Emission Control Strategies for Small Industrial Gas Turbines

Bruce W. Rising
Allison Gas Turbine
P.O. Box 420
Speed Code U4A
Indianapolis, In. 46206.

Richard J. Vacherot
Horizon Air Measurement
996 Lawrence Drive
Suite 108
Newbury Park, Ca. 91320

James J. Hamill
International Power Technology
100 Marine Pkwy
Suite 325
Redwood City Ca. 94065

Ellen K. Collins
Horizon Air Measurement
996 Lawrence Drive
Suite 108
Newbury Park, Ca. 91320

I. INTRODUCTION

In 1987, an Allison 501-K industrial gas turbine was installed at the world headquarters of SRI International in Menlo Park, California. The turbine, a model 501-KH equipped for steam and water injection, is installed at the cogeneration facility using International Power Technology's (IPT) Cheng Cycle technology[1]. The 501-KH engine is a member of the Allison 501-K family which includes the following engines:

501-KB and 501-KB5: Single shaft engines capable of dry operation, or water injection.
501-KH: Single shaft engine identical to the 501-KB and 501-KB5, but with the capability for steam injection.
501-KC and 501-KC5: Two shaft version of the single shaft 501-KB and 501-KB5.

Over a period of two years the gas turbine and auxiliary facilities were extensively tested for emissions using this 501-KH gas turbine (i.e. no overhaul or replacement of the unit). While there are a number of 501-K gas turbine installations around the world, this facility was selected because the control over steam or water injection allowed the engine to be tested as either a 501-KH or a 501-KB/KB5 , thus making the results applicable to a broader range of engine configurations. Testing primarily focused on using the various diluent injection methods to specifically control NOx emissions from the gas turbine, however, other criteria pollutant emissions were measured simultaneously.

II. BACKGROUND

In the early development of the 501-KH gas turbine, steam injection was explored primarily as a method of increasing engine power production and thermal efficiency. Steam, produced in a Heat Recovery Steam Generator (HRSG) located at the engine exhaust, is injected directly into the gas turbine engine, in contrast to the approach where a separate steam turbine would be used for power generation. Combining the gas turbine (Brayton Cycle) with a steam turbine (Rankine Cycle) is basis of the Cheng cycle. With this approach, total engine power increases due to the increased mass flow via equation 1:

$$\text{Eq 1:}\quad Power = Mass\ Flow * Cp * \Delta T$$

Where ***Mass Flow*** is a combination of Air, Steam, and Fuel injection rates. For the 501-KH, the total power increase is approximately 43% when the maximum amount of steam is injected into the engine. Thermal efficiency of the plant (gas turbine and support equipment) improves because a substantial part of the energy in the hot exhaust gas is recovered. In addition to increasing power, NO_x emissions are significantly reduced. This is because large quantities of steam injected into the gas turbine outer combustion case suppress peak combustion temperatures and reduce the formation of thermal NO_x.[2] The objective of the program was to understand this relationship between diluents injected for power augmentation and their combined impact on emissions.

Facility and Test Program

The gas turbine at SRI is the prime electrical generator for the site. The installation includes the following equipment:

1) Evaporative cooler at the gas turbine inlet;
2) Allison 501-KH gas turbine;
3) Water treatment system for the Nozzle Water injection and
4) Heat Recovery Steam Generator (HRSG) for the Case or Nozzle Steam injection.

A diagram of the facility and the general location of the steam injection points is shown in Figure 1.

Two steam injection modes are available for this facility: 1) Case Steam Injection and 2) Nozzle Steam Injection. They differ primarily in the location of steam injection: Case Steam is injected around through the outer combustion case, which surrounds the six can-type combustors (hence the name Case Steam Injection); Nozzle Steam is injected directly into the combustor through a nozzle that carries both the gas fuel and steam. For Case Steam Injection, superheated steam from the HRSG (at 900 °F) is delivered to the gas turbine where it is divided into one of two manifolds for injection into the engine. The front (or upstream) manifold delivers superheated steam into the region of the gas turbine near the front of the combustion chamber. A second manifold delivers superheated steam farther downstream, just before the combustion gases enter the power turbine. The steam delivery is controlled by a Staged-Steam valve located on the downstream manifold. When closed, all of the steam is injected into the front manifold (closest to the combustion zone). In the open position (an even or 'split' injection mode) , the steam flow is approximately evenly divided between the two manifolds.

When using water injection, the water enters through the fuel nozzle and passes directly into the high temperature region of the combustor. With Nozzle Steam injection, the steam enters in the same location, except that a different nozzle is required, and the steam temperature is only 400 °F (as compared to 900 °F steam for Steam Case Injection).

III. TEST PROGRAMS AND METHODS

Two series of field tests were conducted in June 1991 and June 1992, respectively. For each test program, emission parameters were monitored at various combinations of turbine inlet temperatures, Nozzle Water, Nozzle Steam, and Case Steam Injection rates.

During the Nozzle Water injection test series (carried out in June, 1991), Calculated Turbine Inlet Temperature (CTIT) set points ranged between 1400°F and 1935°F (maximum load). By varying the water injection rate or fuel consumption, water-to-fuel ratios from 0.0 to 1.3 were tested over this CTIT range. Water injection combined with Case Steam Injection tests were conducted over a CTIT range of 1700 to 1935°F. Water-to-fuel ratios ranging from 0.0 to 0.75 and Case Steam rates from 1 to 5.5 pounds per second (lb/sec) were tested during this testing phase.

During the Nozzle Steam injection test series, CTIT ranged from 1700°F to 1935°F (1700°F, 1800°F, 1895°F, 1935°F) with Nozzle Steam-to-fuel ratios ranging from 0.0 to 2.0. A series of tests were also conducted using both Nozzle Steam and Case Steam injection simultaneously over a CIT operating range of 1700°F to 1935°F. Nozzle Steam-to-fuel ratios of 0.0 to 1.5 and Case Steam Injection rates from 1 to 6 lb/sec were varied during this test phase.

Emissions data were collected at each turbine set point for a minimum period of six minutes after turbine stabilization. All samples were obtained from a rectangular exhaust stack (10 ft 2.5 in. x 6 ft 6.25 in.) at a location downstream of the boiler and economizer. The auxiliary burners for the HRSG were not operational during testing, and the air dampers were sealed to minimize the intrusion of ambient air. An integrated sample probe capable of obtaining a representative sample (6 sample points) was positioned across the entire length of the long axis of the rectangular stack for sample collection.

The emission parameters monitored and associated methodology used is provided in Table I.

Oxides of Nitrogen, Carbon Monoxide, Oxygen and Carbon Dioxide

The continuous emission monitoring (CEM) system consisted of a Thermo Electron Model 10 chemiluminescence NO/NO_x analyzer, a Teledyne Model 326R electro chemical O_2 analyzer, a Servomex Model 1400B paramagnetic O_2 analyzer, a Thermo Electron Model 48H CO gas filter correlation analyzer and a Fuji non dispersive infrared (NDIR) CO_2 analyzer. All stack concentrations were continuously recorded, on a dry basis, on a Soltec 10-inch strip chart recorder.

The NO_x analyzer was operated alternately in the "NO_x" and "NO" mode to determine the NO_2-to-NO_x fraction. The extractive monitoring system utilized in the testing program conformed with the requirements of EPA Methods 7E/3A/10. The sampling probe, constructed of 1/2 inch diameter 316 stainless steel, was connected to a condenser with a two foot length of 1/4 inch Teflon line. The sample exiting the condenser was then transported through 1/4 inch O.D. Teflon tubing, through a 47 mm glass fiber filter and a Teflon coated diaphragm pump to the sample manifold. The sample manifold was constructed of stainless steel tubing and directs the sample through each of five rotameters to each respective analyzer.

Prior to and at the conclusion of each test series, the CEM system and individual analyzers underwent performance checks to determine response time, linearity, system bias and NO_x converter efficiency in accordance with EPA Method(s).

Total Non Methane Hydrocarbons

Total non methane hydrocarbon concentration was monitored using US EPA Method 25A. Sample was continuously extracted from the outlet exhaust through a stainless steel probe and a heated Teflon sample line (250°F) into a two-way stainless steel valve, and then into the (Ratfisch RS55CA FID) analyzer . The valve was first placed into the "total hydrocarbon" position which routed sample directly into the analyzer. The valve was then switched to the "methane" position where the sample is drawn through a cooled charcoal cartridge to scrub out the non methane hydrocarbons. Methane passes through the charcoal into the analyzer. The methane result was then subtracted from the total hydrocarbon result to obtain total non methane hydrocarbons. All concentrations were recorded on a 10-inch strip chart.

Prior to and at the conclusion of each test series, the Method 25A system/FID analyzer underwent performance checks for response time, linearity and system bias. Methane was used for FID calibration.

Operating Parameters

All pertinent engine operating parameters, including fuel flow, CTIT, steam flow, water flow, kilowatt output, vibration and inlet temperature were monitored and recorded at three minute intervals using the Bailey control systems Trend Log.

IV SUMMARY AND TEST RESULTS

Water Injection Results

Water injection for emission control has been studied and used extensively with gas turbines.[3,4] In the first phase of this test program, NO_X emission control with water injection was evaluated. These results are displayed in Figure 2 where the corrected NO_X concentration is plotted utilizing a range of water/fuel ratios at different engine operating temperatures. As engine power increases (as measured by the engine CTIT), NO_X increases (comparing results at 90% of engine load to that at 100% load). But at high water injection rates there is little effect of engine operating point on the NO_X (corrected to 15% O2). (The maximum water/fuel ratio permitted for this engine is 1.3).

Nozzle Steam Injection Results

Following the liquid water injection tests, the engine was re-configured for Nozzle Steam injection. Steam piping was installed to the HRSG to deliver dry saturated steam to the gas turbine. Steam from this location is at 400 °F, versus the 900 °F superheated steam injected around the combustion chamber. Both the lower steam temperature and the direct injection into the combustor primary zone make this an effective means of NOx reduction as shown in Figure 3.

The data in Figure 3 reveal that NO_X emissions less than 25 ppm are possible with Nozzle Steam injection. However, the maximum steam injection rate for the engine is approximately 1.3 lb/sec, thus limiting the NO_X emission reduction to slightly less than 20 ppm.

Case Steam Injection Results

As mentioned earlier, Case Steam injection is accomplished by injecting into either the upstream manifold or evenly split between both manifolds. Either method of steam injection allows for significantly greater mass flow through the gas turbine than either Nozzle Steam or Nozzle Water injection. This produces a significant increase in both power generated by the gas turbine and total plant thermal efficiency.

Figure 4 shows the effectiveness of Case Steam injection for NO_X control. Two approaches are shown: 1) upstream injection (Staged Steam Valve is closed), all steam reaches the front manifold (closest to the NO_X producing zone); and 2) split injection (Staged Steam Valve Open),approximately equal distribution of steam between the manifolds. Clearly upstream injection is a more effective method of NO_X control, although injecting the maximum amount of steam into the upstream manifold causes increased CO emissions along with higher engine vibration. In either case, the total power generated by the gas turbine is unaffected by the location of the steam injection.

Combined Case Steam and Water Injection Results

While Case Steam injection by itself augments engine power production and reduces NO_X emissions, utilizing a combination of Case Steam injection with small amounts of supplemental Nozzle Water injection improves the versatility of the 501-KH engine. Using a combination of low water injection rates (e.g.

water/fuel=0.25) and moderate steam injection (1 to 3 lb/sec), NOx emissions can be consistently maintained at less than 25 ppm. This is demonstrated in Figure 5 where NO_X emissions are shown for a range of engine operating temperatures. Also, placing most of the steam through the front (upstream) manifold allows minimal NO_X emissions to be achieved at reduced steam rates (as shown in Figure 4). The combination of Nozzle Water injection and Case Steam injection gives facility operators the opportunity to divert steam from the gas turbine (where it is used for emission control) to other facility operations (such as facility heating or cooling). Without the assistance of Nozzle Water injection, over 80% of the available steam from the HRSG must be injected into the gas turbine to produce 25 ppm NOx

Combined Case Steam and Nozzle Steam Injection Results

Much like water injection, Case Steam Injection combined with Nozzle Steam injection is an effective mechanism for both NO_X control and enhanced power augmentation. With this combination, it is also possible to consistently achieve 25 ppm NOx over a wide range of operating conditions. Nozzle Steam injection offers the additional advantage of improved cycle efficiency compared to liquid water injection (due to the heat energy recovered in the steam). Also, with a combination of Case Steam and Nozzle Steam, there is no requirement for the water treatment system used in the water injection cycle. Elimination of this component is a significant cost savings for the facility.

Figure 6 shows how NO_X is influenced by the combination of Nozzle and Case Steam injection. In this example the Staged-Steam valve is in the OPEN position (i.e. steam is evenly split between the front and rear manifolds). While very low NO_X emission levels are shown on this figure, secondary emissions (CO and unburned hydrocarbons) become excessive as the NO_X levels are driven below 20 ppm. The relationship between NOx and secondary emissions is discussed in the next section.

V. DISCUSSION

All methods of diluent injection just described are effective NOx control methods, but only those which use steam improve the gas turbine cycle efficiency. Comparing nozzle injection techniques, water is a much more effective medium for reducing NO_X than steam on a per unit mass basis although both methods are capable of achieving 25 ppm NOx. This is shown in Figure 7 where the two methods are compared. This is because liquid water provides a greater thermal load on combustion zone temperatures than steam. However, liquid water injection alone only moderately increases engine power because the added mass flow is relatively low (less than 2,500 lbs/hr at maximum flow rate). This negative thermal loading from liquid water injection increases the fuel consumption considerably, producing a moderate decrease in the thermal efficiency. At equal mass ratios of diluent/fuel, water is the most effective, particularly at low diluent/fuel ratios. As the ratio increases, the gap (in terms of NO_X reduction) shrinks somewhat.

While liquid water injection increases fuel consumption and reduces the cycle efficiency, it is the preferred control method for the simple cycle gas turbine. This is because the technology for water injection requires only a relatively small water treatment system. It is less expensive than other alternatives, including steam injection (which requires a larger facility and HRSG) or Selective Catalytic Reduction (SCR) which is also costly and requires a larger facility for the catalyst and ammonia storage.

For Case Steam Injection (Only), the NO_X reduction effectiveness ranks as follows: Staged-Steam Valve Closed>Staged-Steam Valve Open. This comparison is made in Figure 8, where Case Steam and Nozzle Steam are compared directly.

When a combination of Case Steam and Nozzle Steam (or water) injection is used, the reduction in NO_x is greater than any individual diluent stream. In fact, this is probably the most effective method of achieving very low NO_x emissions on a consistent basis while operating the facility with the highest thermal efficiency.

CO Emissions

Carbon Monoxide (CO) emissions are an ubiquitous by-product of the combustion process. As with NO_x, CO was measured in all of the tests. For the most part, CO emissions were quite low, seldom above 10 ppm at most engine power levels and injection rates studied. However, at extreme cases of diluent injection (or a combination of high diluent injection at reduced engine power), combustion conditions shift sufficiently to produce significant amounts of CO. Significant in this test is defined as 25 ppm.

Since the purpose of the test program was to relate diluent injection rates to NOx reduction, it was also of interest to correlate NO_x emissions to the CO and unburned hydrocarbons, and also to correlate CO and unburned hydrocarbons to each other. The relationship between CO and NO_x is shown in Figure 9 which compares the CO to the total, measured NO_x in the exhaust gases. As NO_x emissions approach the 25 ppm level, CO emissions increase rapidly. These results are for all data: water injection, Nozzle Steam injection, and Case Steam injection. The increased CO indicates that the combustion process is being inhibited resulting in a decrease in combustion efficiency and stability of the engine.

Once CO emissions become excessive, the presence of unburned hydrocarbons also increases rapidly. This is shown in Figure 10, where there is roughly a 2:1 relationship between CO and unburned hydrocarbons (unburned hydrocarbons are expressed as methane).

There is also an interesting relationship between the total CO in the exhaust, and the fraction of NO_2 in the NO_x. Figure 11 shows that when the NO_2 in the exhaust is greater than 30 percent, the concentration of CO begins to increase noticeably. As total NO_x concentration decreases, the NO_2 becomes a major fraction of it.

Also depicted in Figure 12, the total NO_2 content in the exhaust is relatively constant, and it appears to decrease slightly as the total NO_x decreases. At low NO_x values, the NO_2 may comprise as much as 100 percent of the total NOx. Since the NO_2 portion is nearly constant, it appears that diluent injection is most effective in reducing NO, while not very effective at controlling NO_2. This suggests that water or steam injection can only reduce NOx emissions in the exhaust to a point where the NO_2 comprises 100% of the NO_x.

Meeting Regulatory Standards for NO_x

Results show that it is possible to meet very low NOx emission with steam/water injection. However, they do not indicate the possibility of meeting low emission standards *on a continuous basis*, over a wide range of operating conditions.

For example, most data show that it is possible to achieve NOx emissions less than 25 ppm NOx (corrected to 15% O2). To *guarantee* regulatory compliance with a 25 ppm standard, *actual* NOx emission level must be something less than 25 ppm, such as 20 ppm. Likewise, to meet a 15 ppm NO_x emission level (typical of an SCR), would require *actual* emission levels of approximately 10 to 11 ppm. The two previous figures show part of the difficulty of achieving such a low NOx emission level. In Figure 12, only the NO seems to be impacted by diluent (i.e. steam or water) injection. As shown in Figure 11, once the bulk of the NO is eliminated, further injection is not possible without creating secondary problems of high CO and unburned hydrocarbon emissions. While these secondary emissions may be controllable with an oxidation catalyst in the exhaust, the presence of high CO emissions in the exhaust is a strong indicator of combustion instability. Sustained instability can degrade engine performance and reduce component life. Further increases in diluent injection (to achieve lower NO_x levels of around 15 ppm) would not be fruitful because 1) with most of the NO reduced already, little if any further total NO_x reduction is possible, and 2) elevated engine vibration levels and combustion instability will continue, further reducing hardware life resulting in increased operating/maintenance costs.

VI CONCLUSIONS

NOx emission levels of less than 25 ppm NO_x (corrected to 15 % O2, dry basis, 60% relative humidity) can be achieved through a combination of diluent injection methods. Guaranteeing regulatory compliance at the 25 ppm NO_x limit, requires NO_x emissions less 25 ppm, possibly as low as 20 ppm..

The lowest NO_x emission levels achieved in this study were below 15 ppm. At this low NO_x concentration, nearly all of the NO_x is comprised of NO_2. Also noted, as the NO_x emissions decrease, there is a threshold level where the CO emissions increase rapidly. A rapid increase in CO occurs when the NO_2 part of the NO_x reaches 30%. When the NO_2 component reaches 100% of the NO_x, further diluent injection for NO_x reduction is not practical. Also, at this point engine vibration levels and combustion rumble indicate that the engine should not operate in this regime for any extended period.

VII. ACKNOWLEDGMENTS

The authors wish to thank those people who assisted in this program. Randy Culler (of IPT) was instrumental in preparing the SRI cogen facility for the test program. Brian Kelleher (of Kelleher and Associates) helped establish the test procedures and collected a large amount of the information necessary for this paper. Robert Halk (of Horizon Air Measurement) endured long hours of data collection and instrument checks to ensure that the emission measurements were accurate.

VIII. REFERENCES

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[2] Y. B. Zeldovich, Y. P. Sadovnikov and D. A. Frank-Kamenetski "Oxidation of Nitrogen in Combustion," Academy of Sciences of USSR, Institute of Chemical Physics, Moscow.

[3] D. W. Bahr and T. F Lyon, "NOx Abatement via Water Injection in Aircraft-Derivative Turbine Engines", ASME paper 84-GT-103.

[4] W.S. Y. Hung and D. Agan, "The Control of NOx and CO Emissions from 7-MW Gas Turbines as Influenced by Ambient Conditions", ASME paper 85-GT-50.

Parameter	Measurement Technique	Method
Oxides of Nitrogen	Continuous - Chemiluminescence	EPA Method 7E/20
Carbon Monoxide	Continuous - NDIR Gas Filter Correlation	EPA Method 10
Oxygen	Continuous - Fuel Cell and Paramagnetic	EPA Method 3A
Carbon Dioxide	Continuous - NDIR	EPA Method 3A
Unburned Hydrocarbons	Continuous - Flame Ionization Detection	EPA Method 25A
Stack Gas Flow Rate	Calculated	Fuel Flow/Expansion Factor

Table I CEM Measurement Methods

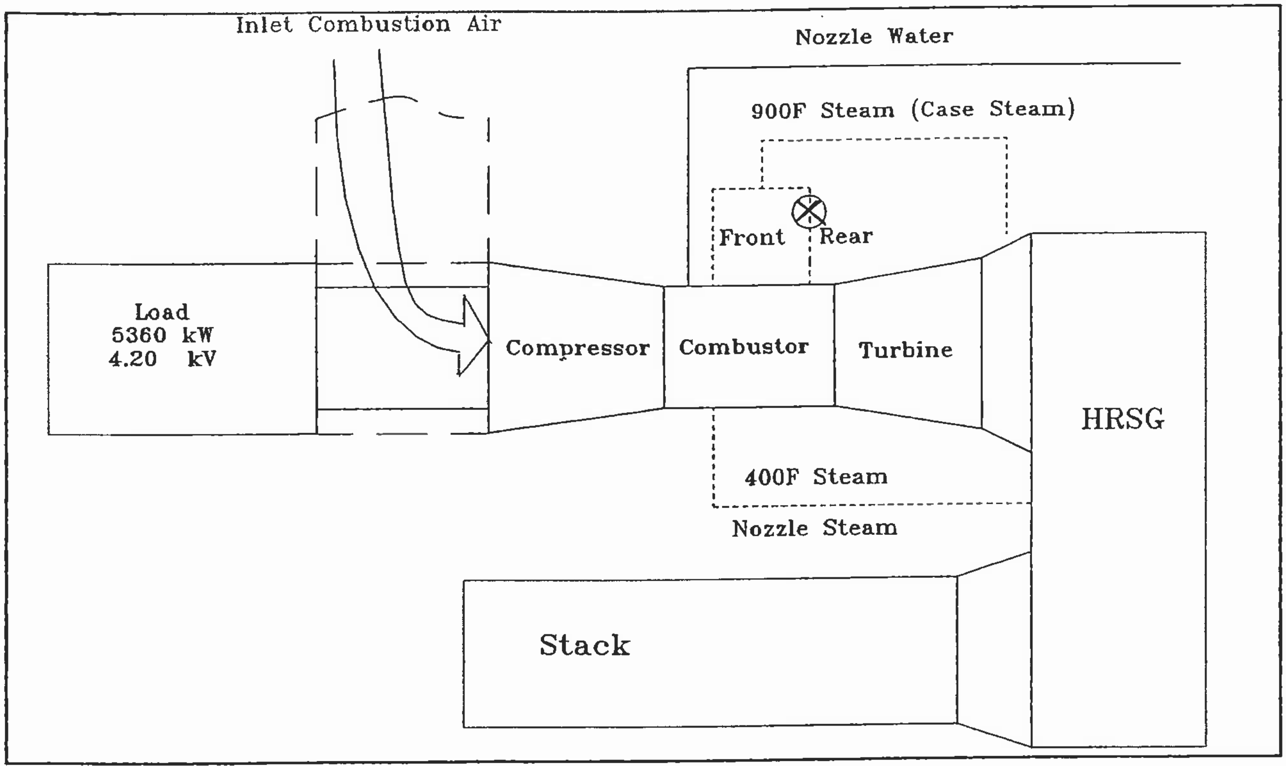
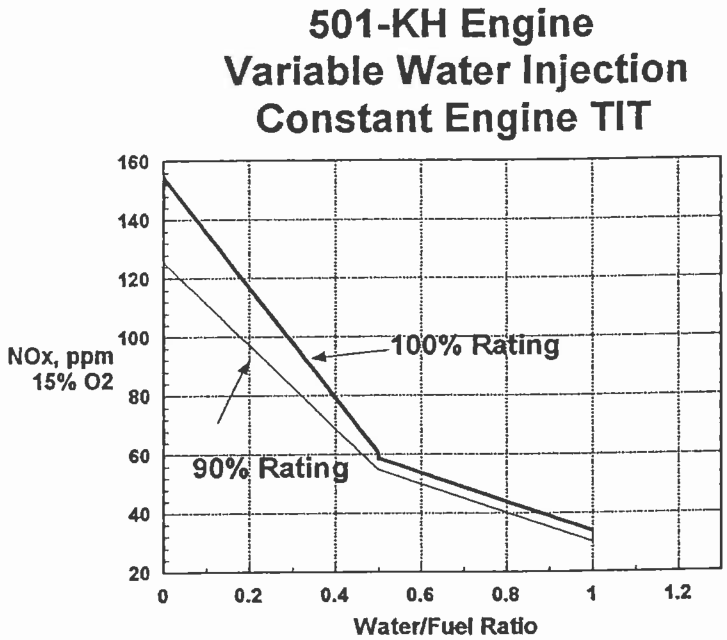
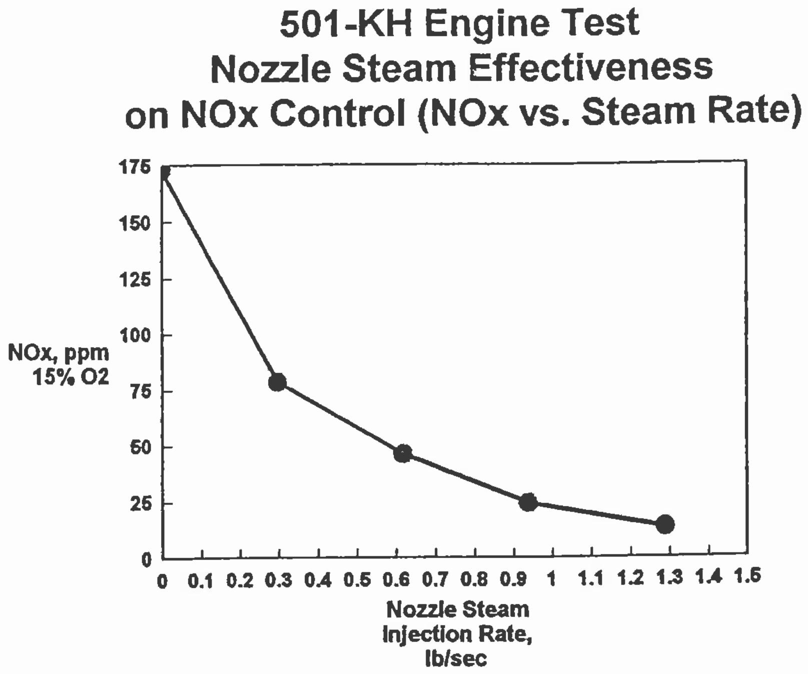


Figure 1. 501-KH Diagram and Facility Plan View.



501-KH Engine
Variable Water Injection
Constant Engine TIT

Figure 2. NOx with nozzle water injection.



501-KH Engine Test
Nozzle Steam Effectiveness
on NOx Control (NOx vs. Steam Rate)

Figure 3 Nozzle Steam injection only (400°F steam); maximum continuous operation.

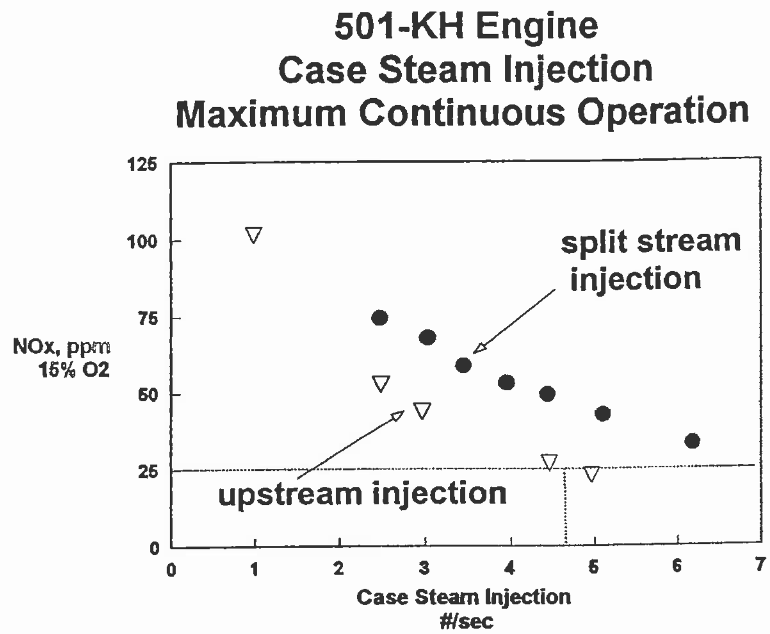


Figure 4. Comparison of steam injection locations for NOx reduction.

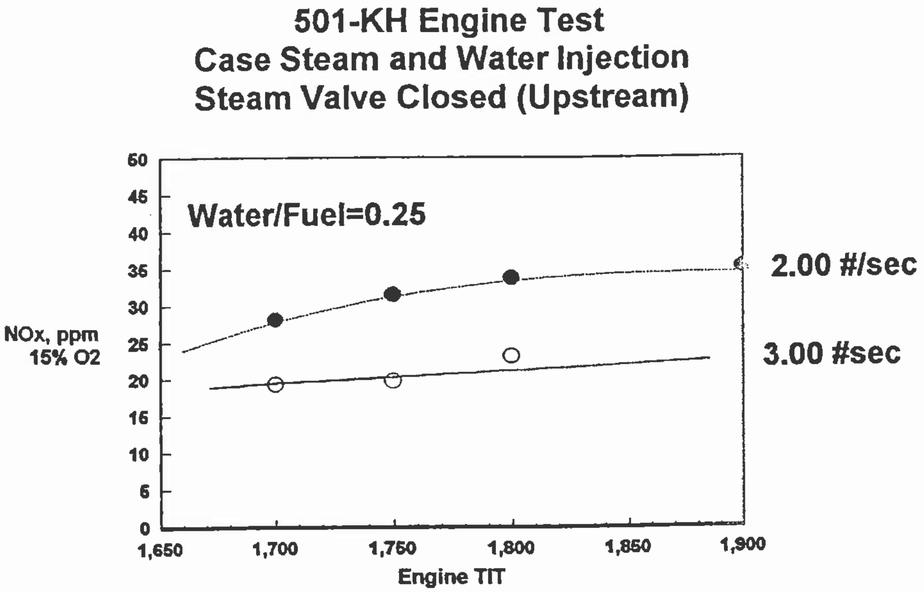


Figure 5. Combined Case Steam injection with Nozzle Water

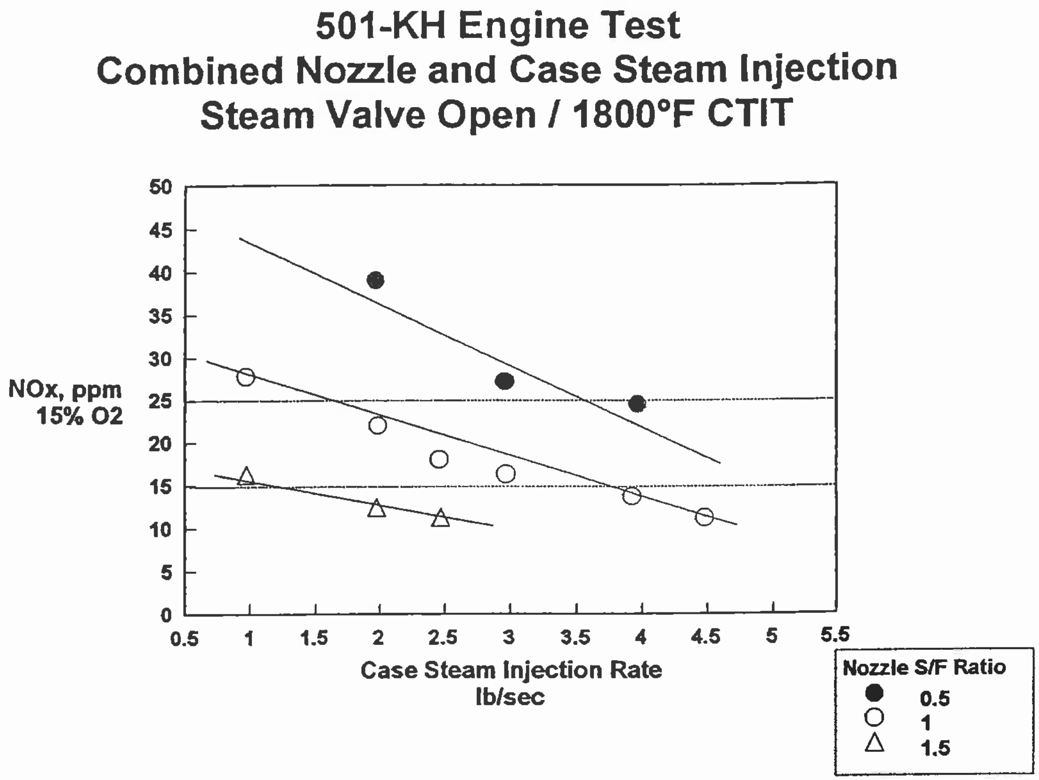


Figure 6 Combined Case Steam Injection with Nozzle Steam Injection.

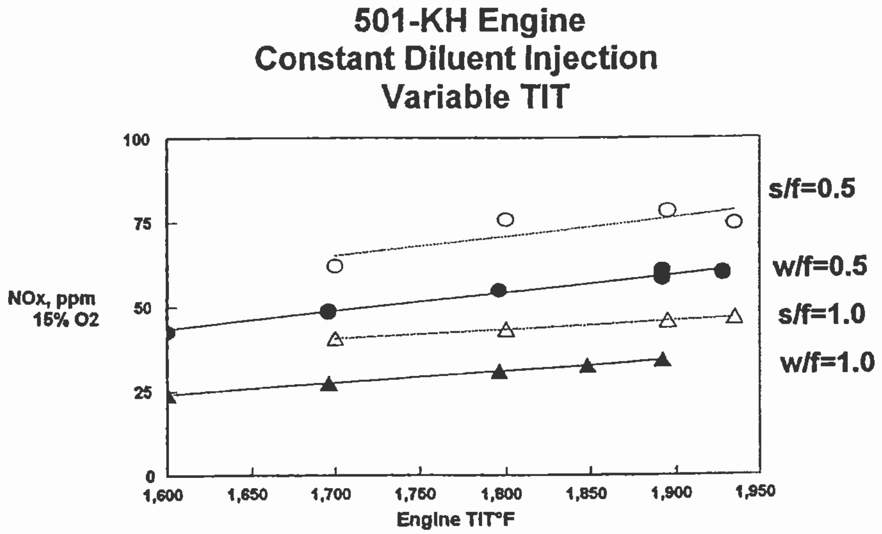


Figure 7. Comparison of Nozzle Steam Injection with Nozzle Water Injection.

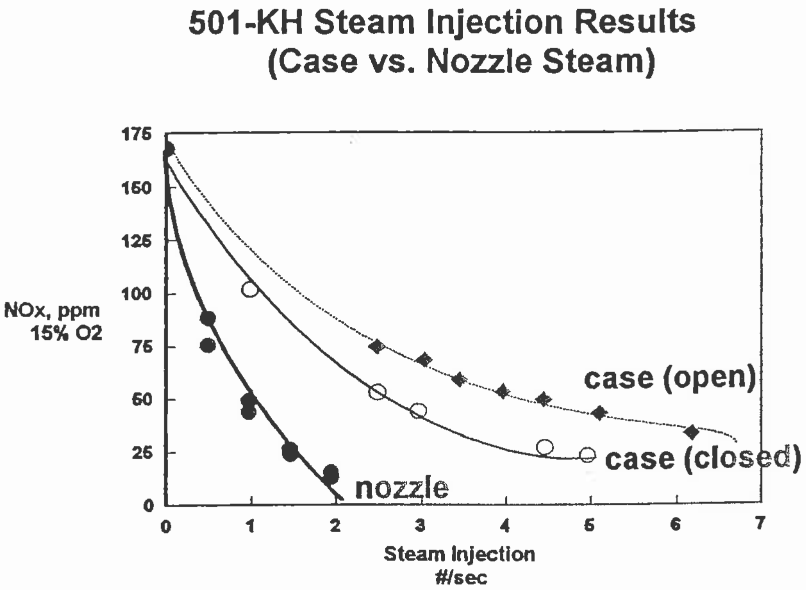

501-KH Steam Injection Results
(Case vs. Nozzle Steam)

Figure 8. Comparison of all steam injection modes.

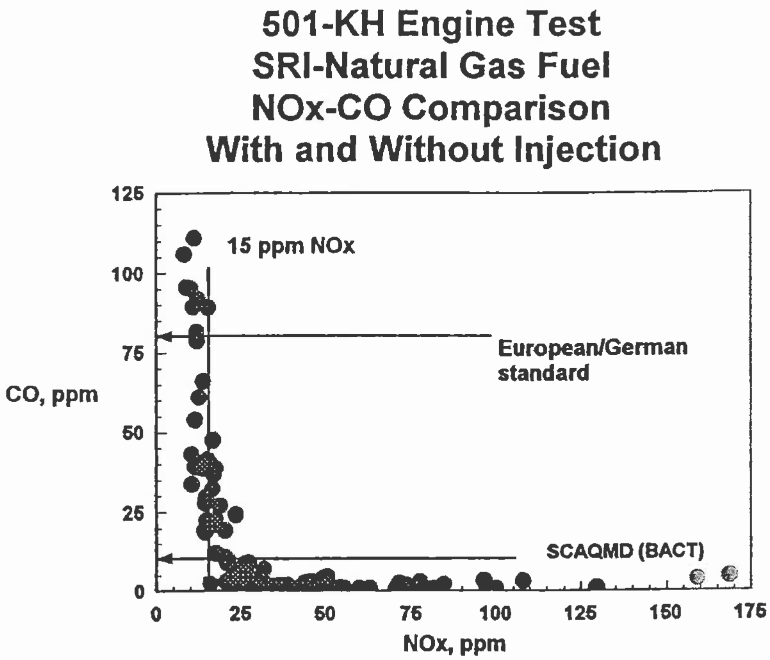

501-KH Engine Test
SRI-Natural Gas Fuel
NOx-CO Comparison
With and Without Injection

Figure 9. Comparison of CO and total exhaust NOx.

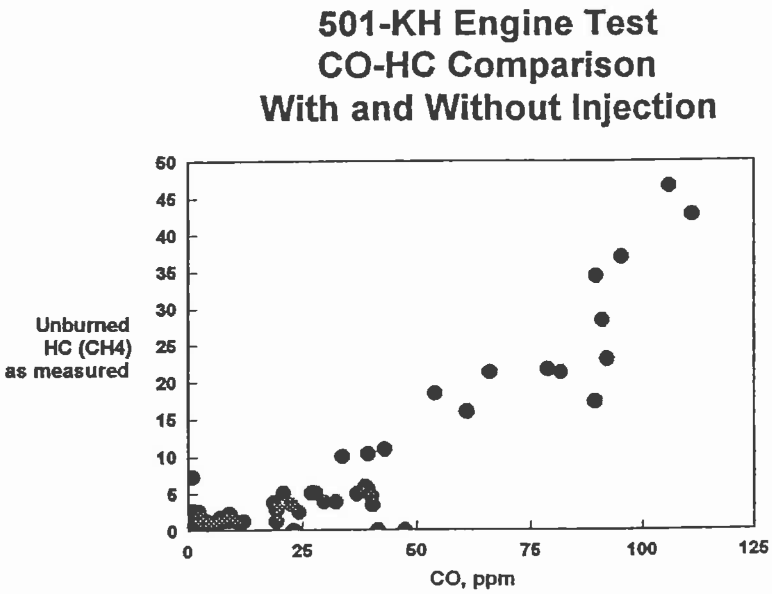


Figure 10 Relationship between unburned hydrocarbon emissions and CO for all injection methods.

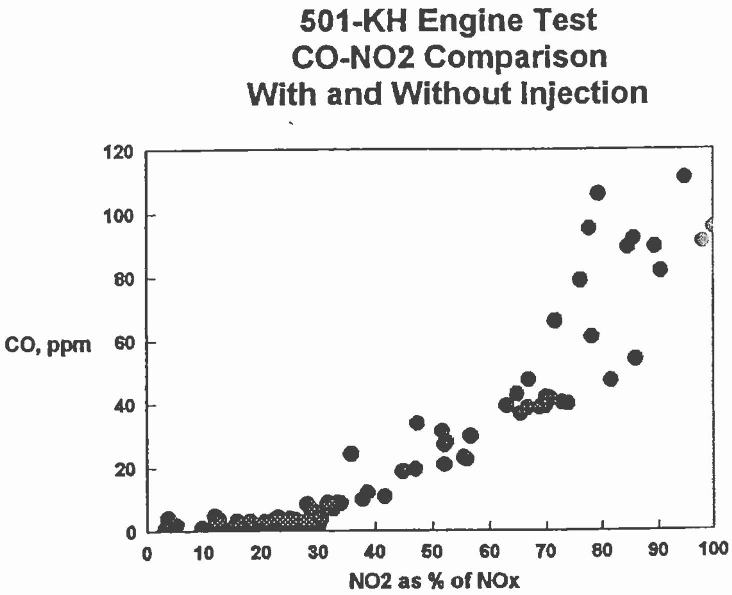


Figure 11. CO emissions as a function of the percent NO_2 in the NO_X.

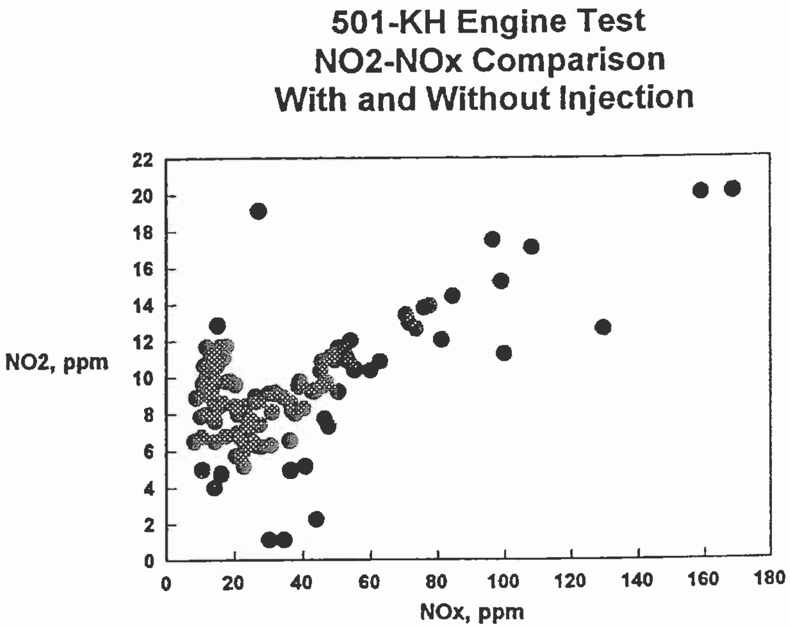


Figure 12. Comparison of the measured NO2 to the total NOx (all data, with and without controls)