Paper No: 07-IAGT-1.2

INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE

CLN® Development to Reduce NOx and Greenhouse Gas

by

Dr. Dah Yu Cheng

Cheng Power Systems, Inc. (CPS)

480 San Antonio Road, Suite 120

Mountain View CA 94040 USA

Phone 650-941-9292 Fax 650-941-9092

dycheng@chengpower.com

Presented at the 17th Symposium on Industrial Application of Gas Turbines (IAGT)
Banff, Alberta, Canada – October 2007

Author's Bio:
Dr. Dah Yu Cheng, 50 years gas turbine experience specializing in combustion technology and gas turbine design. Joined NASA in 1966, developed quiet nozzles for fan jets. Developed steam injected gas turbine cycle (Cheng Cycle®) in 1974. The high efficiency low emission engines developed are: RR 501KH, Kawasaki M001A-CC and LM2500PH.

ABSTRACT

Market driven emission control technology, CLN® reduces NOx and greenhouse gas (CO_2) simultaneously. Special efforts are focused on applying the technology to aero-derivative gas turbines, such as the Rolls Royce (RR) Allison 501K series, RR Avon, GE LM2500 and GE LM6000 Sprint. NOx levels below 5ppmvd and CO in single digits are feasible. CO_2 reduction by 20% is immediately available. Examples of financial benefits for gas turbine owners adopting CLN® technology will be presented.

Table of Contents

1.0. Introduction 2

2.0. Technology 2

2.1. The Rig Test 6

2.2. Application of CLN® to RR Avon 1535 7

2.3. Modification of the Combustion Liner for CO Emission Performance 9

3.0. The Dynamic Response of the CLN® Control System 11

3.1. Emission Test on the LM2500 13

3.2. Baseline Water Injection Emission Data 13

3.3. Steam Injection for the LM2500 15

4.0. Greenhouse Gas Reduction 16

5.0. Potential Financial Benefit Examples 17

6.0. Comparison of Water Injection, DLE and CLN® on an Economical Payback Basis 19

7.0. Conclusion 20

8.0. References 20

1.0. Introduction

Regulation has been the methodology to force gas turbine owners to follow stringent NOx emission regulations. With global warming as a worldwide issue, CO_2 is added to the other pollutants, NOx and CO, as a new gas needing control. The only methodology to reduce CO_2 that can be obtained now is by improvement of gas turbine efficiency because CO_2 emissions are directly linked to fuel burned per megawatt hour. There are many other technologies, such as DLE and SCR systems, on the market to control the NOx and CO. All existing technology increases greenhouse gas emissions due to the fact that they constitute an increased rather than a reduced heat rate. Enforcement of emissions by regulation has made the gas turbine owners focus on the lowest cost technology just to satisfy governmental regulations and nothing beyond that. With that background, the CLN® emission control system was introduced. CLN® was invented based on the concept of market driven emission control technology so the system can simultaneously reduce NOx, CO and CO_2 and create a savings for the gas turbine owners. The lower the emissions, the more benefits the owner will get. Once the technology is wide spread, the owners should automatically want the CLN® system due to the potential benefits they will receive. Therefore, we expect global emission control will be done by market driven forces rather than by governmental regulations. CPS has been developing the system since year 2000 and a number of these have been installed around the world. In this paper, we are focusing on the RR Avon and GE LM2500s with some projected performance on the LM6000 Sprint.

2.0. Technology

Water and steam injection in the combustion zone is a well known technology for controlling NOx by lowering the flame temperature. When NOx is being reduced, CO emissions rise rapidly. This is the limitation of water and steam injection emissions control. The high CO is an indication of reduced combustion efficiency, therefore, an increased heat rate in gas turbines. A review of the classic steam injected system can be divided into injecting the steam around the fuel nozzles, whether premixed with fuel or not, vs. the injection of steam in the compressor discharge air to reduce the oxygen content of the air. All of these have the one general purpose of reducing the flame temperature. Steam for emission control is currently limited to a steam-to-fuel ratio of 2:1. The limitation of that steam-to-fuel ratio is due to unacceptably high CO. In investigating the current steam injection systems, Cheng Power Systems, Inc. (CPS) discovered that mixing steam with the air or the fuel is not homogeneous enough so that both constituted a condition for high CO when fuel was burned. In general, this violates the diffusion flame principle. The diffusion flame works when the fuel and oxidizer counter diffuse into each other. The flame occurs when the concentration ratio of the fuel and oxidizer reach the Stoichiometric ratio. This means that combustion should take place in a media that is uniform in concentration whether steam is added or not. Up to this point, that was not the focus of mechanical engineers who designed the combustion system. The level of homogeneity (uniformity) should be down to mean free paths length in order to constitute the classic principle of a diffusion flame. However, the majority of the mixing schemes cannot fulfill that requirement. Research work at CPS is focused on the homogeneity of mixing diluent and fuel in a diffusion flame. Figure 1 shows the experimental results of a typical industrial gas turbine combustor using steam as a diluent which is premixed with fuel at different steam-to-fuel ratios. (Ref. 1, Wang et al., 2002)

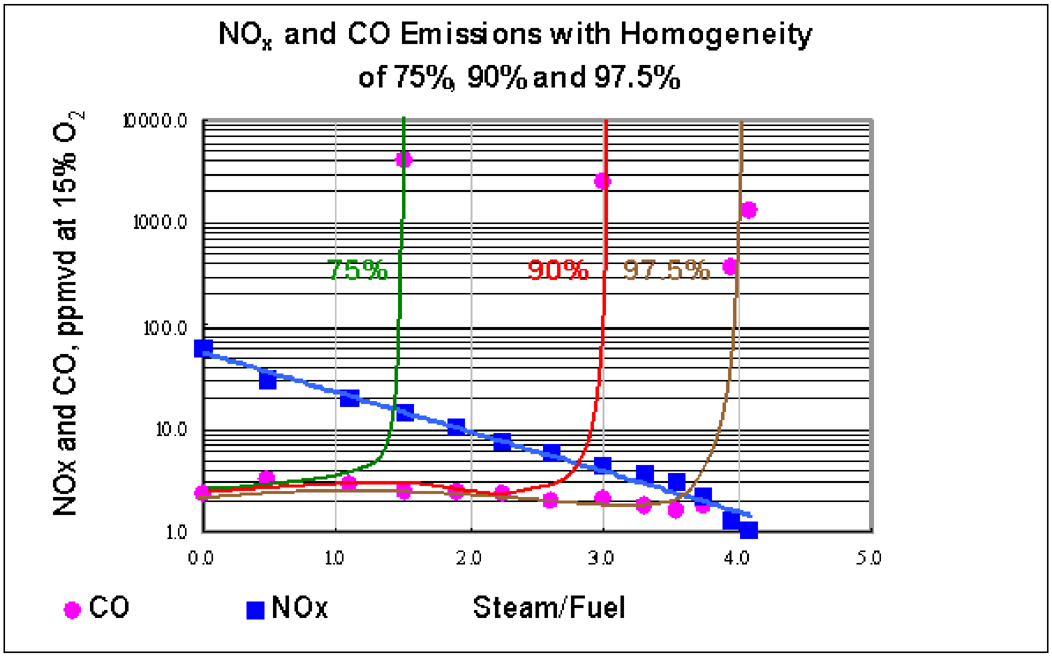

Figure 1

CO was at a very low level until a sudden takeoff (flame instability limit). That limit can be changed when the homogeneity level is improved, such as when a homogeneity level is 75%, the takeoff steam-to-fuel ratio is at 2:1. When the homogeneity level is increased to 90% the takeoff point is at a steam-to-fuel ratio of approximately 3:1. Then when the homogeneity level is greater than 97%, the CO takeoff point is approximately 4:1 steam-to-fuel ratio. One can see the homogeneity did not influence the NOx reduction by a high steam-to-fuel ratio. However, it had a profound effect on CO emissions. These high CO emissions also indicated the combustion reached a limit of flame-out which is unacceptable for any gas turbine operation.

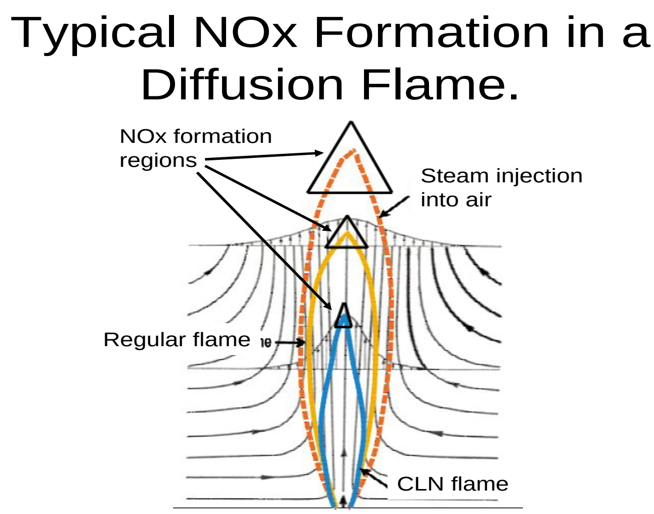

Figure 2

Figure 2 illustrates the region where NOx is being formed in a diffusion flame. (Ref. 2, Sahai, et al, 2003) The middle flame envelope represents a normal natural gas diffusion flame height. The region indicated by a triangle is where the NOx formation takes place. NOx is being formed only after the combustion of hydrogen and CO is completed. The hot tip zone within the triangle has the highest temperature to cause nitrogen and oxygen in air to react to each other forming NOx. Traditionally, when steam is injected into compressed air before the combustion chamber, the oxygen content of the air is reduced due to the addition of steam. This makes the flame envelope balloon into a bigger volume but also has a bigger volume to produce NOx, regardless; the maximum temperature has been reduced. The mixing of steam and fuel homogeneously shrinks the flame height which reduces the maximum flame temperature and reduces the volume where NOx can be formed. It is this double effect of reducing flame temperature and NOx formation volume that constitutes the physical effects behind CLN® emission control technology.

Steam for this process was typically obtained by heat regeneration of exhaust from the gas turbine. This additional energy recovery and mass flow reduces the fuel burned requirement per megawatt hour generated and potentially more power for fuel burned reduces the gas turbine heat rate tremendously. This reduction of the heat rate constitutes the physical principle behind CO_2 reduction.

The potential benefit of CLN® is a system designed to follow the KISS principle (Keep It Simple) in order to reduce equipment costs and increase power generated. Upon installation of the CLN® system, reduction of the heat rate will allow payback within one or two years of operation. In addition, the shrinking of the flame volume keeps the combustion hot components cool, reduces maintenance costs of gas turbines and reduces the unwanted outage for hot section overhaul.

2.1. The Rig Test

CPS has a combustion facility capable of testing real gas turbine components with the CLN® system. The layout of the test system can be seen in Figure 3.

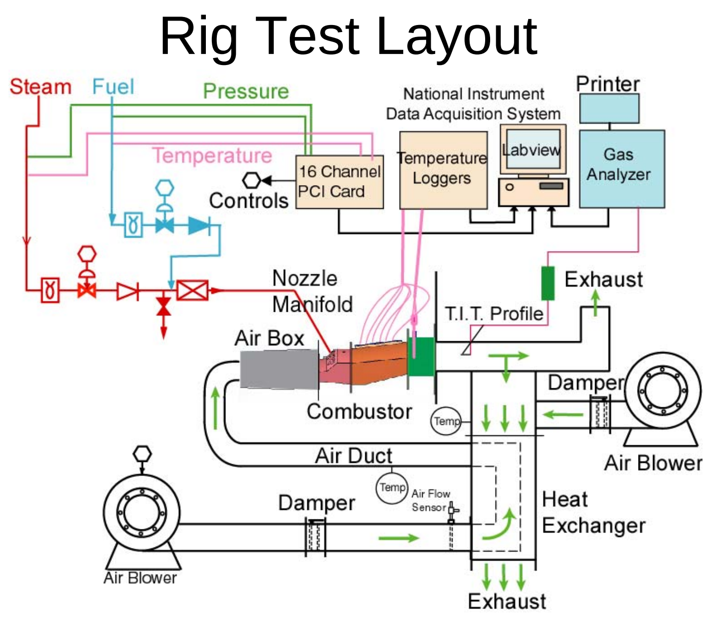

Figure 3

This system has been previously described and published. (Reference 1, Wang et al., 2002) In summary, the system consists of a steam-to-fuel mixing system with variable homogeneity levels and an air supply system which is preheated to a temperature equivalent to a compressor discharge temperature of various gas turbine systems being tested. The combustion system utilizes the real components and viewed through a high temperature window to observe the flame. The component temperature is monitored by thermocouples attached throughout the combustion liner. The flow rate is controlled to meet the scaling criteria for each of the gas turbine systems being tested. After combustion, the emission data is collected by a Horiba system. This measures NO, NO_2 or NOx as NOx emissions with CO and O_2 for the 15% O_2 correction factors, etc. The Horiba system has a conditioner to freeze out the moisture content of the sample gas then reheat it to a designated temperature for the instrument. The measured data is considered to be emission data under dry conditions.

The compressor discharge temperature has a tremendous amount of influence on the final flame temperature in the gas turbine. The diffusion coefficient for combustion is not pressure dependent. However, the diffusion coefficient can be temperature dependent. To control the compressor discharge temperature for the test rig to match the existing engine data becomes the key factor for this test rig. In general, modification of the combustion liner, and modification of the fuel nozzle, if needed, all take place in the combustion test rig. The question commonly raised addresses the pressure ratio of the real engine which may deviate from the combustion test rig results. Therefore, real engine tests are needed to check out the theory of the test rig and establish the experience of applying CLN® to real engine conditions.

2.2. Application of CLN® to RR Avon 1535

The comparison of CLN® performance between the rig test and real engine test was first performed on the RR Allison 501. The second real engine test was performed on the RR Avon 1535. The actual test was carried out in an engine test facility using the gas generator portion of the Avon 1535 which is coupled to an RR standard nozzle to simulate the power turbine in pressure drop and thrust for equivalent mechanical power output. The engine set up can be seen in Figure 4.

CLN® Engine Test

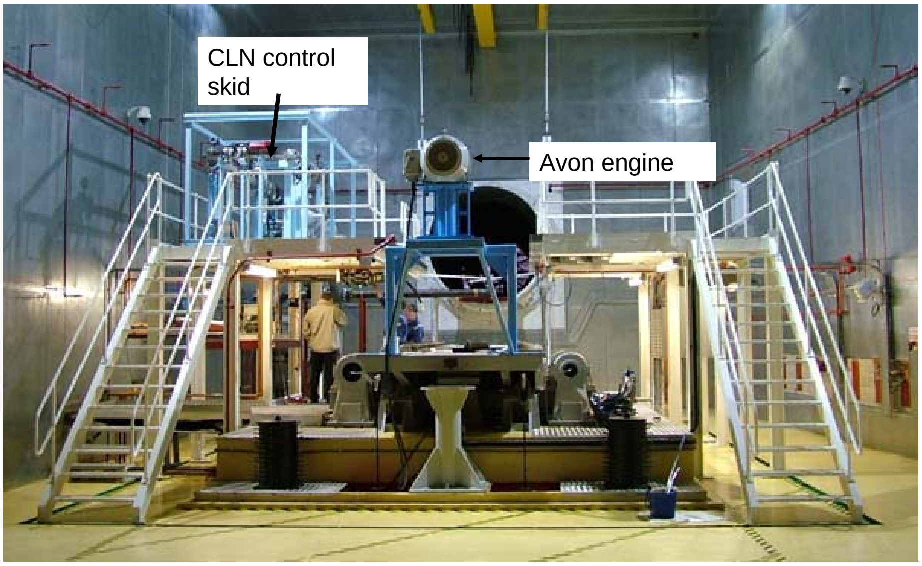

Figure 4

The picture represents the front view of the engine setup. The CLN® control is on the left hand side of the picture, next to the engine. The computer control is to maintain a preset steam-to-fuel ratio, regardless of load conditions. The emission test instrument is on the lower right hand side. The results of the test can be seen in Figure 5. Figure 5 is a plot of steam-to-fuel ratio vs. NOX in ppmvd with 15% O_2 correction.

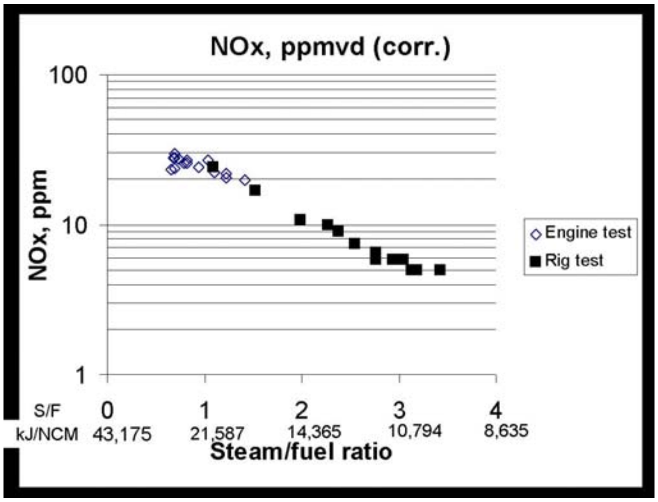

Figure 5

The rig test results of the Avon combustion liner were superimposed on the engine test. Basically one can see that the NOx results vs. steam-to-fuel ratio from the engine follows exactly the same relationship obtained for the atmospheric rig test. This means the emission measurement using the rig test is valid and indicated no pressure ratio dependent issues as long as the compressor's discharge temperature for the rig test matches the real engine temperature.

2.3. Modification of the Combustion Liner for CO Emission Performance

The RR Avon 1535 has very high CO emissions. From the real engine data, it can be seen that CO emission is in the range of 125ppmvd to 325ppmvd. In most countries, the CO emission limit is 30 ppmvd. Rolls Royce has a modified liner with a potential replacement kit to lower the CO from 125ppmvd to 35ppmvd. That emission still exceeds most CO emission limits in industrial countries. Figure 6 shows the combustion liner modification.

Combustion Liner Modification

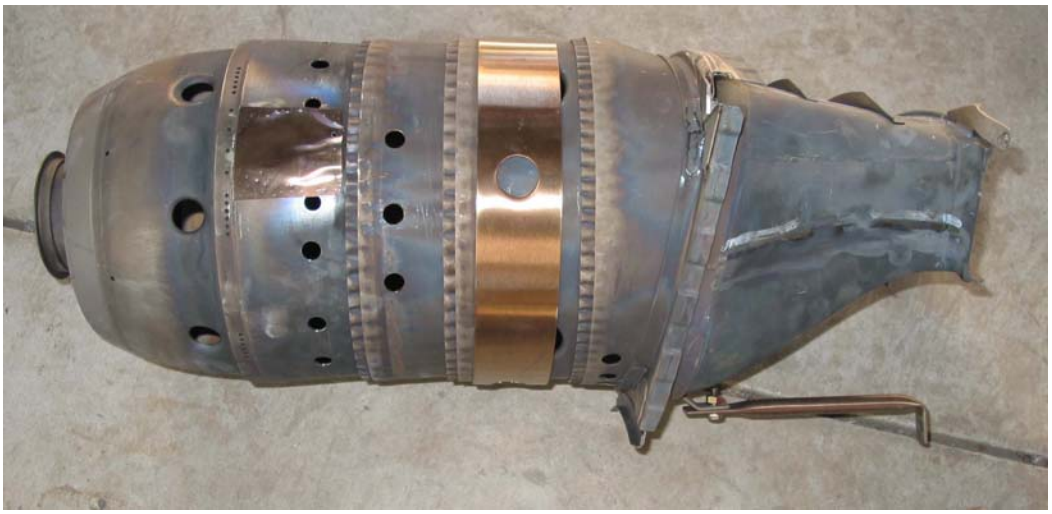

Figure 6

The primary air coming from the compressor discharge is through the first row of holes. The RR offered low CO liner has eight additional holes located between the combustor inlet to the first set of holes. CPS realized that the CO has lesser chemical potential than hydrogen. Therefore, CO would be burned at a much later stage at a distance away from the fuel nozzle. This is contrary to RR's attempt to lower CO. CPS added additional holes behind the primary holes to the combustion liner to supply fresh air into the CO combustion zone. This helped to burn up the CO. Those holes were strategically located and deliberately punched through the combustion liner without the rolled up edge. CPS reasons that the spray angle of the fuel made the combustion closer to the wall. The rolled edge hole caused the air to penetrate past the combustion zone so it would not assist the supply of fresh air to burn up the CO efficiently. Without the rolled edge this will make the air penetration shallower and therefore supply the additional O_2 to the CO combustion zone. The results of the combined CO and NOx test can be seen in Figure 7.

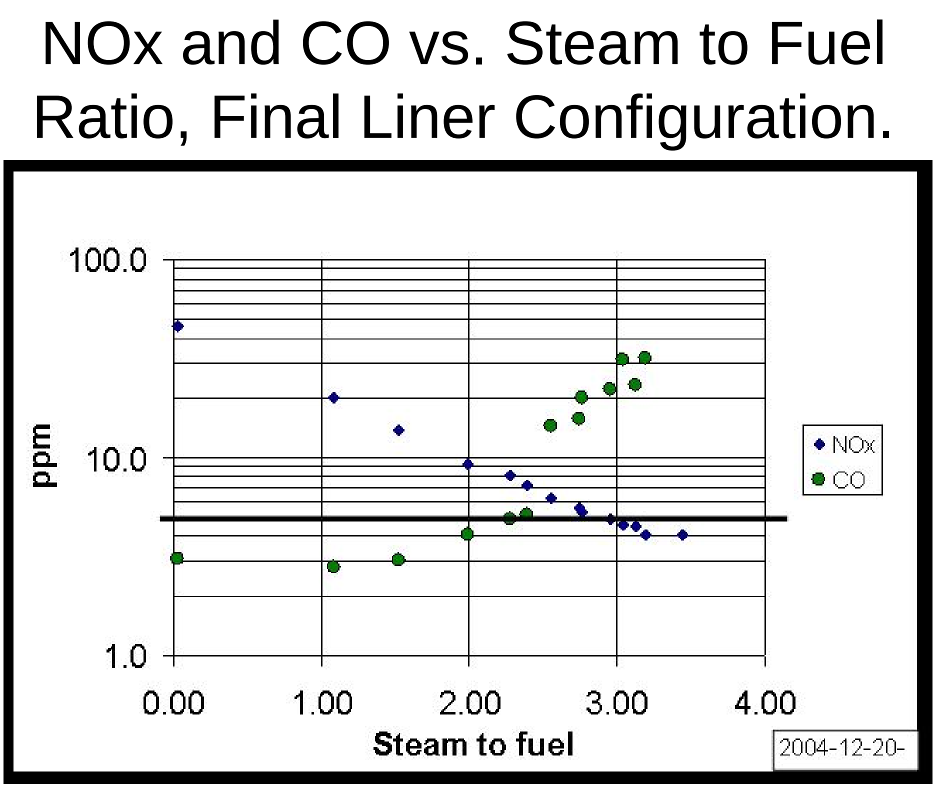

Figure 7

One can see that without any steam injection, the CO level for the engine has dropped from 125ppmvd down to 3ppmvd. CO remained low in the steam-to-fuel ratio up to 2. When the NOx reached 5ppm, the international standard for NOx, at the steam-to-fuel ratio of 3:1, CO would still be below 30ppmvd therefore meeting the emission limits without an additional catalytic converter.

3.0. The Dynamic Response of the CLN® Control System

The gas turbine has to perform below emissions limits throughout the operating range. In order to meet emission standards, an automatic control system was designed. This will maintain the steam-to-fuel ratio to a preset value regardless of the variation of parameters. A simplified flow block diagram can be seen in Figure 8.

CLN® Emission Control System

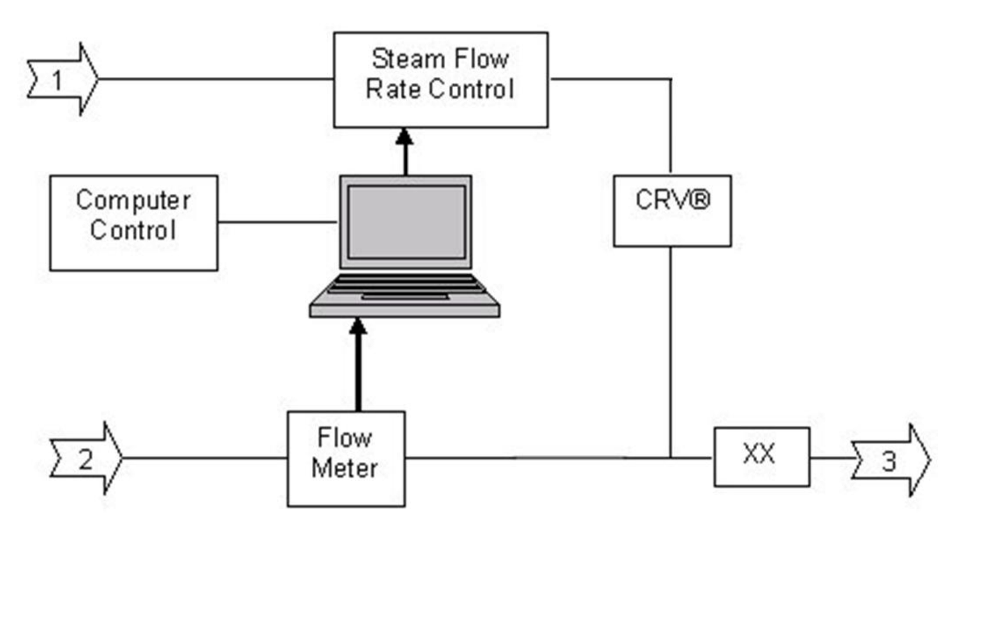

Figure 8

The computer has specialty boards to function as PID diagram logic. It enables the computer to sense the temperature, pressure and velocity which computes into flow rates of steam or fuel. In Figure 8, the fuel comes into the piping system from the lower left corner. Flow rates were measured by the instruments and fed into the computer which utilizes a proprietary computer software program to control the steam flow from the upper left corner. The steam coming down from the upper left hand corner is controlled by the computer to maintain a designated steam-to-fuel ratio. The steam coming down through the supply line through a CRV®, prior to entering the T-section as a preliminary mixing system, enters into a static mixer labeled XX to have a homogeneity level that exceeds 97% before entering the fuel distribution manifold, of the fuel nozzles. The computer software was programmed to handle autonomous control for the steam-to-fuel ratio. In addition, the software also has a feature to handle the acceleration and deceleration speeds of the steam control valve in order to prevent flame-out. A unique test program was set up to detect the functionality of the dynamic response of the CLN® control system. The results can be seen in Figure 9.

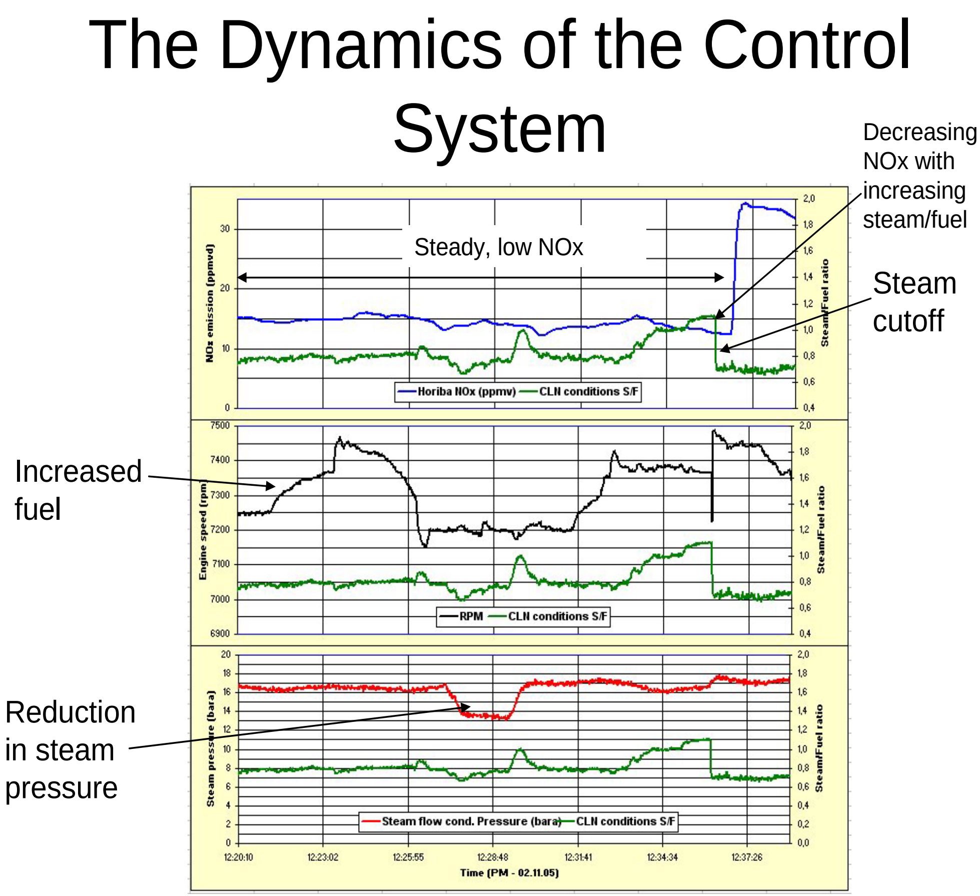

Figure 9

The plot is against time vs. other features. The very top traces correlate the NOx emission with steam-to-fuel ratio. The middle figures show the variations of rpm vs. steam-to-fuel ratio. The bottom traces are the variation of steam source pressure. Starting from the middle pair of traces, the first test shows the fuel flow deliberately increased which caused the engine rpm to go up. Underneath the rpm curve is the steam-to-fuel ratio curve which remains constant. The engine returned to the same normal fuel flow condition. The second test increased the steam supply pressure up and down as seen in the bottom pair of curves. Again, the lower curve represents the steam-to-fuel ratio value which, besides some blip signals, is due to the building acceleration and deceleration timing. However, the steam-to-fuel ratio remains approximately constant independent of the pressure change. The third test is increased steam-to-fuel ratio. When the steam-to-fuel ratio is increased, the gas turbine received additional mass. The engine rpm went up again without additional fuel. This was followed by a sudden cut off of the steam. The steam-to-fuel ratio was down to minimal. The NOx trace on the top pair of curves indicated the NOx level suddenly jumped up. In the middle pair, the rpm first goes up then down due to the engine control system reacting to the sudden loss of steam. The bottom pair indicated that regardless of the steam pressure, the steam-to-fuel ratio dropped to a minimum value.

3.1. Emission Test on the LM2500

The emission tests were done in several configurations which included: 1) a water injection baseline data, 2) the LM2500 rig test data and 3) field operational data of the LM2500 and LM6000 Sprint.

3.2. Baseline Water Injection Emission Data

Water injections of the LM2500 to lower NOx to a level suitable for entering the SCR are common. Figure 10 shows the results measured on the LM2500 PE with a combined cycle configuration. The test was done with full load up to 23 Megawatts (MW) then approximately 3/4 load at 18MW and half load at 14MW. One can see that the test followed the GE Cycle Deck at 0 steam and 1:1 water/steam ratio at full load. In general, the water injected gas turbine rarely exceeded 1:1 water/fuel ratio.

Water Injection Test

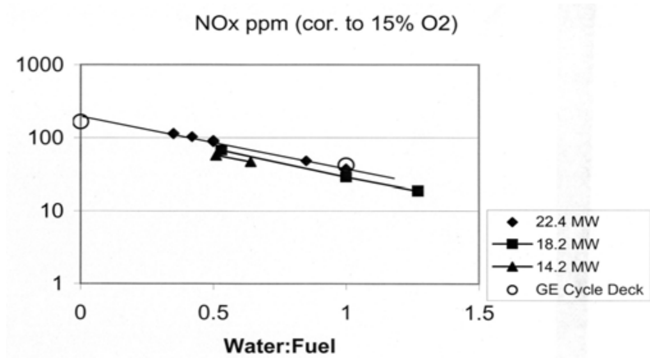

Figure 10

Figure 10 indicates a straight line relationship between NOx and water/fuel ratio. Figure 11 is the data collected for the CO emissions against a water/fuel ratio. The test was limited to about 30ppm for CO. There was concern that higher CO would cause flame-out. In Figure 11, the bottom curve is at full load CO emission vs. water/fuel ratio. The middle one is the 18MW load. The top one is 14MW. One can see that CO increases more rapidly at low load than at full load. Based on the CO data at full load conditions, CO performance would be within the GE Cycle Deck projections. This is indicated by the open circle. Unfortunately, at 18MW on down, CO is much too high for a higher water/fuel ratio.

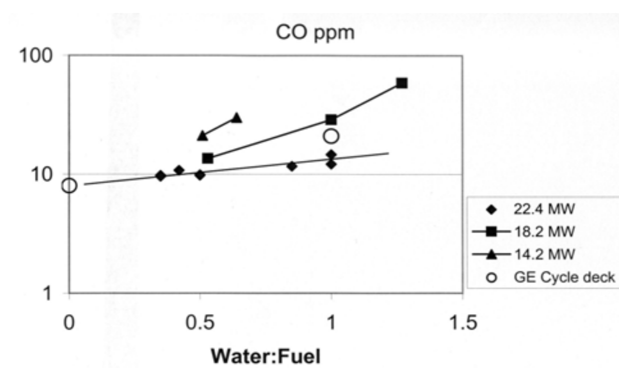

Figure 11

3.3. Steam Injection for the LM2500

There are plenty of steam injection data for the LM2500. However there are different steam injection configurations. There are mixing nozzles, concentric nozzles for steam and fuel and CLN® steam-to-fuel mixed conditions. In Figure 12, there is a correlation between the engine Cycle Deck and the rig test for the LM2500. The slope at the low steam-to-fuel ratio was a projection by GE on steam-to-fuel ratio vs. NOx. In this case, the fuel is Naphtha which has a low vaporization temperature point. The evaporation occurs very rapidly and therefore the combustion characteristics resemble that of a gaseous fueled system. The lower slope is the combustion rig test performed at CPS' rig test facility in Menlo Park, California. The Naphtha data merged with the rig test data after the steam-to-fuel ratio reached 2:1.

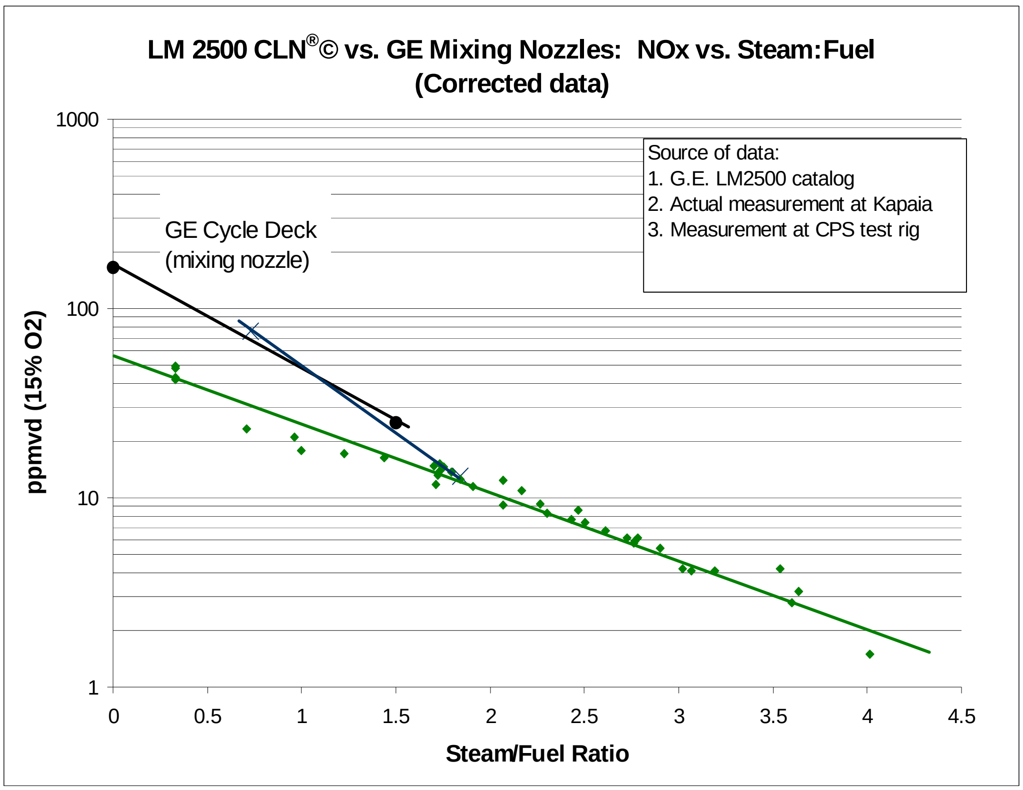

Figure 12

Figure 13 is a plot of CO vs. steam-to-fuel ratio. During the test, the homogeneity level is over 99%. One can see that CO during the test is extremely low and becomes lower at the higher steam-to-fuel ratio up to 3.7:1. The flame is still stable to reach a 4:1 ratio. When the NOx went as low as 1.8ppmvd the CO jumped to 350ppmvd. The flame still exists and becomes laminar combustion and very quiet. However, no flame-out was observed.

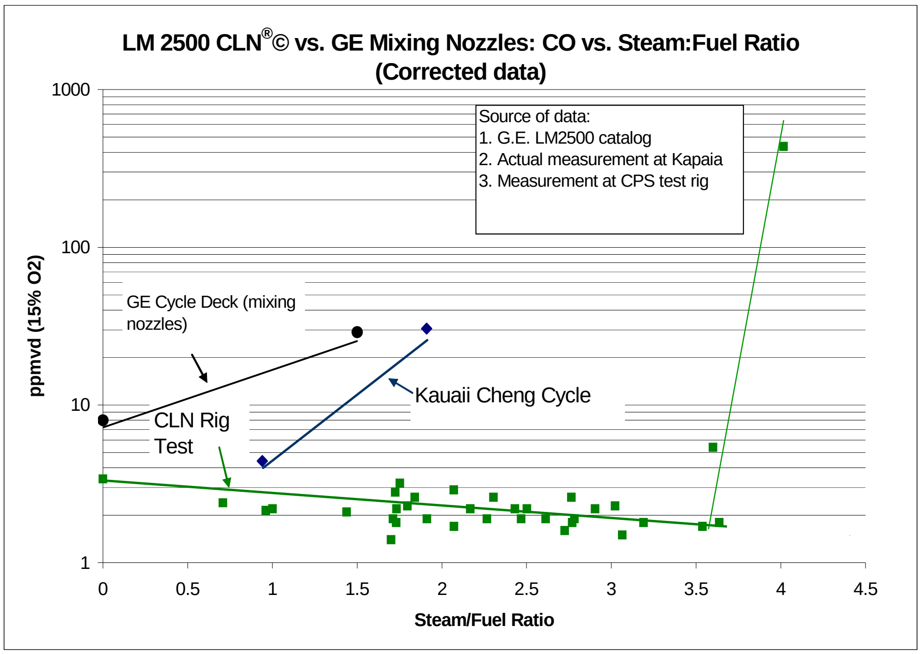

Figure 13

4.0. Greenhouse Gas Reduction

The CLN® system received its steam from the waste heat boiler which reduces the fuel required per MW hour power generated. Besides the CLN® application for NOx reduction, additional steam can be injected down stream of the combustion zone to produce additional power or reduction of fuel flow. Table 1 is a performance projection of RR Avon, LM2500 PE and LM6000 Sprint and their respective fuel savings in percentages. This directly correlates to the CO_2 reduction potential for those engines.

	Mass flow	P/R	Steam flow	Power	Heat rate	% CO2
	Kg/sec		Kg/sec	MW	LHV, kJ/MWHr	reduction
Avon	77	8.8	0	15.16	12,585	
1535	77	9.4	6.09	21.68	9,555	-24.08%
LM2500	69	18.8		22.56	10,008	
PE	69	19.0	5.43	30.00	7,878	-21.28%
LM6000	134	31.3	3.84	48.89	9,163	
Sprint	134	32.9	10.49	61.98	7,155	-21.92%

Table 1

It can be seen that with CLN® and steam injection technology, all the gas turbines have the potential to reduce CO_2 by at least 20%. The State of California, USA has targeted CO_2 reduction by 20% by the year 2020.

5.0. Potential Financial Benefit Examples

The LM2500 performance was obtained by the fully injected LM Cheng Cycle data from the Kapaia Power Station on Kauai, Hawaii. The advantage of such a system is reflected upon its partial load heat rate as seen in Figure 14. (Ref. 3, Peltier, 2006).

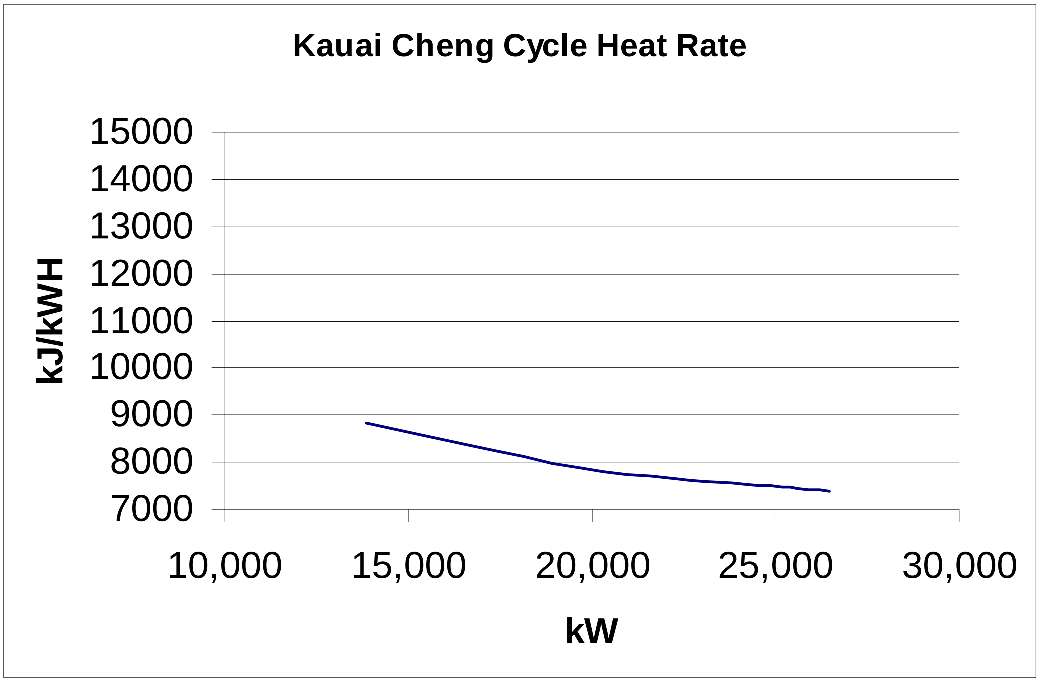

Figure 14

The steam injection retrofit paybacks for the Avon, LM2500 and LM6000 Sprint can be seen in Table 2.

				Dispatch hours		
		1000	2000	3000	4000	6000
Avon	Fuel	$514,199	$1,028,398	$1,542,596	$2,056,795	$3,085,193
	Power	$586,890	$1,173,780	$1,760,670	$2,347,560	$3,521,340
	Total	$1,101,089	$2,202,178	$3,303,266	$4,404,355	$6,606,533
LM2500	Fuel	$500,198	$1,000,395	$1,500,593	$2,000,790	$3,001,185
	Power	$669,510	$1,339,020	$2,008,530	$2,678,040	$4,017,060
	Total	$1,169,708	$2,339,415	$3,509,123	$4,678,830	$7,018,245
LM6000	Fuel	$974,526	$1,949,052	$2,923,578	$3,898,104	$5,847,155
	Power	$1,177,380	$2,354,760	$3,532,140	$4,709,520	$7,064,280
	Total	$2,151,906	$4,303,812	$6,455,718	$8,607,624	$12,911,435
Note:	Fuel price = ($7.50/MMBtu, HHV);			$7.12/million kJ		
	Power = $.09/kWH					

Table 2

Table 2 values were derived from the current price of fuel and power in California, USA. Based on the potential savings of fuel and increased power output capacity, in general, the payback to implement

CLN® technology in a Cheng Cycle will usually be on the order of one year from installation. (Ref. de Biasi, 2004).

6.0. Comparison of Water Injection, DLE and CLN® on an Economical Payback Basis

By request of reviewers, Table 3 compares the economical payback of the three available emission control systems based on 8,000 hours of operation.

Comparison of Water Injection, DLE and CLN® for Emission Control of the LM2500 PE over a Year									
Model	Heat Rate kJ/kWH	Power (Kw)	NOx (ppm)	Heat Rate Variation kJ/kWH	Power Variation	Fuel Exp. Per Year ($M)	Electrical Income ($M)	Revenue Per Year ($M)	Revenue vs. Water Injection ($M)
LM 2500 PE	9,278	22,801	168	0	0	12.83	18.24	5.41	0.93
LM 2500 PE (Water)	10,099	23,879	42	821	1,078	14.62	19.10	4.48	0.00
LM 2500 J (DLE)	10,184	21,719	15	906	-1,082	13.41	17.38	3.96	-0.52
LM 2500 CLN®	9,097	26,125	5	-181	3,324	14.41	20.90	6.49	**2.01**
NOTE:									
Fuel Price is USD 7.58/Mil Per kJ									
Electrical Price is US .1 Cent Per KwH									

Table 3

The current operating standard in the industry uses water injection coupled with SCR. DLE systems also require SCR to meet NOx emissions standards in California. Only CLN® does not require SCR. The comparison of the economical value is with water injection systems in terms of revenue income for a year of operation. It is obvious that DLE systems cost more than water injection. In contrast, CLN® makes $2Mil more than water injection systems.

7.0. Conclusion

The introduction of CLN® as an emission control system will be the only money saving control technology to be installed. In addition, it is the only proven greenhouse gas emission reduction technology available now to meet the 20% reduction before the targeted date of 2020. Such a retrofit retains the fast start up characteristics of the simple cycle which is typically used as peaking units or mechanical drive applications for compressors and pumps for the oil and gas industries.

8.0. References

1. Wang, D, Sahai V, and Cheng, DY, 2002, A Unique Combination Test Facility for Testing Low NOx Combustion Systems, ASME Turbo Expo Conference, June 3-6, 2002, Amsterdam, The Netherlands.

2. Sahai, V, Cheng, DY, 2003, Reduction of NOx and CO to below 2ppm in a Diffusion Flame, ASME Turbo Expo Conference, June 16-19, 2003, Atlanta, Georgia, USA.

3. Peltier, R, 2006, Cheng Cycle flirts with 2ppm NOx and CO, *Power Magazine*, May, 2006.

4. de Biasi, V, 2004, Steam-Fuel Mix Limits NOx and CO below 3ppm without DLN or SCR, *Gas Turbine World*, October-November, 2004.