ENGINUITY

Cost-Effective Emissions Reduction of Clark BA-6 Natural Gas Engines
(A Case Study)

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ABSTRACT

Existing and pending clean air regulations, and the associated costs of meeting them, are forcing many operators of I/C engines in gas compression and transmission applications to seek innovative ways to reduce emissions to compliance levels. This paper illustrates the Warren Petroleum Company's recent successful efforts to reduce NOx emissions levels of five Clark BA-6 natural gas engines to meet the Texas Natural Resource Conservation Commission (TNRCC) permit requirements. The permits required Warren to reduce emissions below 8 gms/bhp-hr NOx. Upon project completion in early 1996, the NOx emissions were reduced by 86% at the permitted engine load, and the fuel efficiency was improved 18%. For successful compliance, the design team developed a system that:

- Improved combustion airflow through the engine
- Provided additional combustion air for leaner operation
- Provided the capability to ignite the leaner air/fuel charge
- Enhanced in-cylinder mixing of the air/fuel charge
- Could automatically control all engine and support system functions.

This case shows that it is possible to combine fairly conventional hardware and principles in a somewhat unconventional manner to attain significant improvements in emissions and operating efficiency.

INTRODUCTION

As most in the energy industry now know, the 1990 Clean Air Act Amendments (CAAA) and the associated rules and regulations have mandated new, reduced emission levels for combustion sources. However, most of the existing plant and pipeline reciprocating horsepower was manufactured in an era when design criteria did not include these low emissions rates. Pre-CAAA, engine manufacturers considered engine and compressor reliability and performance the main design considerations.

Today's challenge for the industry has grown to not only includes engine reliability and performance, but also the ability to meet federal, state, and local emissions requirements. And to do it cost-effectively.

This case study, based on the experience of Warren Petroleum at its Sand Hills, Texas gas processing complex, outlines the company's successful approach to compliance in the state of Texas.

EMISSIONS

In order to more fully understand the engine modifications required in this program and their resulting effects, some discussion is required regarding emissions formation, air/fuel ratio, mixing, and general emissions control schemes.

When permitting combustion sources, EPA, state and local agencies commonly refer to two primary pollutants of concern: oxides of nitrogen (NO_x), and carbon monoxide (CO).

Oxides of Nitrogen (NOx)

NO_x is represented by two primary species: Nitric Oxide (NO) and Nitrogen Dioxide NO_2. NO formation occurs at high temperatures, when nitrogen and oxygen are present. The formation of NO from nitrogen and oxygen is highly time and temperature dependent. There is a threshold energy level above which the reactants have sufficient energy (activation energy) to go to products. The number of molecules at or above this activation energy level, and therefore, the number of reactions occurring is highly dependent on temperature. In fact, Arrhenius postulated that the rate of reaction is exponentially dependent on temperature. Additionally, the more time the reactants spend at these elevated temperatures, the higher concentration of products will be formed. [1]

NO_2 is formed by oxidizing NO. This commonly occurs in the flame zone of combustion; however, it is generally quickly converted back to NO. Chemical equilibrium considerations indicate that for burned gases at typical temperatures, the NO_2/NO_x ratios should be negligibly small. NO_2 will persist, however, if the flame is quenched by mixing with a cooler fluid. This is fairly common in lean burn applications where significant excess air is present to reduce peak combustion temperatures.[2] In these applications, it is not uncommon to measure NO_2/NO_x ratios as high as 40-50 % or higher.

Carbon Monoxide (CO)

The primary factor influencing Carbon Monoxide (CO) emission levels is air/fuel ratio. This dependence on air/fuel ratio is due to the availability of oxygen for the combustion process. CO, along with many hydrocarbon species, is an intermediate product of combustion. Lack of O_2 due to rich air/fuel ratio is the primary contributor to the premature termination of combustion in the power cylinder. When this occurs, the concentration of CO increases. Other contributors to the premature termination of combustion are combustion instability, flame quenching, and partial or total misfires.

Air/Fuel Ratio

The primary pollutants (CO, NO_x) have specific, well-established relations with air/fuel ratio (see figure 1). Air/Fuel Ratio is defined as the mass ratio of air and fuel present at the time of combustion. A stoichiometric mixture is the chemically correct point at which the ratio of fuel and oxygen molecules is exactly correct, thus, under ideal conditions, the oxygen and fuel molecules are completely consumed during combustion. The only products from ideal stoichiometric combustion are nitrogen (due to presence in air), carbon dioxide and water vapor. This stoichiometric point for any fuel is referred to as the relative air/fuel ratio 1 (λ=1). The relative air/fuel ratio (λ) is a measure of the actual air fuel ratio as compared to the stoichiometric ratio. Any number less than 1 is rich of stoichiometric (excess fuel), and greater than 1 is lean (excess oxygen). The relative air/fuel ratio λ=1 for natural gas is approximately 17:1.

There are many factors that contribute to combustion under non-ideal conditions. Incomplete combustion, reverse reactions, and the presence of nitrogen, lead to byproducts in addition to CO_2, nitrogen and water. Figure 1 shows the general relationship between relative air/fuel ratio and these byproducts.

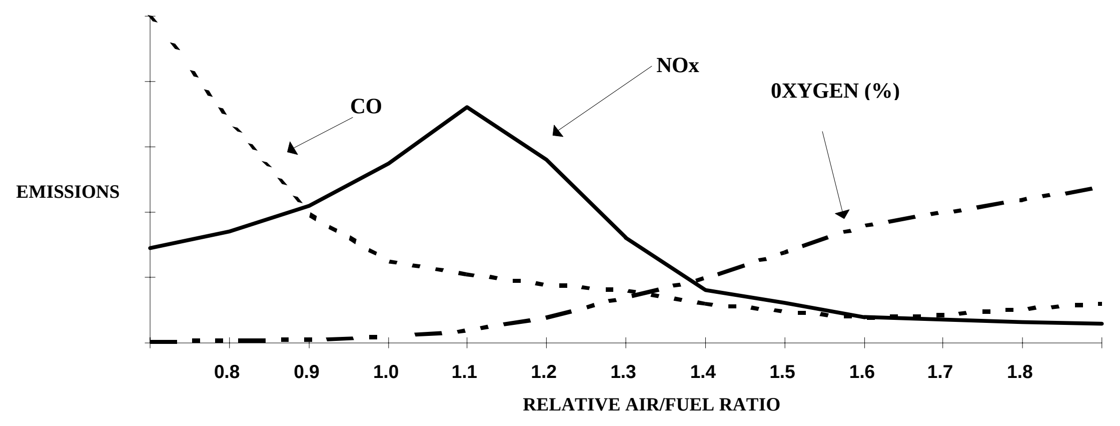

Figure 1

Figure 1 clearly illustrates the motivation to operate in the lean region when trying to reduce NO_x and/or CO emissions. Maximum combustion gas temperatures actually occur at λ = 0.9; however, at this relative air/fuel ratio, oxygen concentrations are low. As the mixture is further enriched, combustion gas temperatures, oxygen availability, and therefore, NO_x emissions, fall. Additionally, the combustion becomes less complete driving CO concentrations up and fuel efficiency down. As the relative air/fuel ratio is increased from stoichiometric, the oxygen concentration initially offsets the falling gas temperatures. The increased availability of oxygen actually boosts the generation of NO_x. This effect is soon reversed, however, as the falling combustion temperatures take over. Additionally, the increasing availability of oxygen promotes more complete combustion. In this portion of the graph ($\lambda > 1.1$), both the CO and the NO_x levels begin to drop, and fuel efficiency increases.[2]

Air/Fuel Mixing

Past and ongoing research into air/fuel charge mixing before and during combustion indicates that the mixed quality of the air/fuel charge plays a significant role in the emissions generation. Poor mixing results in local rich and lean air/fuel zones within the combustion chamber. Therefore, the local emission levels vary according to the relationships shown in Figure 1. In two cycle engines where the overall air/fuel mixture is typically lean of stoichiometric, this can lead to generally higher emissions than would be expected for the bulk relative air/fuel ratios at a given operating point. By improving the mixing process and homogenizing the air/fuel ratio throughout the combustion chamber, it can be possible to reduce the overall engine emissions without changing the engine operating conditions.

Emissions Control

Because exhaust oxygen concentrations can be easily controlled below 0.5% in naturally aspirated four stroke-cycle high-speed engines, a three-way catalytic converter and air/fuel ratio controller can be used to affordably maintain low emissions levels. Excess oxygen in the exhaust stream of two stroke-cycle, large bore, reciprocating engines is a consequence of utilizing airflow to scavenge combustion products and introduce a fresh charge of air for the next combustion cycle. This excess airflow can provide additional benefits such as increased horsepower, increased cooling, and lower emissions.

Turbocharging, which results in compression and increased volume flow of the combustion/scavenging air, is the primary means used by today’s lean-burn packages to supply air to the engine. New or uprated turbochargers are capable of supplying higher pressure and volume airflow to the power cylinders. The increased pressure increases the total mass of air trapped in the combustion process. The increased volume flow increases scavenging efficiency and ensures the replacement of combustion products with a fresh charge of air.

The increased mass of trapped air in the power cylinders can be utilized to increase the power output if the mass of fuel introduced into the combustion process is also increased. However, if the amount of fuel is not increased in proportion to the air mass, the net affect is a higher relative air/fuel ratio. In the latter case, the increased mass present during combustion absorbs more heat, which reduces the peak combustion temperatures. Because NO formation is exponentially dependent on temperature, reduced peak temperatures can provide dramatic NO_x emission reductions.

Reality

NO_x and CO emissions reduction has been a major issue long enough to enjoy a wide understanding throughout the industry. With even a rudimentary understanding of the above fundamentals, the common response provided when talking about NO_x reduction is simply "add air and install a high energy ignition system." Unfortunately, however, it is also common for the reality of applying these fundamentals to present challenges that are not accounted for in the basic theories.

Issues such as an engine's inability to breathe due to insufficient porting, poor air/fuel charge mixing due to fuel injection method and power cylinder configurations, and insufficient exhaust stream energy due to specific operating conditions can cause "generic solutions" to fail. Situations such as these require a more thorough understanding of the emissions formation, the physical laws governing gaseous flow, and the physical configuration of the engine. A true understanding leads to "engineered solutions" which account for reality, and ultimately, to the success of the project.

THE PROJECT

Diesel Supply Company (DSC) was hired by Warren Petroleum to reduce the emissions of five Clark BA-6 engines at their Sand Hills, Texas, gas-processing complex. The Clark BA series engines are piston-scavenged, 17" bore X 17" stroke, and operate at a rated speed of 300 revolutions per minute (RPM). The BA engine began manufacture in the early 1940s and is rated at 200 horsepower per cylinder.

The subject units are utilized for recompression and transmission of residue gas from the cryogenic liquefaction plant. By permit, the units are limited to 1000 horsepower (hp) output by the compressors. Due to their application in the gas refining process, the units are run at rated speed and permitted loads continuously, 24 hours a day, 365 days per year.

Previous to the permit's enforcement, the units were emitting approximately 19 gms/bhp-hr NO_x and 0.9 gms/bhp-hr CO and operating at 11,823 btu/bhp-hr fuel efficiency. Under the current permit, emissions output is limited to 8 gms/bhp-hr NO_x and 3 gms/bhp-hr CO.

The project began as a highly experimental feasibility study. Diesel Supply and Warren Petroleum investigated many concepts in a search for the most cost effective means to reduce emissions. Some of the concepts included: intercooling the piston scavenged supply air, using a portable roots blower to supply additional combustion air directly into the air manifold, and high-flow (pressure) fuel valves. The final package included high-flow fuel valves, an off-mounted turbocharger, and a multi-strike ignition system.

After the initial investigation period, DSC hired Enginuity International, Inc. (Enginuity) to design the system controls, and provide program management and installation supervision, and Turbine Specialties Inc. (TSI) to supply the turbocharger package.

Components

In order to accomplish the required emissions reductions, the design team set out to improve the air/fuel charge mixing by replacing the original Clark fuel injection valves with high-flow fuel injection valves, and increasing the trapped air/fuel ratio through turbocharging. This approach had the added benefit of reducing the unit's parasitic load (and therefore total engine load) by disabling the scavenging pistons and providing the combustion/scavenging air via the turbocharger. The new turbocharger system was to be controlled and allow system parameter monitoring through an Opto-22 Mistic programmable controller.

High-Flow Fuel Valves:

The high-flow fuel valve is a Wesco style cartridge valve that is installed in a modified Clark valve cage, thus allowing an easy field retro-fit by requiring little or no engine modification. The purpose of the high-flow fuel valve is to improve the in-cylinder mixing of the fuel and air thus promoting more complete combustion. This is accomplished by reducing the fuel valve orifice diameter. The smaller orifice increases the valve's flow restriction, thereby allowing the fuel header pressure to be increased. The higher-pressure fuel flow through the smaller orifice increases the gas velocity into the cylinder, thereby improving the mixing of the fuel with the intake air. Additionally, a shroud has been incorporated into the valve nozzle, which has been engineered to promote fuel dispersion into the combustion chamber.

Turbocharger System:

Disabling the scavenging pistons was calculated to reduce the unit's parasitic load by 93 horsepower. This was approximately 40% of the engine's pre-conversion parasitic load. Completely blanking off the scavenging pistons and installing a new air manifold header was considered; however, it was decided to utilize the existing air inlet piping and blow the inlet air through the scavenging pistons. This provided the most cost-effective method for getting the air from the turbocharger to the air chest with minimum impact to existing engine systems.

Maintaining the emphasis of impacting existing systems as little as possible, the turbocharger was specified to be an off-engine, skid-mounted unit. The final turbocharger skid package chosen and installed was an Elliot L-40, provided by TSI. The turbocharger skid package featured a stand-alone lubrication system, and a cooling system that was tied directly into the engine jacket water system. The engine air manifold pressure is controlled by controlling the turbocharger speed. This is done using a wastegate butterfly valve, which controls the amount of exhaust flow bypassing the turbocharger. The turbocharger uses a compressed air jet assist system to bring the turbo up to speed during initial startup.

After calculating the temperature rise due to compression to the air manifold pressure levels specified, it was determined that intercooling was not required. This was also an economic decision. Because the existing jacket water-cooling systems were not designed to handle the increased load of intercooling, complete new systems would have to be designed and installed. Additionally, the contribution of high air manifold temperature to NO_x formation could easily be overcome using other methods such as operating at leaner air/fuel ratios.

Ignition System:

Discussion was held regarding the choice of ignition systems available and their cost effectiveness for meeting the desired emissions goals. It was understood that if extremely low emission rates were required, screw-in pre-combustion chambers would be required to reliably ignite the lean air/fuel mixture. However, due to the moderate permit limits and restricted useful load, it was not necessary to operate at these lean air/fuel ratios.

The existing Altronic CPU-90 ignition system was replaced with an Altronic CPU-2000 multi-strike ignition system primarily due to its high-energy output and multi-strike capability. The CPU-2000 is capable of a operating in a single strike mode (only one ignition pulse per combustion event), or in a multi-strike mode (a series of four strikes per combustion event). The capability of multi-strike ignition systems to extend the lean limit beyond that of single strike systems has been proven previously in both laboratory and field-testing.

Control System:

The new control system was originally required to fulfill those functions added by the addition of the turbocharger and its subsystems. These functions included:

- Air/fuel ratio control via wastegate positioning - based on fuel flow, engine speed, air manifold pressure (AMP), and air manifold temperature (AMT)
- Jet assist activation/deactivation at engine start
- Turbocharger lubrication system - pre/post and run lubrication sequences
- Turbocharger cooling water pump activation
- Ignition retard and advance during engine start
- System safety alarms and shutdowns.

After the start-up of the first unit, however, Warren Petroleum decided to incorporate the functions of the original engine control panels into the new control system. The Mistic controller was chosen due to its capacity for expansion. This made it relatively easy to incorporate the additional inputs and outputs (I/O) and to reprogram the unit to accommodate the additional controls and safety/shutdowns.

All engine and turbocharger system parameters, alarms and shutdown signals can be viewed at either the controller or the annunciator display within the control panel. Additionally, the primary engine and turbocharger pressures have secondary gauge displays housed beside the ignition system controller on the control panel face. The software available for remote communication with the controller includes many features geared toward trouble shooting during initial start-up and confirmation of proper control program function and operation.

System Installation And Shakedown

Air Flow:

In the initial specification, Warren Petroleum was attempting to be proactive and provide enough reserve combustion and scavenging air from the turbocharger to reduce emissions to 2 gm/bhp-hr NO_x. The controller was to maintain the air/fuel ratio at a level, which would meet the current permit levels, but would be capable of easy reprogramming to comply with possible stricter regulations in the future. For this purpose the initial turbocharger specifications called for more airflow and pressure capacity than necessary to fulfill the permit requirements.

The turbocharger was installed adjacent to the engine room and set up to use the existing inlet air piping. The reed valves were removed from the scavenging pistons to allow minimal airflow restriction between the turbocharger and the air manifold.

The exhaust stack was replaced in order to interface with the turbocharger. By permit requirement, the stack height was increased from 20 feet to 40 feet at the same time.

In the early stages of the project, it become apparent that the BA has significant flow restriction issues. These issues made it difficult to provide a match between the turbocharger and the engine. As a result, it required more than one attempt to develop a turbocharger/engine system, which would operate properly and efficiently. The scavenging pistons of the unmodified engines were providing approximately 5-psi air manifold pressure. The exhaust pressure was less than ½ psi. This flow restriction proved to be too great for the available turbochargers to overcome and still provide adequate airflow for combustion.

Because the necessary information required to characterize the engine's breathing capability was not initially available, the design team had to go back and perform detailed testing and analysis of the engine's airflow capability. These investigations showed that the basic airflow through the engine had to be modified to allow the necessary air volumes at a reasonable pressure drop. By inspecting the porting of BA, HBA, and HBAT power cylinders, the design team discovered that Clark had identified the same limitations.

The exhaust and inlet port areas, and their ratio (A_e/A_i), play a key role in a loop-scavenged engine's breathing capacity and scavenging efficiency. As is the case in the BA series engine, if the inlet port area is too small, the airflow will be restricted. If the ratio of the exhaust port area to the inlet port area (A_e/A_i) is too large, the airflow through the cylinder will short circuit and not adequately scavenge the combustion products.

Testing has proven that for engines with piston speeds in the ranges experienced in the BA engine (850 ft/min.) scavenging efficiency increases markedly as the A_e/A_i is decreased from 1.2 to 1.0, and even to as low as 0.6.[3] The BA cylinders have an A_e/A_i of 1.20 and a total inlet port area of approximately 37 inches^2 per cylinder. The HBAT power cylinders considered in the design team's calculations have a total inlet port area of approximately 53.5 inches^2 per cylinder and an A_e/A_i of 1.04. This represents a 46% increase over the BA inlet port area, and an A_e/A_i which leads to a much improved scavenging efficiency. Additionally, the inlet ports are angled up to improve airflow direction and therefore scavenging and mixing.

To take advantage of the design improvements of the HBAT cylinders, the design team replaced the power side (piston crowns, cylinder liners, and cylinder heads) with HBAT components.

Controls:

As indicated above, the control system was originally specified to control only those functions required by the new turbocharger lubrication and cooling, air/fuel ratio control, ignition retard at startup, jet assist, and safeties. Warren Petroleum was so satisfied with its operation and capabilities they requested the functions of the existing engine control panel be incorporated into the Mistic system. The Opto-22, Mistic 200 controller was originally chosen for its flexibility and capacity for expansion. This allowed for the addition of the necessary I/O to fulfill the new charter.

RESULTS

Table I illustrates the "as found" and post modification, emissions and fuel efficiency. This level of performance has been maintained throughout all seasonal and operational fluctuations of the facility and ambient conditions. In fact, the first conversion has been in operation for nearly a year. Testing in September, 1996, indicated the performance and emissions are comparable with those tested in January, 1996, immediately after conversion.

Table I

Parameter	Before Conversion	After Conversion
Tested Horsepower:	917	975
Air Manifold Pressure [in. Hg]:	10.0	14.0
Air Manifold Temperature [°F]:	174	154
Fuel Flow [scfh]:	11,759	10,271
BSFC [btu/bhp-hr]:	11,823	9,713
NOx [ppm]:	1560	215
CO [ppm]:	120	197
Brake Specific NOx [gm/bhp-hr]:	19.25	2.75
Brake Specific CO [gm/bhp-hr]:	0.9	1.53

The improvement in NO_x emissions shown in Table I represents nearly an 86% reduction. As was anticipated due to leaner operation, the CO emissions increased 0.63 gm/bhp-hr; however, they are still acceptably low.

The combination of the parasitic load reduction due to disabling the scavenging pistons and the air flow/mixing improvements provided by the power cylinder conversion and high-flow fuel valves resulted in lower airflow requirements than originally anticipated. The airflow required to produce the desired emissions reduction is only 10-20% higher than that provided by the scavenging pistons.

Another significant comparison shown in Table I is the fuel usage and efficiency numbers. The fuel efficiency was improved by nearly 18%. This savings is reflective of the reduced total engine load by the disablement of the scavenging pistons, as well as improved mixing and therefore more efficient combustion. The majority of the improvement (approximately 13%) is the result of reduced parasitic load. However, the remainder of the savings (approximately 5%) can be attributed to the improvement in mixing and scavenging. This savings is not due to improved engine condition, balance or maintenance. The units at the Sand Hills facility were in excellent mechanical and operational condition before the conversions were begun.

Table II presents the before and after air/fuel ratio information. Both the total air/fuel ratios and the calculated trapped air/fuel ratios are provided. From past experience, these numbers seem to indicate that the reductions and improvements shown in Table I are due to improvements of the basic mixing and scavenging processes within the combustion chamber as well as by increasing the air/fuel ratio. Previous field and laboratory testing has shown larger relative increases in air/fuel ratio are required to achieve similar reductions when the reductions are achieved by air/fuel ratio increases alone.[4]

Table II

Parameter	Before Conversion	After Conversion
Total Air/Fuel Ratio:	28.6	36.4
Trapped Air/Fuel Ratio: (calculated)	17.0	23.2

In addition to the increased air/fuel ratio, the emissions benefited from the reduction in parasitic load due to the replacement of the scavenging pistons with a turbocharger. As indicated above, the power reduction due to the disablement of the scavenging pistons was calculated to be 93 hp. The actual reduction in parasitic load after the conversion was measured to be 134 hp. The discrepancy is most likely due to an over statement of the scavenging piston efficiency in the original calculations. The 134 hp represents a 58 % reduction in the parasitic engine load and 10.8 % reduction to the total power output of the power cylinders. This load reduction manifested itself in lower peak combustion pressures, and therefore, lower peak combustion temperatures. As previously discussed, NO_x formation is exponentially dependent on temperature.

The combustion quality was an initial concern because the engine would be operating at leaner air/fuel ratios, which are more difficult to ignite. A reliable means of providing a quantitative comparison of the before and after combustion stability was not available. However, the methods at hand were sufficient to provide a qualitative comparison. All indications are that the combustion stability is not quite as good as the pre-conversion stability; however, it is acceptable. In fact, the combustion quality is satisfactory enough to warrant continued use of the multi-strike ignition.

CONCLUSIONS

The Warren Petroleum Sand Hills case is a classic example of the need for engineered solutions in today's new compliance atmosphere. Blind implementation of heretofore solutions would have failed to produce the expected results. Due to the physical limitations of the Clark BA power cylinder configuration, many key assumptions required for the success of the "more air - less NO_x" approach fail to apply. Specifically, the assumption that more air can be forced through the engine with the means available. Another failed assumption would have been the assumption that the air/fuel charge was sufficiently mixed.

This application required specifically engineered solution providing improved mixing and improved (as well as slightly increased) airflow. Successful project completion required the following:

- Improved air/fuel charge mixing by installation of high-flow fuel valves
- Improved airflow and scavenging capabilities by replacement of power cylinders with better designed inlet and exhaust port configurations

- Increased air volume flow and air/fuel ratio by turbocharging
- Reduction of parasitic load by deactivating scavenging pistons
- Improved ignition system capable of igniting leaner air/fuel mixture
- Design and installation of flexible control system capable of expansion and modification.

Because these issues were successfully addressed, the design team was able to reduce the NO_x emissions to below the required level of 8 gm/bhp-hr (86% reduction), and improve the fuel efficiency by 18%.

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