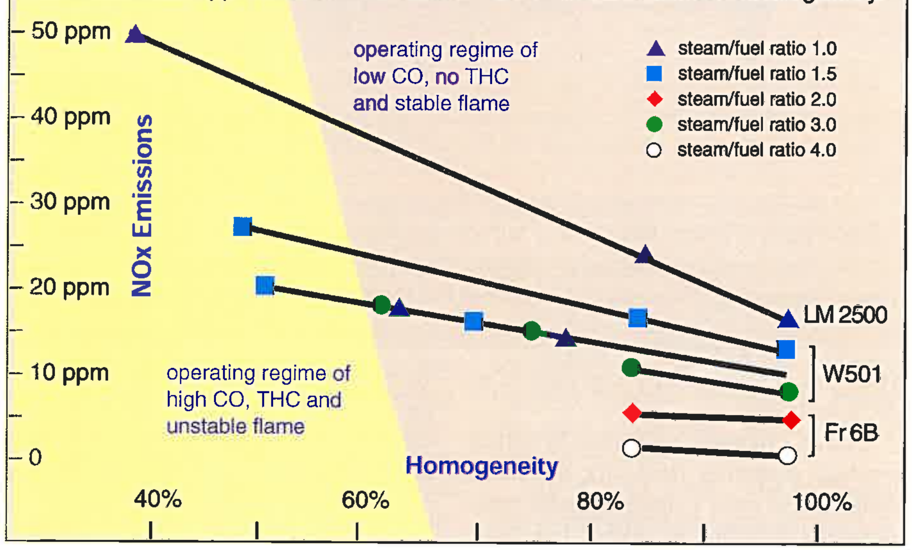
Test vs. Predicted NOx Reduction

Actual engine and test stand results show a close correlation with predicted NOx reduction at different steam-to-fuel ratios for LM 2500, Fr 6B and W501 gas turbines.



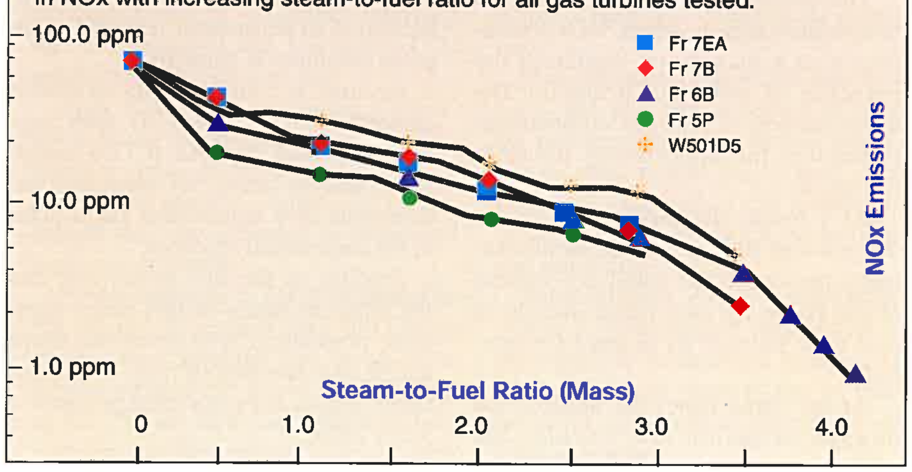
NOx Emissions vs. Homogeneity

LM2500, Fr 6B and W501D gas turbine test results show that homogeneous mixing is critical to NOx reduction regardless of steam-to-fuel ratio. Cheng has demonstrated 2 ppm NOx and CO with a 4.0 steam ratio and 97% homogeneity.



Summary of Test Stand Results

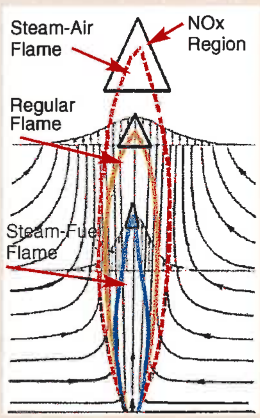
Cheng test stand data at 97.5% homogeneity demonstrate consistent reduction in NOx with increasing steam-to-fuel ratio for all gas turbines tested.



Steam-Fuel Mix Makes the Difference

Gas turbine CLN technology mixes steam with fuel to reduce NOx and CO – as opposed to mixing steam with combustion air which reduces NOx but not CO.

Steam mixed with air lowers peak flame temperature and helps minimize thermal NOx formation. But it also reduces the concentration of oxygen so that the flame surface moves outward and expands into a larger volume (steam-air flame).



Combustion takes place in the thin layer or "skin" of the flame where there is a concentration of fuel and oxidants. However, the dilution of oxygen has a quenching effect. It leads to incomplete and less efficient combustion which produces CO and unburned hydrocarbon emissions.

In contrast, with CLN technology, the steam enhances oxygen supply by increasing the oxygen diffusion rate, thus reducing the flame envelope (steam-fuel flame) and allowing the oxygen to penetrate deep into the fuel zone and accelerate the combustion rate.

Increasing the oxygen diffusion rate of the surrounding air into the diffusion flame reduces the burning and residence time of hot nitrogen and oxygen, thus diminishing NOx production. At the same time, the accelerated rate increases combustion efficiency such that CO and hydrocarbons are burned as completely as possible.

In short, CLN technology 1) shrinks the diffusion flame envelope, 2) enhances the oxygen diffusion rate, and 3) suppresses the nitrogen concentration diffusion rate. And it reduces the residence time for oxygen and nitrogen to be simultaneously present (in the small hot volume at the flame tip) by orders of magnitude.

flame envelope, a key ingredient in NOx reduction.

These changes in flame kinetics produce a smaller flame for the same heat release rate, a more uniform temperature distribution, lower hot zone and peak temperatures, and shorter residence time – all of which inhibit NOx formation.

The presence of steam in the high temperature region, where NOx formation is at a maximum, displaces the presence of nitrogen. Reducing the mass fraction of nitrogen automatically reduces the opportunity for NOx formation.

As a result, the residence time for oxygen and nitrogen to be simultaneously present in the small hot volume at the flame tip (see flame sketch) is said to be reduced by orders of magnitude.

At the same time, the accelerated oxygen diffusion rate enables the flame to increase its combustion efficiency such that CO and unburned hydrocarbons, which lead to the formation of VOCs, are almost completely consumed.

Computer simulation

Dr. Cheng has developed and refined his theoretical understanding of clean low-NOx technology through a combination of experimental test and computer combustion simulation.

He uses a commercially available computer program, Star C-D, with computational fluid dynamic (CFD) modeling to analyze steam-fuel interaction and determine how combustion takes place in the combustion chamber.

Profiles of the fuel mass flow rate for different steam-to-fuel ratios show close correlation with predicted flame length as a function of ratio -- and that flame length does not change above a 3 to 1 ratio.

CFD modeling also shows that the maximum temperature region occurs after the fuel is consumed, and that the steam and fuel mixture lowers the maximum temperature by 95 K for a 1 to 1 steam and by 300 K for 3 to 1 (due to the high heat capacity of the steam).

Results show that the production of CO stays approximately the same, independently of steam ratio, and that the amount of CO production does not increase with the homogeneous mixture of steam and fuel.

Maximum NOx mass formation, which occurs at the tip of the flame after the fuel has been consumed, is reduced by a factor of three at a 1.0 ratio and then by two orders of magnitude at a 3 to 1 steam-to-fuel ratio.

Test validation

Project engineers at Cheng Power Systems have performed extensive atmospheric testing of full-size combustor can and fuel nozzle hardware to evaluate CLN technology.

Preheating combustion air to match gas turbine compressor discharge temperature allows atmospheric testing to simulate actual engine conditions, says Dr. Cheng.

Test data show there is very little or no pressure dependency between results obtained under actual engine and atmospheric test lab results.

Results of lab and engine testing confirm that NOx reduction is a function of homogeneity and steam-to-fuel ratio – and pretty much the same for all gas turbine models regardless of size.

And, more importantly for CLN theory, that both lab and engine test data closely confirm predicted performance.

Economic evaluation

CLN technology offers gas turbine owner-operators the retrofit potential to achieve very low gas turbine power plant NOx and CO emissions without the cost and complexity of going to post-combustion catalytic treatment.

Reportedly, a CLN system can be installed for about one-third the cost of dry low emission or dry low NOx combustion hardware. And it pays for itself several times over each year in

Retrofit application of CLN technology to achieve 5 ppm NOx

As shown here, for different gas turbine models, nominal 3.0 steam-to-fuel ratio required to get down to 5 ppm NOx or less often requires a tradeoff such as cutting back on turbine rotor inlet temperature (firing temp) to keep from exceeding pressure ratio or power output limitations imposed by the gas turbine or site permit.

Model	Air Flow (lb/sec)	Steam Flow (lb/hr)	Fuel Flow (lb/hr)	Firing Temp	Pressure Ratio	Heat Rate (Btu/kWh)	Power Output	Steam to Fuel Ratio
Frame 5P								
No Steam	.270 lb	0	15,810 lb	1750 F	10.5	11,780 Btu	26,175 kW	0
CLN Steam	.270 lb	52,195 lb	16,065 lb	1700 F	11.5	10,055 Btu	31,160 kW	3.
Frame 6B								
No Steam	.305 lb	0	20,985 lb	2020 F	12.0	10,440 Btu	39,210 kW	0
CLN Steam	.305 lb	68,625 lb	21,840 lb	1900 F	13.0	8,840 Btu	48,160 kW	3.14
Frame 7EA								
No Steam	.658 lb	0	46,660 lb	2020 F	12.6	10,985 Btu	82,825 kW	0
CLN Steam	.658 lb	143,550 lb	46,225 lb	1900 F	13.5	9,100 Btu	99,065 kW	3.11
W 251								
No Steam	.389 lb	0	27,160 lb	2050 F	15.3	10,465 Btu	50,615 kW	0
CLN Steam	.389 lb	83,860 lb	26,105 lb	1900 F	16.2	8,710 Btu	58,460 kW	3.21
W 501D5								
No Steam	.863 lb	0	59,795 lb	2050 F	14.2	10,690 Btu	109,055 kW	0
CLN Steam	.863 lb	184,975 lb	62,730 lb	2000 F	15.5	8,795 Btu	139,070 kW	2.95

extra revenue and fuel savings.

CLN adds value by increasing gas turbine generating capacity (particularly during hot day operation), improving plant heat rate to save fuel costs, and reducing the amount of carbon dioxide produced per kW-hr of electricity generated.

Finally, if successfully demonstrated in commercial operation, CLN will meet strict emissions limits coming along such as those required by the California Air Resources Board in the year 2007.

Near-term, project engineers point out, a conservative 3 to 1 steam-to-fuel ratio will provide the 5 ppm limit on NOx that the EPA has specified for plants retrofitted to meet new emissions regulations.

Limits and tradeoffs

Typically, steam injection at this ratio can boost power output by 30 percent. However, equipment or site permit limitations may not allow plants to accept or tolerate that full increase in power output.

Factors that come into play include gas turbine compressor surge margin, gearbox or output shaft power capacity, electric generator rating, average ambient temperature, authorized site generating capacity.

Generally, hot day operation is not a problem because of the decrease in gas turbine power output with increasing ambient temperature. But at low ambient temperatures, where gas turbine output increases, the added boost from steam injection can exceed permissible limits.

The tradeoff is to operate at lower firing temperatures so as to keep power output below those limits. This has the added benefit of further reducing fuel consumption and associated CO_2 production (greenhouse gas).

Parts life is also prolonged. Operating at lower firing temperature reduces thermal stress to prolong the service life of hot section components even though they are designed to withstand higher temperatures.

Steam injection is not detrimental to life. Many of the more than 100 Cheng cycle steam injected gas turbines in service around the world are injecting up to 18% air flow (equivalent to 6 to 1 steam-to-fuel ratio) without any problems, Dr. Cheng notes.

Still to come

There is still work to be done before the industry is ready to accept CLN technology as economically and operationally superior to SCR to achieve less than 2 ppm NOx and CO in commercial service.

But it is in reach. The technology has already proven it can limit NOx to 5 ppm with a 3 to 1 steam-to-pressure ratio, says Dr. Cheng, which is well within gas turbine operating experience. "We now have to demonstrate below 2 ppm on a commercial installation."

That will require new fuel nozzle designs, lab and engine testing to evaluate performance over the full range of idle to peak power gas turbine operation, and ultimately field installations to demonstrate hardware performance and durability.

International Power Technology's ongoing development and test of applying CLN technology to the 501K gas turbine, and plans to test an installation in commercial service, is just what is needed. ■

Retrofit studies show CLN technology a money maker rather than operating loss

Cheng Power Systems has made several gas turbine model studies to evaluate the relative cost (and gain) of retrofitting CLN technology to prevent emissions rather than clean up the exhaust with SCR post combustion treatment.

Comparative results are shown here for Fr 6B, Fr 7EA, W251 and W501D5 gas turbine installations using conservative estimates of turnkey retrofit prices for CLN and SCR installations, their annual operating and maintenance costs, and their annual net profit or loss.

Economic calculations are based on $5 per MMBtu fuel price, $0.06 per kW-hr value of electricity, close to 8,000 hours in base load service (90% plant availability), $0.35 per MW-hr for general SCR operation and maintenance, and $5 per 1,000 gallons of water. These are current prices and costs quoted in 2004 U.S. dollars.

Results can be updated or modified to reflect changes in prices and plant operating conditions. Value of NOx and CO offsets are not factored in because they apply equally to both emissions control technologies. All of the calculated numbers quoted have been rounded off for simplicity. ■

Frame 6B performance and costs

Studies indicate a CLN retrofit can realize close to $3.2 million per year in extra power sales for a Fr 6B plant compared to $110,000 loss for an SCR system.

Frame 6B Operation	CLN Retrofit	SCR Retrofit
Steam rate (per hr)	68,630 lb	none
Steam-fuel ratio (mass)	3.1 to 1	none
Extra power output	8,950 kW	none
Total plant output	48,160 kW	39,210 kW
Plant heat rate (per kWh)	8,840 Btu	10,440 Btu
Plant efficiency	38.6%	32.7%
Turnkey retrofit cost (est)	$2,250,000	$3,000,000

Annual Profit (Cost)	CLN Retrofit	SCR Retrofit
Extra power sales	$4,240,000	none
Water/SCR cost	($340,000)	($110,000)
Extra fuel cost	($720,000)	none
Net profit (loss)	$3,180,000	($110,000)

Frame 7EA performance and costs

Studies indicate a CLN retrofit can realize close to $6.6 million per year in extra power sales for a Fr 7EA plant compared to $230,000 loss for an SCR system.

Frame 7EA Operation	CLN Retrofit	SCR Retrofit
Steam rate (per hr)	143,500 lb	none
Steam-fuel ratio (mass)	3.1 to 1	none
Extra power output	16,100kW	none
Total plant output	99,100 kW	83,000 kW
Plant heat rate (per kWh)	9,100 Btu	10,990 Btu
Plant efficiency	37.5%	31.1%
Turnkey retrofit cost (est)	$2,750,000	$3,500,000

Annual Profit (Cost)	CLN Retrofit	SCR Retrofit
Extra power sales	$7,700,000	none
Water/SCR cost	($710,000)	($230,000)
Extra fuel cost	($365,000)	none
Net profit (loss)	$6,625,000	($230,000)

W251 performance and costs

Studies indicate a CLN retrofit can realize close to $1.95 million per year in extra power sales for a W251 plant compared to $140,000 loss for an SCR system.

W251 Operation	CLN Retrofit	SCR Retrofit
Steam rate (per hr)	83,900 lb	none
Steam-fuel ratio (mass)	3.2 to 1	none
Extra power output	7,900 kW	none
Total plant output	58,500 kW	50,600 kW
Plant heat rate (per kWh)	8,710 Btu	10,660 Btu
Plant efficiency	39.2%	32.0%
Turnkey retrofit cost (est)	$2,250,000	$3,000,000

Annual Profit (Cost)	CLN Retrofit	SCR Retrofit
Extra power sales	$3,700,000	none
Water/SCR cost	($415,000)	($140,000)
Extra fuel cost	($1,335,000)	none
Net profit (loss)	$1,950,000	($140,000)

W501D5 performance and costs

Studies indicate a CLN retrofit can realize close to $11 million per year in extra power sales for a W501D5 plant compared to $300,000 loss for an SCR system.

W501D5 Operation	CLN Retrofit	SCR Retrofit
Steam rate (per hr)	185,000 lb	none
Steam-fuel ratio (mass)	2.95 to 1	none
Extra power output	30,000 kW	none
Total plant output	139,000 kW	109,000 kW
Plant heat rate (per kWh)	8,800 Btu	10,700 Btu
Plant efficiency	38.8%	31.9%
Turnkey retrofit cost (est)	$3,000,000	$4,500,000

Annual Profit (Cost)	CLN Retrofit	SCR Retrofit
Extra power sales	$14,200,000	none
Water/SCR cost	($910,000)	($300,000)
Extra fuel cost	($2,500,000)	none
Net profit (loss)	$10,790,000	($300,000)

California NOx and CO offsets for 6 MW CHP retrofit valued at $500,000 per year

International Power Technology is running field tests to evaluate alternative fuel designs and configurations in preparation for retrofitting CLN technology to a gas-fired cogeneration installation in Menlo Park, California in the first quarter of 2005.

CHP plant is powered by an Allison 501KH steam-injected gas turbine, generates from 3.5 to 6.0 MW of electrical power and from 37 to 45 MMbtu of thermal energy. Site is permitted for 25 ppm NOx (140 lbs/day) and 70 ppm CO (270 lbs/day) in CHP mode of operation.

Retrofitting CLN operation for the gas turbine and duct burner has the potential of reducing emissions down to sub 5 ppm NOx and CO levels.

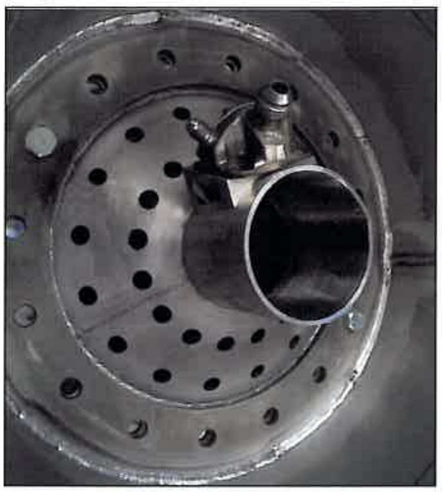
Project can then re-permit under the reduced emissions levels and bank the differences between the original permit levels and the reduced levels.

Those "offset" emissions no longer being sent into the atmosphere can be put into the local air districts emissions bank which can then be sold on the open market to other generators.

Current value of these offsets, based on Bay Area Air Quality Management District 2001 transactions, is $450,000 per year for the NOx and $44,000 per year for the CO. That is the value placed on producing 46,000 lbs less NOx and 90,000 lbs less CO per year.

To date, IPT has tested seven nozzle configurations under varying conditions. Three are standard OEM designs and four are IPT designs. Target steam to fuel ratio of maximum turbine output and NOx reduction is 4 to 1.

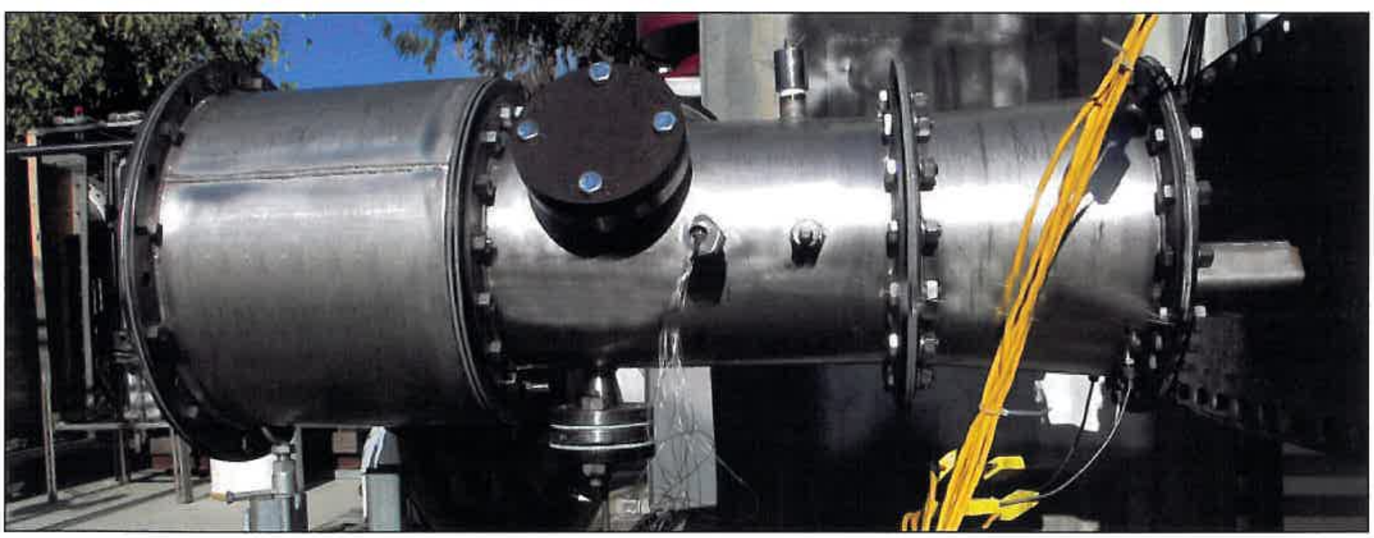
Company reports that more testing on test rig is needed to determine the exact nozzle configuration that will allow up to a 4 to 1 ratio. Six nozzles of that design will be fabricated for use in engine testing early next year. ■



Nozzle and Diffuser. Inside view of the single-combustion liner test fixture shows dual fuel nozzle installation ready for steam-fuel mix testing.

Dual Fuel Nozzle. Stock dual fuel nozzle designed to operate on natural gas and distillate. Nozzle tip has twelve 0.100-inch diameter holes.

Low-Btu Nozzle. Stock steam injection nozzle designed for conventional NOx reduction and natural gas fuel injection, with ten 0.210-inch diameter holes.



Test Stand. Combustion air (entering at the left) is preheated to the compressor discharge temperature of the 501KH to simulate gas turbine operating conditions. Rig testing follows similar testing performed by Cheng Power Systems to evaluate different gas turbine model applications.