REM Technology Inc.

Field Evaluation of the REMVue® LHP Technology

Final Report – Revision 2.0

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Executive Summary

The expected Canadian regulations for NO_x and CO emissions from existing, non-emergency natural gas engines > 100 to 200 kW will require the application of control technology to most existing engines. The recently developed REMVue® LHP (low horsepower) technology provides a way to meet these regulatory limits for turbocharged engines in the 100 to 600 kW range by means of lean combustion.

This report, commissioned by the Petroleum Technology Alliance of Canada (PTAC) and carried out by REM Technology Inc. (RTI), contains the findings from the application of the REMVue® LHP technology to 3 different engine models in the 100 to 600 kW size range that are in regular field service. The project duration was 24 months.

The work included an initial inspection, performance tests of the engine at specified operating conditions (pre-audit), the installation of the LHP controller and associated apparatus, site commissioning, re-inspection, and performance tests at OEM (original equipment manufacturer) settings and at lean combustion conditions (post-audit). Significant project delays occurred due to site ownership changes and coordination issues. The report contains considerable detail on fuel efficiency, emissions of NO_x and CO, and intake/exhaust temperatures for several load and rpm settings.

Caterpillar 3408 TA - Compared to OEM settings at 2.0 % exhaust oxygen, lean combustion gave a reduction in NO_x from 35 to 39 g/kW-hr to < 12 g/kW-hr, an efficiency improvement of 3 to 5 %, and a 55 °C reduction in exhaust temperatures. The existing turbocharger could not supply sufficient air to reduce the NO_x emissions further. Oil analysis showed a reduction in engine oil viscosity coincident with reduced NO_x emissions of lean operation.

Waukesha F11 GSI – Compared to “best power” settings, the LHP lean combustion reduced CO from 66 to 98 g/kW-hr to < 1.7 g/kW-hr, reduced the NO_x from 10 to 12 g/kW-hr to < 6 g/kW-hr, and provided an efficiency improvement of 6 to 15 %. Compared to “best economy” settings, the LHP lean combustion reduced NO_x from 32 g/kW-hr to < 6 g/kW-hr and reduced the exhaust temperature by 70 °C. The existing turbocharger could not deliver sufficient air to further reduce the NO_x emissions.

Waukesha H24 GL – This engine already operated lean with NO_x emissions of about 3 g/kW-hr. The LHP technology improved the excess air and NO_x control compared to the existing carburetor control. This will be critical for meeting NO_x emission limits under all operating and ambient conditions.

As expected with the introduction of new technology to the field, deficiencies were encountered. These were corrected and changes implemented to improve the field reliability of the technology.

The results show that the technology is viable for many, but not all, engines in the range 100 to 600 kW. Both life cycle costs and engine specific parameters must be evaluated before consideration of the REMVue® LHP technology.

New technology, such as improved ignition devices, and the re-application of selected parts of the LHP technology can provide efficiency and emissions benefits for a wider range of natural gas engines in the future.

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Introduction

This report contains the findings of a study funded by PTAC on the application of the REMVue® LHP technology to natural gas engines ranging from 100 to 600 kW (150 to 800 HP) in output power. The key factors of interest were:

- Fuel consumption
- Exhaust temperatures
- Exhaust emissions
- Reliability
- Maintenance costs

The initial work scope called for testing on 4 different engine make-models which represent the majority of the units in Western Canadian service in the upstream oil and gas sector, UOGS. It also called for the addition of the REMVue® SlipStream® technology and a third party audit. A change in funding and critical unit considerations led to a revision of project scope which excluded the addition of the SlipStream® technology and the third party audit.

The report provides details on:

- Project background
- Project scope change
- Measurement methodology
- Engine details
- Results

Since the study was commissioned, the sales price for natural gas has dropped considerably and it appears that NO_x and CO emission limits will soon come in to force for existing engines in 100 to 600 kW size range. The report discusses the best application of this technology in light of these changed economic and environmental conditions.

Project Background

The Need

In early 2005 REM Technology Inc. (RTI) was approached by several major oil and gas companies regarding problems with their low horsepower compression equipment. The customers expressed dissatisfaction with operation of many of their low horsepower units and commented on the looming emission regulations for these smaller units. Customers enunciated significant problems with head life, spark plug life, valve recession and reliability due to high operating head temperatures. Customers also expressed concern about potential problems with converting existing units, set to best economy (typically 2.0 % exhaust oxygen), to stoichiometric operation with 3-way exhaust catalysts to meet expected air emissions regulations.

In the past 1.5 years Environment Canada (EC) has consulted with industry segments, environmental groups and provincial government bodies to make recommendations for the introduction of Canada-wide air emissions limits for nitrogen oxides, NO_x, and carbon monoxide, CO. While at the time of this report the EC recommendations are not final for existing engines, it appears that the NO_x and CO limits will be applied to **all existing and new** natural gas engines with rated outputs greater than 100 to 200 kW (150 to 267 HP) in non-emergency service. Emissions limits will likely be **at or below** 6 g/kW-hr for NO_x and 5.4 g/kW-hr for CO[1] (new engines only). The majority of existing natural engines with outputs less than 600 kW (800 HP) do not meet these NO_x limits.

Fleet estimates show that in the Western Canada upstream oil and gas segment there are over 5000 engines with outputs less than 600 kW currently in regular service for gas compression. Most of these engines are operated at the best efficiency point (1.5 to 2.5 % O_2) or rich, which, unfortunately, produce NO_x or CO emissions well in excess of the proposed regulations.

These expected regulations will have a major impact on the existing Western Canadian engine fleet used in gas compression applications.

The Technology

The available technologies for meeting the CO and NO_x emissions limits are:

- Adding a stoichiometric control system and 3-way exhaust gas catalyst (NSCR)[2]
- Operating the engine lean without a catalyst

Studies show that, in comparison to stoichiometric operation, lean operation (excess air) provides better fuel efficiency and lower exhaust temperatures that result in improved reliability. Lean operation with more than 1.15 times the amount of air needed for full combustion reduces the NO_x and CO emissions, refer to Figure 1.

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[1] Conversion factor: 1.34 g/kW-hr = 1.00 g/hp-hr

[2] Non-Selective Catalytic Reduction

Most existing lower-power engines, not subject to emissions regulations, are operated with high NO_x emissions, either slightly rich or slightly lean of stoichiometric. Operation slightly rich of stoichiometric results in OEM[3] best power, while slightly lean operation results in OEM best economy. The REMVue® LHP system was designed for conversion of turbocharged natural gas engines with outputs less than 600 kW to lean operation. In comparison to the REMVue® rich to lean conversion for larger engines, the REMVue® LHP technology has a reduced cost.

Exhaust gas oxygen is a measure of the amount of excess air added to the engine. The REMVue® LHP system uses a wide-range exhaust oxygen sensor to control the air-fuel ratio produced by the existing carburetor. A throttle position sensor controls the turbocharger output pressure by means of a turbocharger wastegate adjustment. This overcomes the existing need for manual wastegate adjustment that is often needed with significant load changes or ambient temperature changes. In addition, throttle losses are reduced, particularly at part-load conditions leading to engine efficiency improvements. In the REMVue® LHP system the existing throttle governor control is retained. An ignition system upgrade may or may not be needed, according to the engine and site details.

The lower exhaust temperatures which result from lean operation have shown to reduce engine maintenance needs due to the high head failure and valve recession rates often encountered with these rich burn or best efficiency engines.

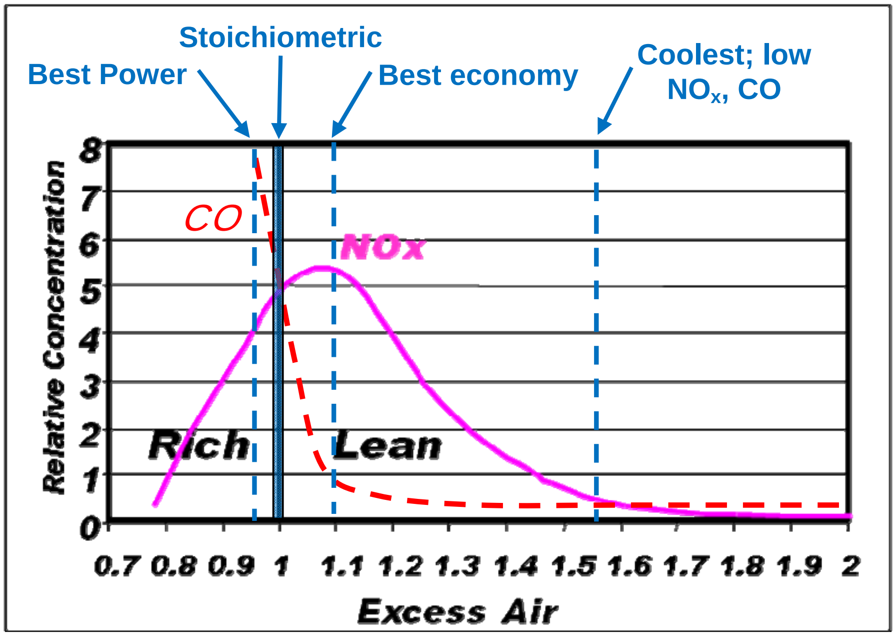

Figure 1: Effect of Excess Air on NO_x and CO Emissions

To ensure high availability for the engine (i.e. keeping the engine running) the LHP system defaults to the original OEM engine settings for exhaust oxygen and turbocharger boost pressure if any LHP control abnormality is observed.

The LHP system was initially designed for the Caterpillar 3300 series of engines. Modifications of hardware and control strategies have been required to extend the application to other engine models in the 100 to 600 kW range.

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[3] Original Equipment Manufacturer

Project Scope

Original Scope

The study commissioned by PTAC was to determine the applicability of the REMVue® LHP technology to several engine models.[4]

The original scope included 4 engines as follows[5]:

- Waukesha F11 GSI (Rich Burn)
- Waukesha H24 GL (Lean Burn)
- Caterpillar 3408 TA (Slightly lean, best economy)
- Caterpillar 3412 TA (Slightly lean, best economy)

Before and after measurements (pre-audit and post-audit) to determine changes were planned for the following items:

- Fuel efficiency (brake specific fuel consumption)
- Exhaust temperatures
- Nitrogen oxide, carbon monoxide and unburned hydrocarbon emissions

In addition, estimates on engine reliability and maintenance cost changes were to be done.

The study was to measure the impact of adding SlipStream® technology to the engines where appropriate.

A final report by a third party summarizing the economic and technical results of the study was included.

Revised Scope

As a result of reduced funding for the project, the third party report was eliminated and replaced by this project report. In addition, no SlipStream® systems were installed.

Initial measurements (pre-audit) were made on all 4 engines; it was decided to abandon further work on one unit (Caterpillar G3412 TA) because company operations personnel considered the unit to be critical for gas production in that area.

Ownership changes (Waukesha F11 GSI; Waukesha H24 GL) delayed completion of the work on those units.

In view of the project delays, time for adaptation to unexpected field conditions and the limited number of test sites, it is pre-mature to provide statements on reliability and maintenance costs. At best, anecdotal observations can be presented.

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[4] Refer to RTI document "Low Horsepower PTAC Study Project Scope - Jan 31 2010 - Customer.pdf" for additional details.

[5] Refer to Table A10 and Table A11 for engine and compressor specifications.

Application Development

Because the LHP technology had been applied only to Caterpillar 3300 and 3400 series engines, modifications of the hardware fittings and apparatus and some software modifications were needed for the Waukesha F11 GSI and H24 GL engines. The adaptations, of necessity, delayed the testing activity while field bugs and malfunctions were corrected.

Additional software modifications were put in place to deal with site specific control needs, including:

- A method to allow for more aggressive system tuning to address large speed and load transients.
- A means to prevent the air-fuel ratio from becoming too lean under light loading.
- A method to allow for the adjustment of the air-fuel ratio set point based on engine speed, load, and other physical parameters.
- A method to richen the air-fuel ratio set point for periods when the engines can not generate sufficient air to meet the desired air-fuel ratio set point.

Time Line

The time charts below show the main activities on a site by site basis.

Caterpillar G3408 TA

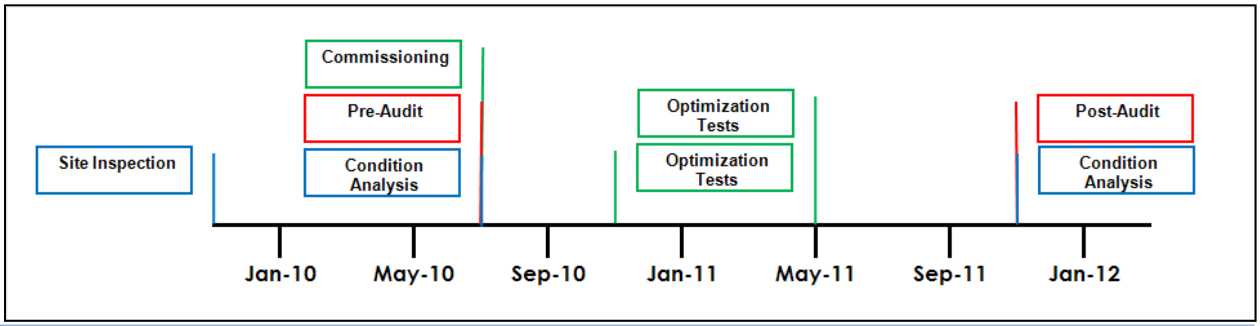

Figure 2: Project Timeline - Caterpillar G3408 TA

Waukesha F11 GSI

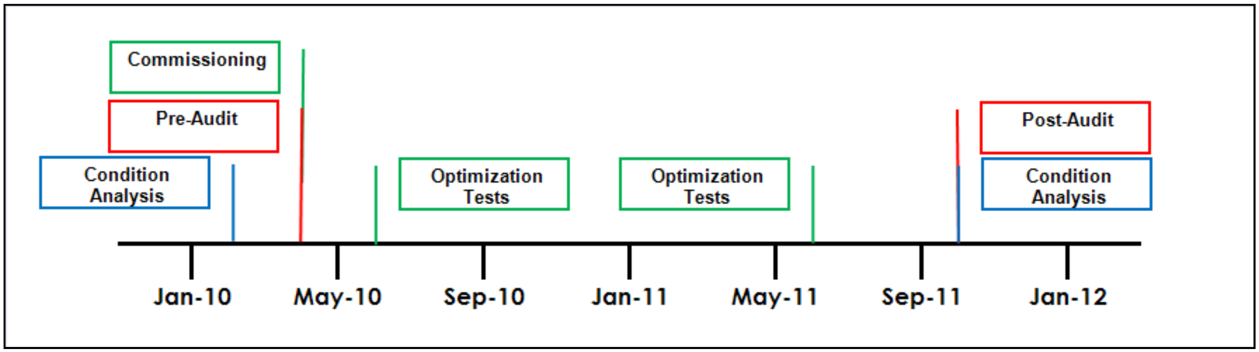

Figure 3: Project Timeline - Waukesha F11 GSI

Waukesha H24 GL

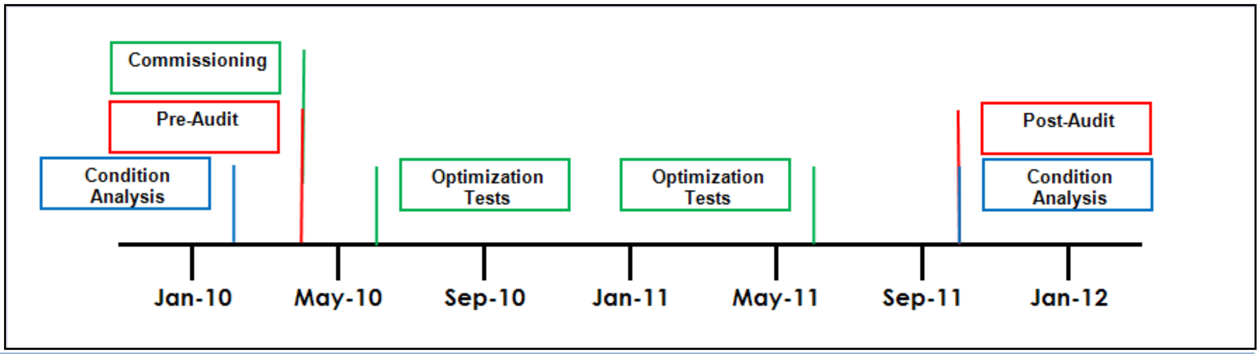

Figure 4: Project Timeline - Waukesha H24 GL

Test procedure

Pre-Audit

A pre-audit, comprised of an engine condition analysis and baseline performance tests, was carried out at each site.

For the engine condition analysis, a thorough mechanical inspection was performed on the engine by a qualified service technician. The inspection included the following measurements:

- Cylinder compression
- Crankcase flow
- Air filter differential pressure
- Intake air temperatures (pre & post-turbocharger, pre & post-intercooler)
- Jacket water temperatures (in & out)
- Intercooler water temperatures (in & out)
- Oil pressure
- Exhaust back pressure
- Ignition coil performance;

A visual inspection of the turbocharger, wastegate, ignition system hardware, and cylinder internals was also performed. Condition analysis measurement results are provided in Table B14, Table C17, and Table D20.

At one of the four test sites, Waukesha H24 GL, the mechanical inspection showed the need for repairs. A major top end overhaul and engine service was performed before the pre-audit performance testing.

After the initial inspection, the engine at the Caterpillar 3408 TA test site was replaced with a reconditioned unit prior to the baseline performance tests as a result of previous damage to the bottom end of the original engine. The inspection was redone for the replacement engine.

To provide a baseline test case, each engine was operated either at OEM settings or at the “as found” settings over a range of speeds and loads. These were selected based on typical site operating conditions, engine and compressor operating limitations, and the availability of process gas. To maintain a given operating point, the engine speed and compressor suction pressure set points were fixed for the duration of each test. In all instances, bypass and slide valves were maintained in the 100 % closed position.

Post-Audit

A post-audit was carried out to evaluate the performance of each engine after the installation of the LHP technology. As for the pre-audit, an engine condition analysis was performed on each engine prior to completing the performance tests.

For the post-audits, the LHP systems were configured to achieve a desired nominal emissions target, which varied from unit to unit due to limitations in the available excess air. Where possible, an attempt was made to operate the unit at 6.0 g/kW-hr and 2.7 g/kW-hr, corresponding to the current Alberta and British Columbia NO_x emissions levels for large natural gas engines respectively.

The air-fuel ratio and ignition timing settings were optimized within the limitations of the available excess air for lean operation. Using these settings, the pre-audit's baseline operating points were repeated where possible. In some cases changes in process conditions prevented an exact matching of conditions between the pre and post-audits. For both the pre and post-audits, the engine speed and compressor suction control set points were fixed and the bypass and slide valves were maintained in the 100% closed position.

Additional tests on the OEM rich burn engines with OEM recommended settings were also undertaken.

Data Collection

Engine and compressor performance data for each test point were collected with manual and electronic data-logs. Where possible, the electronic logs were acquired for a minimum of 5 minutes at a rate of 1 sample per second. A list of typical measurements is provided below:

- Unit speed
- Engine air intake manifold pressure
- Engine air intake manifold temperature
- Engine exhaust gas temperatures
- Engine ignition timing
- Compressor process pressures
- Compressor process temperatures
- Compressor slide valve and bypass valve positions

In all cases, electronic data logs were setup to collect fuel flow data from a Micro Motion Mass Flow Meter and emissions data from a portable ECOM Gas Analyzer. Fuel flow and exhaust gas measurements occurred over a 5 minute period at a rate of 1 sample per second and 1 sample every 5 s, respectively. Exhaust gas samples were acquired at each operating point with evacuated sample bottles. These samples, along with a set of process and fuel gas samples, were provided to an independent laboratory for detailed analysis

Ambient conditions were monitored by a portable weather station.

Emissions equipment calibration was carried out prior to each audit at a qualified calibration facility. Pre and post-zero checks were carried out on site. For the post-audit tests, two emissions analyzers were provided to allow for online spot checks of analyzer readings. Where possible, skid end device readings were spot checked against readings from a portable measurement device before acquiring audit data, ensuring a high level of data integrity for the engine performance measurements. Redundant exhaust, fuel and process gas samples were acquired in the event that sampling or analytical errors occurred.

Analysis

Where electronic data-logs were collected, the results of each test run were averaged and a standard deviation calculated before incorporating the data into an Excel spreadsheet with the manually recorded data. Where tests showed excessive deviations in the controlled variables the tests were removed from the analysis.

Fuel and compressor gas properties were determined from the mole fraction analysis of the gas samples using the gas property values in Reference [2].

For units with reciprocating compressors, engine power was determined by measuring compressor power with a portable machinery analyzer and providing an estimate for auxiliary loads.

For rotary screw compressor applications, OEM modeling software was used to provide a theoretical power calculation based on process measurements and gas properties. A fixed load of 5 % of the engine's rated power was added for auxiliary loads.

Engine efficiency was calculated on a brake specific energy basis. For each test point, the calculated BSFC was normalized to a fixed load condition using the calculations provided in Reference [1]. Parasitic losses of 24.5 % and 21.0 % of the rated power at 100 % torque were used for rich burn and lean burn engines, respectively, to determine the engine's parasitic load for use in the normalization calculation.

All emissions calculations utilize the EPA's Method 19 analytical process and are presented on a brake specific basis.

Neither of the lower cost methods used for exhaust hydrocarbon content provided reliable results so the unburned HC in the exhaust gases were not reported. For the exhaust samples collected for laboratory analysis, the correction for oxygen in the sample provided erratic results. The total hydrocarbon sensor in the ECOM analyzer does not give valid results for low exhaust oxygen fractions. The use of large evacuated sample canisters with gas chromatograph analysis, or dedicated exhaust hydrocarbon measurement equipment, was beyond the scope of this study.

Results

The pre and post-audit results are presented below for the following engines:

- Caterpillar G3408 TA
- Waukesha F11 GSI
- Waukesha H24 GL

Caterpillar G3408 TA

The Caterpillar G3408 TA is an open chamber engine (Refer to Table 1 for OEM ratings). A picture of the engine is shown in Figure 5. The engine nominally operates at 2.0 % exhaust gas oxygen.

Table 1: Engine Emissions at Rated Speed and Load (OEM Published) - Caterpillar G3408 TA

Rated Speed [rpm]	1800
Rated Load [kW]	298
NO_x [g/kW-hr]	33.04
CO [g/kW-hr]	2.15
THC [g/kW-hr]	3.48
HC (non-methane) [g/kW-hr]	0.52
O_2 [%]	2.0

The following engine modifications were implemented for the study:

- LHP system
  - Wide-band O_2 exhaust sensor
  - Current to pressure controller and fuel trim valve for air-fuel control
  - Throttle position sensor
  - Current to pressure controller and pneumatic relay for waste-gate control
- Carburetor and adapters suitable for higher intake air pressures
- Fuel regulator upgrade
- Higher-energy ignition system
- Iridium spark plugs

Prior to the installation of the higher-energy ignition system the engine was unable to reliably ignite air-fuel mixtures leaner than 6.0 % O_2. With the higher-energy ignition in place the lean operating limit was extended beyond 7.5 % O_2. Insufficient excess air prevented a true determination of the lean operating limit.

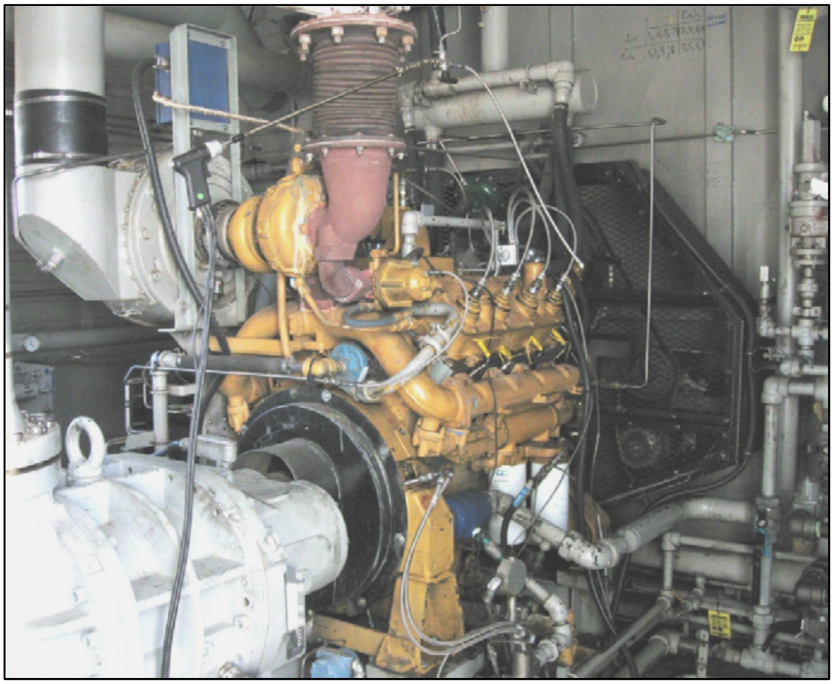

Figure 5: Caterpillar G3408 TA

Audit Results

The engine test configuration and test points are shown in Table 2 and Table B12, respectively. Plots of engine power and air manifold temperature for each test are provided in Figure B16 and Figure B17 for reference. Pre and post-audit fuel gas properties are provided in Table B13.

No data is presented from the pre-audit tests as the engine was found to be operating in a condition with very high NO_x emissions conducive to oil nitration. Instead, performance tests with the engine operating at OEM recommended conditions were performed after the LHP technology was installed.

Table 2: Test Configuration - Caterpillar G3408 TA

	Test Configuration[6]	
	Post-Audit (OEM)	**Post-Audit (LHP)**
Air-Fuel Control	Closed Loop LHP	Closed Loop LHP
Exhaust Gas Oxygen [%]	1.8 – 2.0	7.1 – 7.2
Ignition Timing [°BTDC]	21.0	27.0

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[6] Standard Rating: Exhaust gas oxygen = 2.0 %, Ignition timing = 22 °BTDC
Site Rating: Exhaust gas oxygen = 2.0 %, Ignition timing = <19 - 21 °BTDC. Unit is not normally rated for Caterpillar Methane Numbers below 70.

Figure 6 shows the impact of lean operation at 7.1 – 7.2 % O_2 on reducing $BSNO_x$ emissions. For this engine substantial reduction in NO_x emissions was observed relative to the OEM test case. A plot of the engine's BSFC for the different test cases is shown in Figure 7. With lean operation a 3 – 5 % improvement in fuel efficiency is observed throughout the range of operating conditions tested relative to the OEM test case.

Because the existing turbocharger could not deliver sufficient excess air to reach the desired NO_x emissions of 6.0 g/kW-hr, the engine was configured to achieve a balance between NO_x emissions reduction and engine fuel efficiency improvement. Figure B19 shows the exhaust gas oxygen percentage.

A reduction in exhaust gas temperature of 50 – 60 °C compared to the OEM test case occurred, see Figure B18. As Caterpillar G3400 series engines are known for their high cylinder head failure rate the reduction in exhaust gas temperatures and potential for reduced oil nitration with very lean operation should extend cylinder head service intervals.

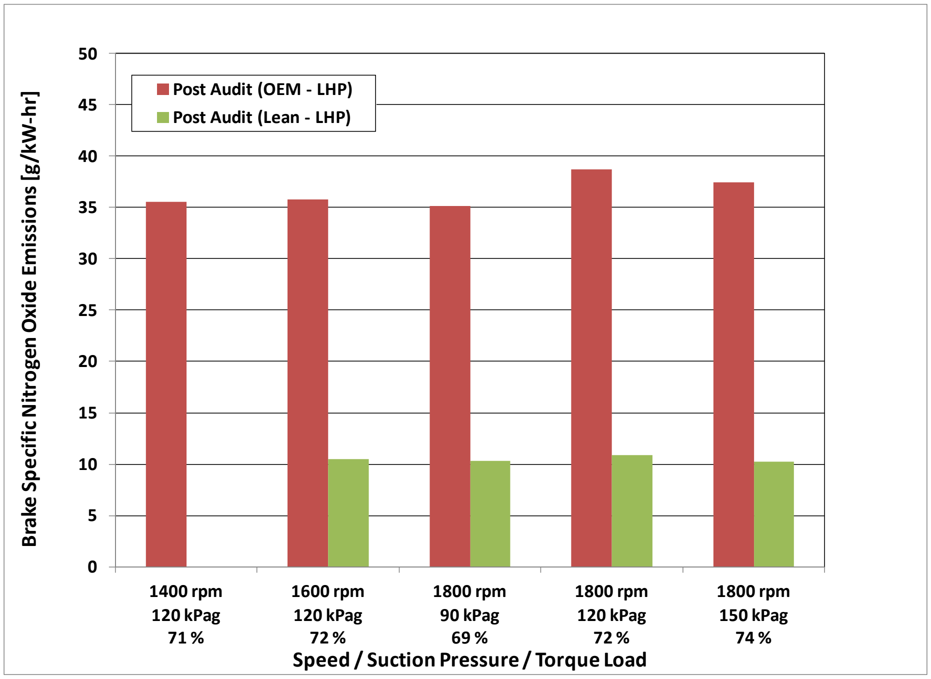

Figure 6: Brake Specific Nitrogen Oxide Emissions - Caterpillar G3408 TA

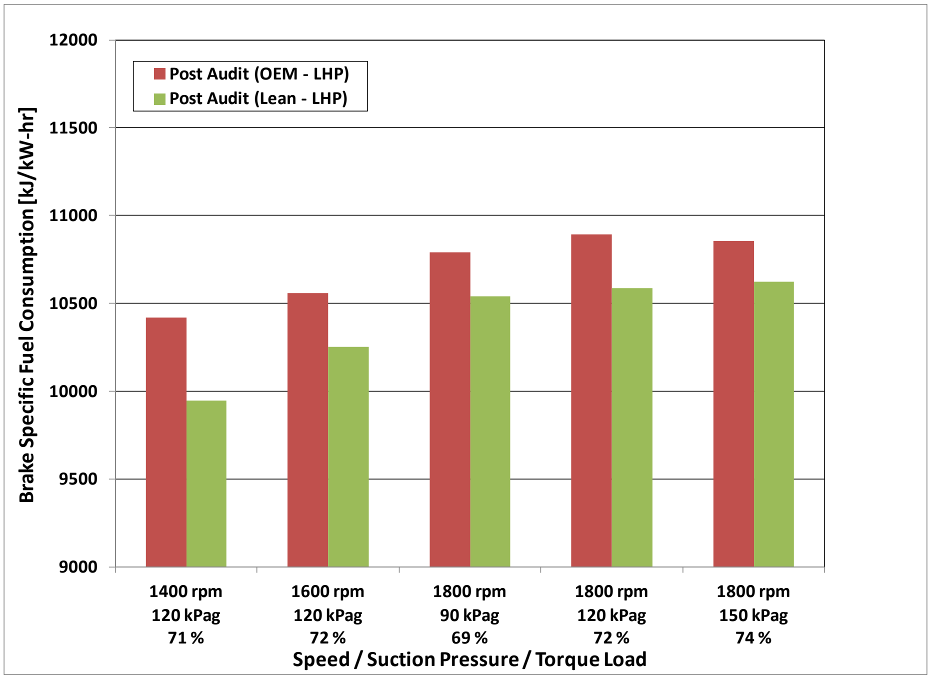

Figure 7: Brake Specific Fuel Consumption - Caterpillar G3408 TA

Site Corrections

Early on in the evaluation period, the waste-gate relay was re-mounted to address failures from excessive vibration. The oxygen sensor control module was also replaced after a poor power connection was identified.

Cold weather precipitated the freezing off of the oxygen sensor tubing line in the air inlet. The addition of a warm air-diverter resolved the issue. An option to route the oxygen sensor tubing from pre to post-turbine also exists.

Over the test period the fuel valve linkage showed the need for regular lubrication. Due to excessive wear the valve linkage was replaced prior to the post-audit.

Engine operation at very light loads with lean air-fuel ratios resulted in unstable engine operation and poor air-fuel control response. Software modifications (see Application Development) appear to have corrected the problem.

Replacement of the OEM carburetor with the IMPCO 600 Varifuel carburetor caused a small increase in engine instability under light loading during default (OEM) operation. A smaller IMPCO 400 Varifuel carburetor would be recommended for future installations.

Long Term Evaluation

The Caterpillar G3408 TA engine was operated for a total of 10770 hours over the duration of the study, 8700 of which the LHP system was in control. The unit was originally setup to operate at 6.5 % exhaust gas oxygen and did so for 4750 out of the first 6200 hours. It became necessary to richen the air-fuel mixture to 4.0 % oxygen to compensate for insufficient excess air during the few hours of the day where temperatures were at their highest and to address the inability of the engine to operate with very lean air-fuel mixtures under light loading. The engine remained at this setting for 3950 out of the final 4500 hours.

A graphical representation of oil analysis wear metals and contaminants for this engine is shown in Figure 8.

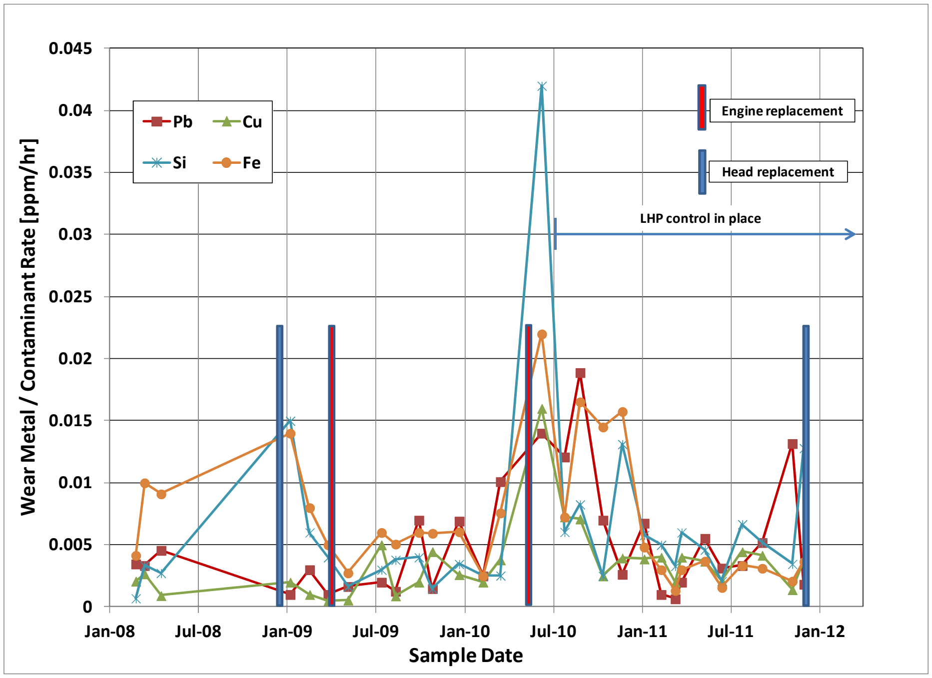

Figure 8: Selected Engine Wear Metals and Contaminants - Caterpillar G3408 TA

Figure 9, oil viscosity shows a reduction in viscosity with the lower NO_x operation of the LHP technology.

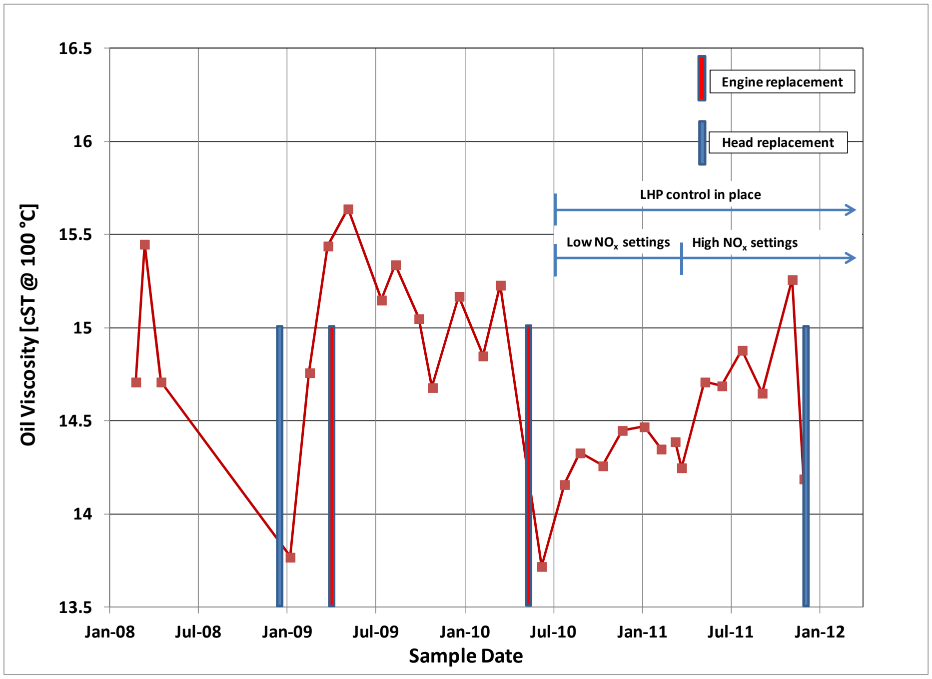

Figure 9: Oil Viscosity - Caterpillar G3408 TA

It is premature to determine if the need for engine maintenance has changed with the operation of the LHP technology. The oil viscosity is lower with the initial low NO_x lean operation; this may allow extended oil change intervals.

Continued monitoring of oil properties and air-fuel ratio settings would be beneficial to better define these effects.

Waukesha F11 GSI

The Waukesha F11 GSI is an open chamber rich burn engine (see Table 3 for OEM ratings). A picture of the engine is shown in Figure 10. The engine is typically operated at the following conditions:

- Best power - 1.15 % exhaust gas carbon monoxide (rich)
- Best economy - 1.4 % exhaust gas oxygen (slightly lean)

Table 3: Engine Emissions at Rated Speed and Load (OEM Published) - Waukesha F11 GSI

Item	Value	
Rated Speed [rpm]	1800	
Rated Load [kW]	186	
	Best Power	**Best Economy**
NO_x [g/kW-hr]	12.7	37.5
CO [g/kW-hr]	51.0	1.1
THC [g/kW-hr]	2.3	1.6
HC (non-methane) [g/kW-hr]	0.34	0.34
O_2 [%]	0.30	1.40

The following engine modifications were implemented for the study:

- LHP system
    - Wide-band O_2 exhaust sensor
    - Current to pressure controller and fuel trim valve for air-fuel control
    - Throttle position sensor
    - Current to pressure controller and pneumatic relay for waste-gate control
- Carburetor and adapters suitable for higher intake air pressures
- Fuel regulator spring change
- Higher-energy ignition system
- Iridium spark plugs

With the higher-energy ignition the lean operating limit was extended beyond 7.5 % O_2. However, the stock turbocharger was not able to provide sufficient air to achieve NO_x targets below 6.0 g/kW-hr.

Audit Results

The test configuration and test points for the unit are provided in Table 4 and Table C15, respectively. Comparisons of the engine power and manifold air temperatures for the test points are provided in Figure C20 and Figure C21 for reference.

In the pre-audit baseline test condition the engine was operated at approximately 2.0 % CO, just rich of the 1.15 % CO OEM setting for best power. The ignition timing was set to 15 °BTDC or 2.5 ° more advanced than the recommended timing from the OEM based on the Waukesha Knock Index (WKI) of the pre-audit fuel sample. The engine setup for the pre-audit test is considered typical for a rich burn engine. Pre and post-audit fuel gas properties are provided in Table C16.

Figure 10: Waukesha F11 GSI

Table 4: Test Configuration - Waukesha F11 GSI

Item	Test Configuration[7]		
	Pre-Audit	**Post-Audit (OEM)**	**Post-Audit (LHP)**
Air-Fuel Control	Open Loop Carburetor	Closed Loop LHP	Closed Loop LHP
Exhaust Gas Oxygen [%]	0.3	1.2	7.0 – 7.2
Ignition Timing [°BTDC]	15.0	14.0	15.5

For the lean LHP post-audit test case the engine was setup to meet a NO_x emissions target of 6.0 g/kW-hr with ignition timing and exhaust gas oxygen settings of 15.5 °BTDC and 6.5 % O2, respectively. The potential for further improvements in engine efficiency and NO_x emissions with leaner operation and additional ignition advance was limited by the availability of excess air.

A third set of tests were performed during the post-audit with the ignition timing set to 14 °BTDC and the exhaust gas oxygen set to 1.2 %. These values represent the OEM settings for best economy for a fuel WKI of over 90. As the WKI for the post-audit fuel sample was only 73.6 the ignition timing setting was more than 4 ° advance of what would be OEM recommended settings. Additional advance results in higher engine efficiency and NO_x emissions than would be normally expected. For this test case, air-fuel control was performed by the LHP system.

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[7] Standard Rating: Exhaust gas carbon monoxide = 1.15 %, Ignition timing = 14 °BTDC
Site Rating: Exhaust gas carbon monoxide = 1.15 %, Ignition timing = 9.5 – 12.5 °BTDC

Plots of $BSNO_x$ and BSFC are shown in Figure 11 and Figure 12, respectively. With lean operation at 7.0 to 7.2 % O_2, fuel efficiency improvements of 6 – 15 % and NO_x emission reductions of 30 – 55 % are realized relative to the pre-audit baseline. Even with the additional advance and various system upgrades present for the post-audit testing at the OEM best economy operating point, lean operation shows comparable fuel efficiency and an 80 % reduction in NO_x emissions. Furthermore, Figure C22 demonstrates that average exhaust gas temperatures are reduced by approximately 70 °C compared to operation at best economy. Exhaust gas temperature measurements were not available for the pre-audit baseline test, however, similar reductions in the exhaust gas temperature would be expected.

Figure C23 shows that the LHP system is able to maintain the exhaust gas oxygen within 0.1 %. This translates to good NO_x control over the range of engine operating conditions.

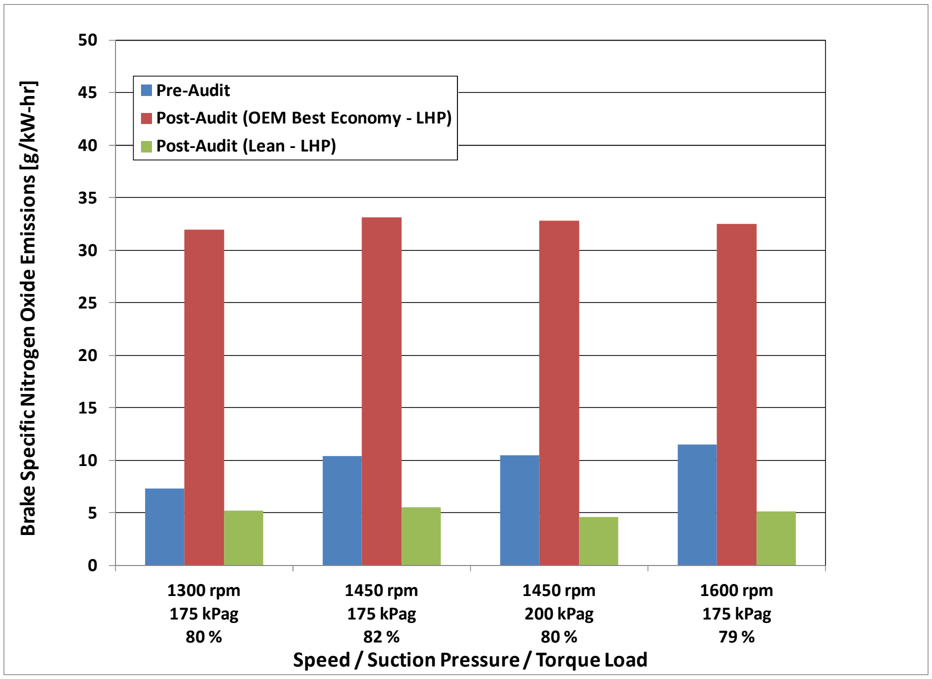

Figure 11: Brake Specific Nitrogen Oxide Emissions - Waukesha F11 GSI

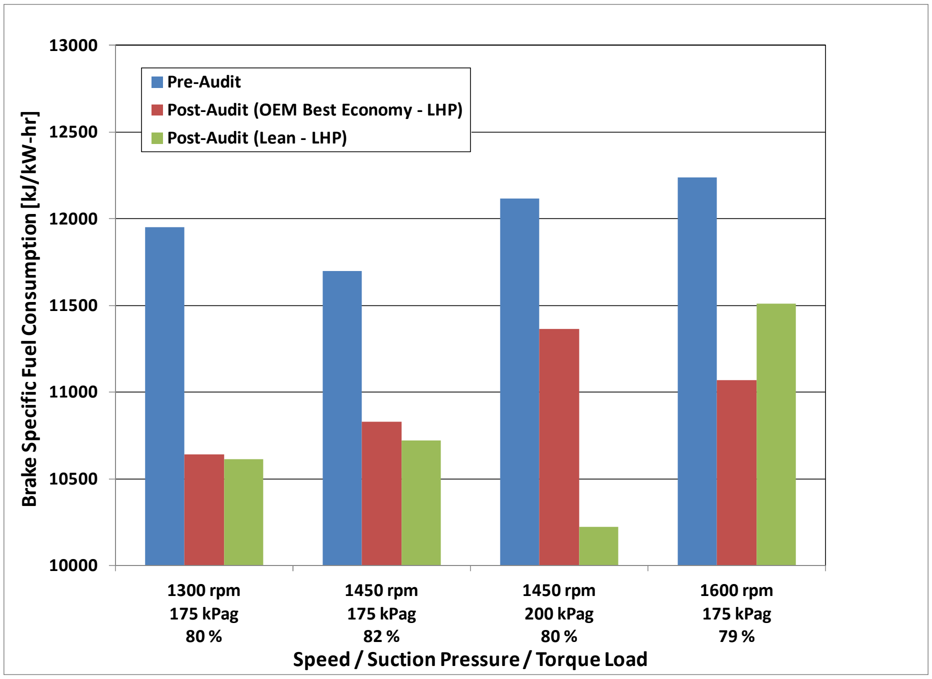

Figure 12: Brake Specific Fuel Consumption - Waukesha F11 GSI

Site Corrections

This site was the first application of the LHP technology to a Waukesha F11 engine; as expected minor problems occurred and were corrected.

The throttle position sensor was relocated during the trial to prevent damage during normal engine servicing.

Line pigging caused rapid load swings to which the LHP software responded poorly. Software modifications (See Application Development) appear to have corrected the problem.

Over the test period the fuel valve linkage showed the need for regular lubrication. Due to excessive wear the valve linkage was replaced prior to the post-audit.

A poor power connection to the oxygen sensor control module was identified and the wiring replaced.

Improved spark plugs were recently installed, which have exceeded the desired service life of 1400 h.

Since the engine operated lean for less than 50 % of the run time, no statement can be made on engine maintenance and reliability.

Waukesha H24 GL

Unlike the other engines in this study, the Waukesha H24 GL is an open chamber lean burn engine (see Table 5 for OEM ratings). A picture of the engine is shown in Figure 13. The LHP technology was applied to this engine to improve the air-fuel control compared to the existing carburetor.

Table 5: Engine Emissions at Rated Speed and Load (OEM Published) - Waukesha H24 GL

Rated Speed [rpm]	1800
Rated Load [kW]	388
NO_x [g/kW-hr]	3.5
CO [g/kW-hr]	2.35
HC [g/kW-hr]	6.7
HC (non-methane) [g/kW-hr]	1.01
O_2 [%]	7.8

The following engine modifications were implemented for the study:

- LHP system
    - Wide-band O_2 exhaust sensor
    - Current to pressure controller and fuel trim valve for air-fuel control
    - Throttle position sensor
    - Current to pressure controller and pneumatic relay for waste-gate control

The LHP control system reduces the air-fuel ratio changes due to load, temperature and atmospheric pressure changes compared to carbureted operation. The addition of waste-gate control reduces the throttle losses, particularly at partial loads with some efficiency improvement. No significant change in NO_x emissions was expected.

Figure 13: Waukesha H24 GL

Audit Results

The engine test configuration and test points are shown in Table 6 and Table D18, respectively. Pre and post-audit fuel gas properties are provided in Table D19. In an attempt to realize an efficiency improvement with the LHP system the engine was operated with 3 ° of additional advance relative to the baseline case and the air-fuel ratio was adjusted to achieve the desired NO_x emissions. Plots of engine power for each test are provided in Figure D24 for reference.

Table 6: Test Configuration - Waukesha H24 GL

	Test Configuration[8]		
	Pre-Audit	**Post-Audit (BC)**	**Post-Audit (AB)**
Air-Fuel Control	Open Loop Carburetor	Closed Loop LHP	Closed Loop LHP
Exhaust Gas Oxygen [%]	7.9 – 8.4	8.8 – 9.0	8.2 – 8.3
Ignition Timing [°BTDC]	9.9	13.2	13.2

Figure 14 and Figure 15, show plots of $BSNO_x$ and BSFC for each test case. The results indicate that no BSFC improvements were realized at a comparable emissions level. What is more telling, however, is that operation with near baseline air-fuel ratios with advanced timings, i.e. Post-Audit (AB), also did not show a BSFC improvement where one would normally be expected.

Part of this efficiency discrepancy may be attributed to the 10 to 15 °C higher air manifold temperatures during the post-audit tests, see Figure D25. More advance timing in combination with leaner operation resulted in a decrease in exhaust gas temperatures, see Figure D26.

One clear benefit of utilizing the LHP system was the ability to maintain tighter air-fuel control over the range of engine speeds and loads. Figure D27 shows that the LHP system maintained the exhaust gas oxygen within 0.2 % O_2 versus 0.5 % for the OEM controls over the speeds and loads tested. The more stable air-fuel control translated into more consistent NO_x emissions at a comparable NO_x target.

Site Corrections

Over the test period of 12790 hours the fuel valve linkage showed the need for regular lubrication.

The oxygen sensor performed well for the test period, well in excess of the expected replacement interval. Occasional plugging of the oxygen sensor lines occurred; a service procedure of blowing out the sample lines was instituted.

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[8] Standard Rating: Exhaust gas oxygen = 7.8 %, Ignition timing = 13 °BTDC
Site Rating: Exhaust gas oxygen = 7.8 %, Ignition timing = 9 °BTDC

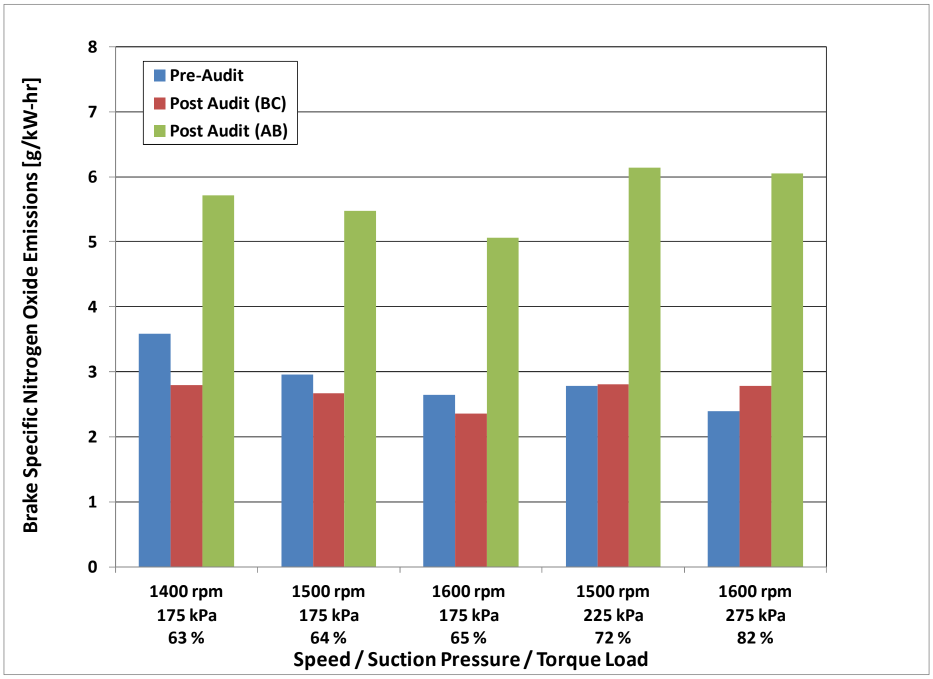

Figure 14: Brake Specific Nitrogen Oxide Emissions - Waukesha H24 GL

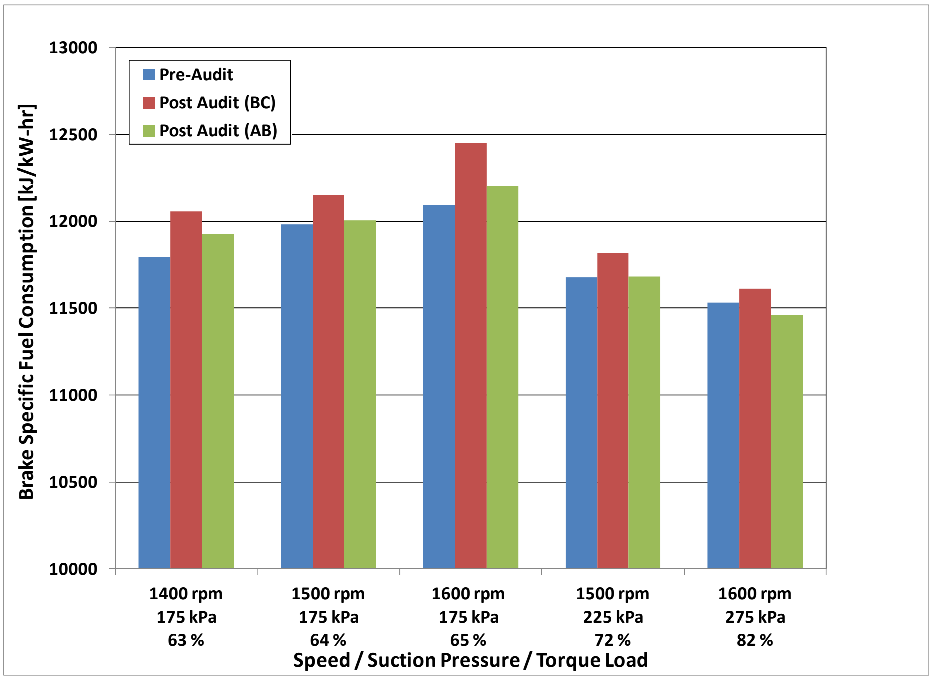

Figure 15: Brake Specific Fuel Consumption - Waukesha H24 GL

Long Term Evaluation

The Waukesha H24 GL engine was operated for a total of 12790 hours over the duration of the study, 11700 of which the LHP system was in control. During most of this period the engine was setup to run at Alberta emissions levels. Although there were signs of ash buildup in the cylinders, the post-audit inspection of the engine revealed no clear differences in engine deposits or wear as compared to the pre-audit inspection prior to the engine overall at 14200 hours. No oil sample data was provided for analysis.

The waste-gate control hardware including the pneumatic relay, throttle position sensor, and throttle position sensor linkage were all in good shape. The O_2 sensor was replaced after the post-audit having been in service for nearly 13000 hours.

Conclusion / Discussion

The forthcoming national engine emissions regulations (NO_x and CO) for natural gas engines with outputs less than 600 kW (800 HP) means that most of these engines in service in Alberta, most of these engines in service in Saskatchewan, and many of these engines in service in British Columbia need some technology for emissions control. The alternatives are stoichiometric control with a three-way catalyst (NSCR) or lean operation with no catalyst.

Stoichiometric control with a catalyst usually requires increased costs and maintenance. In contrast, lean operation without a catalyst requires reduced maintenance.

This study covered the application of the REMVue® LHP system, a relatively new technology, to the most common engine make-models with outputs less than 600 kW in current use in Western Canada.

As expected with a new technology, real-life field operation showed the strengths and weaknesses for each engine make-model. Changes were made to deal with specific weaknesses revealed by the testing.

As expected, the results show significant reductions in engine emissions are possible while maintaining or improving fuel efficiency with lean operation with the LHP technology. The amount of NO_x reduction achieved was dependent on the availability of excess air with the existing turbocharger and cooler. While many engines have sufficient air to achieve expected NO_x emissions limits, many need a turbocharger upgrade.

In this study no turbocharger upgrades were performed.

The results are shown below for each engine in the study.

- **Caterpillar G3408 TA:**

Table 7: Performance Summary - Caterpillar G3408 TA

Item	OEM Operation[9]	Lean Operation	Notes
Rated Power	298 kW	Unchanged	
Exhaust Gas Oxygen	1.8 – 2.0 %	7.1 – 7.2 %	
Nitrogen Oxide Emissions	35.2 – 38.7 g/kW-hr	10.2 – 10.9 g/kW-hr	Insufficient air to achieve ≤ 6 g/kW-hr
Carbon Monoxide Emissions	1.8 – 2.0 g/kW-hr	3.0 – 3.2 g/kW-hr	
Engine Fuel Efficiency		3 - 5 % improvement	
Exhaust Gas Temperature		55 °C reduction	May reduce maintenance needs

---

[9] OEM results generated using LHP closed loop air-fuel control

For reference, previous work on a Caterpillar 3306 TA with air-to-air inter-cooling showed that emissions levels of 6.0 g/kW-hr NO_x could be achieved with the OEM turbocharger and that that levels of 2.0 g/kW-hr NO_x could be achieved with minor upgrades to the existing turbocharger. Other tests on a Caterpillar 3406 TA genset with air-to-air inter-cooling showed that emissions levels of 2.0 g/kW-hr NO_x could be achieved with no modifications to the air system. In both cases a high energy ignition system was required to ignite the lean air-fuel mixtures.

As noted previously, the reduced NO_x associated with lean operation is coincident with a drop in oil viscosity due to reduced oil nitration.

- **Waukesha F11 GSI engine:**

Table 8: Performance Summary - Waukesha F11 GSI

Item	OEM Operation (Best Power / Economy[10])	Lean Operation	Notes
Rated Power	186 kW	Unchanged	
Exhaust Gas Oxygen	0.3 % / 1.2 %	7.0 – 7.2 %	
Nitrogen Oxide Emissions	10.3 – 11.5 g/kW-hr / 32 – 33.1 g/kW-hr	4.6 – 5.5 g/kW-hr	Insufficient air to achieve << 6 g/kW-hr
Carbon Monoxide Emissions	66 - 98 g/kW-hr / 0.6 – 0.7 g/kW-hr	1.5 – 1.7 g/kW-hr	
Engine Fuel Efficiency		6 – 15 % improvement vs. best power	
Exhaust Gas Temperature		70 °C reduction	May reduce maintenance needs

For the Waukesha F11 GSI application, small improvements in intake air cooling and a reduction in the air and exhaust system restrictions would ensure long term compliance to NO_x emissions levels of 6 g/kW-hr NO_x. For lower emissions targets a more complete upgrade to the air system would be required, for example, the addition of a second inter-cooler and the replacement of the existing turbocharger.

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[10] Best economy results generated using LHP closed loop air-fuel control

- **Waukesha H24 GL:**

Table 9: Performance Summary - Waukesha H24 GL

Item	OEM Operation	Lean Operation (2.7 g/kW-hr / 6.0 g/kW-hr)	Notes
Rated Power	388	Unchanged	
Exhaust Gas Oxygen	7.9 – 8.4 %	8.8 – 9.0 % / 8.2 – 8.3 %	Improved control
Nitrogen Oxide Emissions	2.4 – 3.6 g/kW-hr (Variability according to ambient)	2.4 – 2.8 g/kW-hr / 5.0 – 6.1 g/kW-hr	Can be tuned to specific NO_x emissions
Carbon Monoxide Emissions	2.8 – 3.1 g/kW-hr	3.5 – 3.7 g/kW-hr / 3.2 – 3.5 g/kW-hr	
Engine Fuel Efficiency		Minor change	
Exhaust Gas Temperature		Unchanged	

For the Waukesha H24 GL, the electronic control maintains tighter air-fuel control, thus providing more consistent NO_x emissions compliance over the range of engine speeds and loads.

For the Caterpillar 3408 TA and Waukesha F11 GSI a slight increase in CO emissions was observed with very lean operation. This increase in CO is likely due to the reduced combustion temperatures which lead to an increase in partially oxidized fuel hydrocarbons adjacent to cylinder walls and in crevice volumes. For the Caterpillar 3408 TA, the increase from 1.8 – 2.0 g/kW-hr to 3.0 – 3.2 g/kW-hr CO corresponds to a loss of 0.25 % of the total fuel energy delivered to the engine. This decrease in combustion efficiency is small relative to the total efficiency gain provided by lean combustion.

Based on the limited maintenance data available, no significant changes in engine maintenance were observed during the study for the three test engines. Due to the significant decrease in nitrogen oxide emissions and thus the potential for oil nitration, longer oil service life is expected with lean operation of OEM rich burn engines. Furthermore, the reductions in exhaust gas temperatures are expected to improve the service life of mechanical components relative to rich burn operation.

The performance of the wide band exhaust oxygen sensor was much better than expected with sensor life extending to a year or more. The strategy of default operation (operation without the oxygen sensor) has proven to be valuable.

The PTAC study provided an opportunity to closely evaluate the LHP control and hardware under a variety of field operating conditions. As expected with a new technology and the need for engine specific modifications, field problems were revealed. The resulting field corrections and product improvements were expected as a normal part of the new technology cycle. To date the software has been upgraded and installed to deal with temporary shortages of air and rapid changes in engine load resulting from field operations. In addition, small improvements to hardware are already showing benefits in improved reliability.

Certainly lean operation of these smaller engines provides benefits. To properly determine the application of the technology to specific engine models a life cycle costing will be needed.

Future Directions

This study has shown that lean operation using LHP technology is suitable for a subset of engines in the 100 to 600 kW (150 to 800 HP) range.

The LHP technology to reduce NO_x emissions was originally developed for the Caterpillar 3306 TA engine where it has worked well. The application to other engines in the 100 to 600 kW range, clearly depends on engine specific devices and design parameters such as the turbocharger, the air cooler and the compression ratio.

LHP technology is most difficult to apply to higher compression engines, which require leaner operation to achieve low NO_x targets, and engines with turbochargers that are relatively expensive to upgrade.

One promising direction is the application of LHP technology to lower compression engine models in the 100 to 600 kW range. Such engine models are the Stoichiometric Waukesha VGF GSI series engines (CR = 8.7 to 1) and the lower compression engines (CR = 8.5 to 1) in the Caterpillar 3400 series.

Favorable performance was demonstrated for three aspects of the LHP technology:

- The relatively long life of the wide-band oxygen sensors
- The elimination of manual wastegate adjustment for engines with large load variations
- The default strategy for continued operation with sensor failure

A second promising direction is the application of these technologies for Stoichiometric operation of engines with NSCR catalysts where lean conversion technology is not appropriate.

Continued monitoring of oil properties and the excess air-fuel ratio (lambda) will be useful in better defining the effect on engine oil viscosity of engine NO_x.

Some user's have indicated the value of BSFC vs. lambda and NO_x vs. lambda data for engines in the 100 to 600 kW range. Getting such data from engines currently equipped with the LHP technology would be relatively straight-forward, as the LHP technology allows the full range of air-fuel ratios from rich to the lean limit, subject to air availability, to be controlled and mapped.

Acknowledgements

REM Technology Inc. would like to extend its gratitude to the Petroleum Technology Alliance of Canada for supporting this study. Special thanks go out to the field operators, mechanics, and supervisors for their invaluable assistance, feedback and time.

We would also like to acknowledge the RTI and Spartan Controls teams for their efforts throughout the study, without their support, ideas, and persistence none of this would have been possible.

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Caterpillar Inc. *Application and Installation Guide - Gaseous Fuels.* LEBW4977-04. 2010.

Appendix A - General

Table A10: Engine Specifications

	Site			
	1	**2**	**3**	**4**
Manufacturer	Caterpillar	Waukesha	Caterpillar	Waukesha
Model	G3412 TA	H24 GL	G3408 TA	F11 GSI
Serial Number	7DB01002/3	C-61870/1	6NB02328	8703464
Specification	102-4404	NA	102-0398	C-14703
Displacement [L]	27.0	24.0	18.0	11.0
Compression Ratio	8.5:1	11.0:1	9.7:1	10.0:1
Rated Speed [rpm]	1800	1800	1800	1800
Rated Power [kW]	503	388	298	186
Combustion Type	Best economy (slightly lean)	Open Chamber Lean Burn	Best economy (slightly lean)	Best power
Aspiration	Turbocharged – After-cooled	Turbocharged – After-cooled	Turbocharged – After-cooled	Turbocharged – After-cooled

Table A11: Compressor Specifications

	Site			
	1	**2**	**3**	**4**
Manufacturer	Ariel	Ariel	Frick	Frick
Model	JGJ/2	JFJ/2	TDSH283S	TDSH233S
Serial Number	F-9902	F-15677	TDSH283S2166GZ	TDSH233S3049EZ
Throws / Stages	2/2	2 / 2	NA	NA
Volume Ratio	NA	NA	3.5	2.2[11]
Rated Speed [rpm]	1800	1800	3600	4500
Type	Reciprocating	Reciprocating	Rotary Screw	Rotary Screw

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[11] Value has not been confirmed.

Appendix B - Caterpillar G3408 TA

Table B12: Nominal Test Points - Caterpillar G3408 TA

Test Number	Speed [rpm]	Suction Pressure [kPa]	Bypass Valve [% Closed]	Slide Valve [% Closed]
1	1400	120	100	100
2	1600	120	100	100
3	1800	90	100	100
4	1800	120	100	100
5	1800	150	100	100

Table B13: Fuel Gas Properties - Caterpillar G3408 TA

Property	Pre-Audit	Post-Audit
Caterpillar Methane Number	74.2	66.7
Density @ 101.3 kPa, 15.6 °C [kg/m^3]	0.747	0.766
Lower Heating Value [MJ/kg]	48.57	48.68

Table B14: Condition Analysis Measurement Results - Caterpillar G3408 TA

Property	Pre-Audit	Post-Audit
Date [dd/mm/yyyy]	19/07/2010	7/11/2011
Panel Hours	NA	74418
Engine Run Hours – PTAC Study	NA	10753
Engine Run Hours – LHP Enabled	NA	8676
Cylinder 1 Compression [psig]	239	207
Cylinder 2 Compression [psig]	236.5	220
Cylinder 3 Compression [psig]	230.5	190
Cylinder 4 Compression [psig]	235	220
Cylinder 5 Compression [psig]	235.5	206
Cylinder 6 Compression [psig]	216	213
Cylinder 7 Compression [psig]	219	193
Cylinder 8 Compression [psig]	224	227
Crankcase Flow [cfm air]	3	2.2
Exhaust Back Pressure [“H_2O]	6	5
Air Intake Restriction [“H_2O]	1	1
Turbo Air Inlet / Outlet Temperature [°C]	22 / 67	18 / 62
Intercooler Air Outlet Temperature [°C]	53	43
Intercooler Water Inlet / Outlet Temperature [°C]	38 / 40.5	17 / 18
Auxiliary Cooler Inlet / Outlet Temperature [°C]	44 / 41.5	NA / NA
Jacket Water Cooler Inlet / Outlet Temperature [°C]	91.5 / 78.5	85.1 / 54.7
Accutek Coil Test	Pass	Pass[12]
Borescope	Completed	Completed

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[12] Cylinder number 1 coil could not be tested.

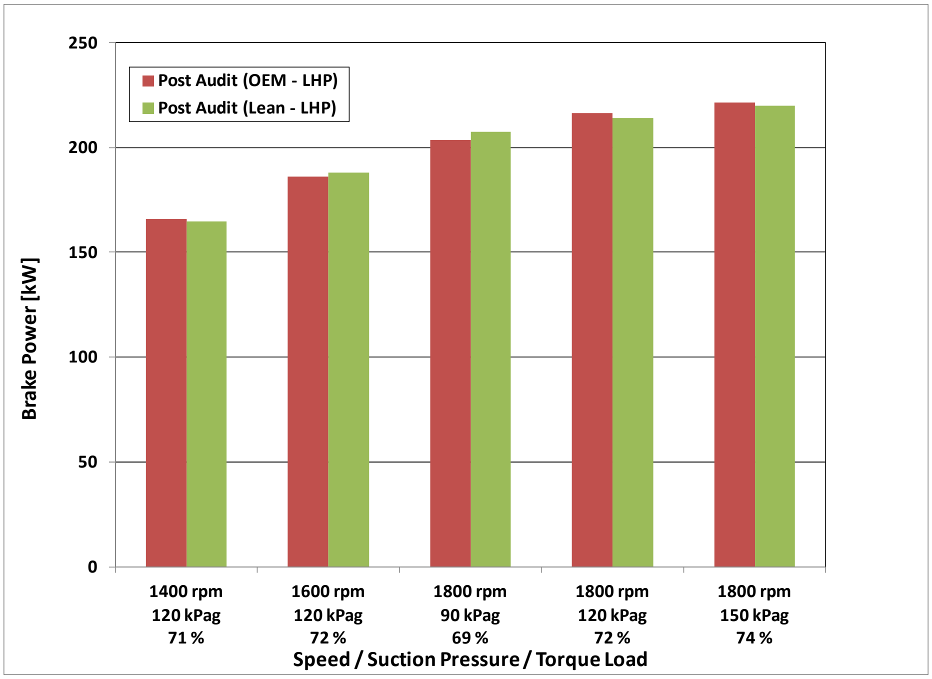

Figure B16: Brake Power - Caterpillar G3408 TA

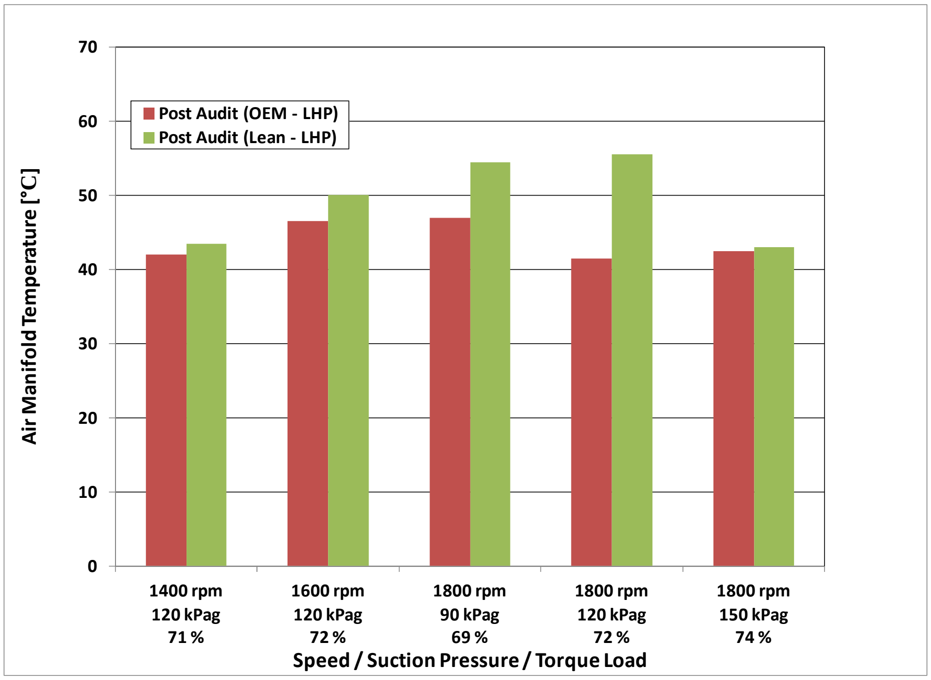

Figure B17: Air Manifold Temperature - Caterpillar G3408 TA

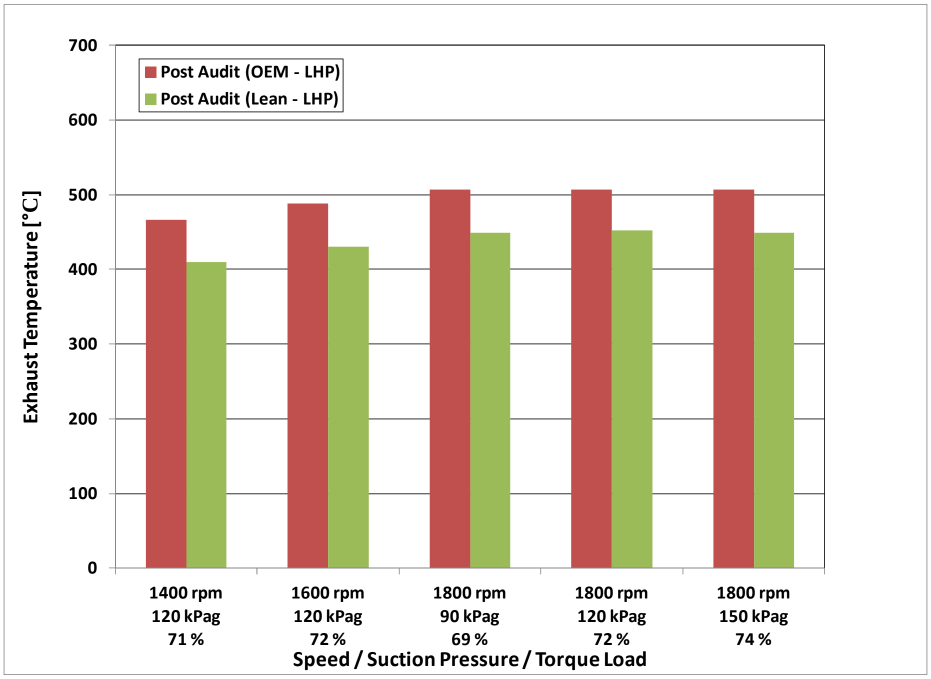

Figure B18: Exhaust Gas Temperature - Caterpillar G3408 TA

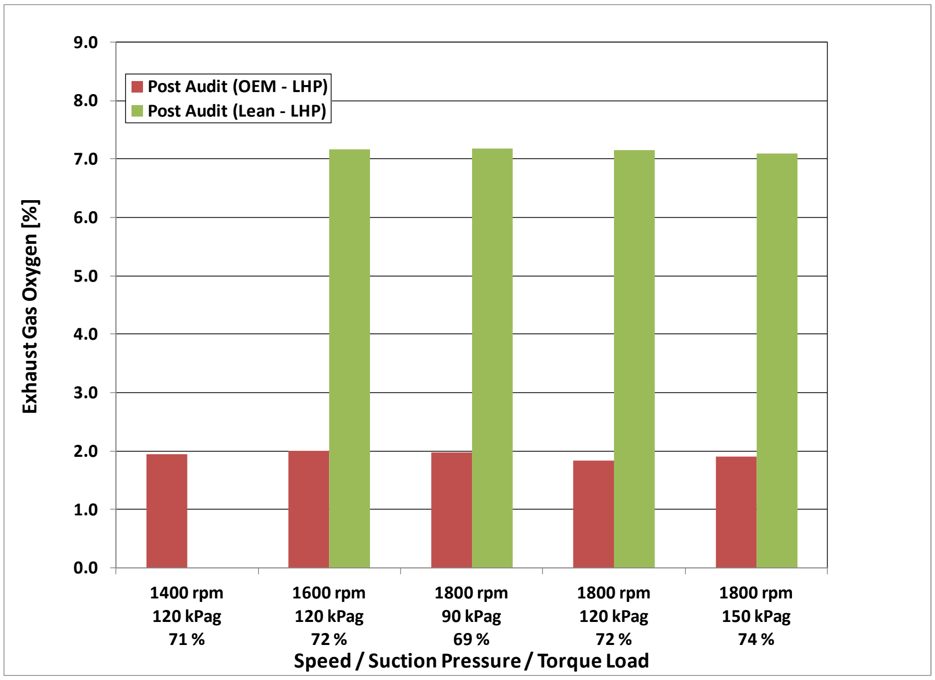

Figure B19: Exhaust Gas Oxygen - Caterpillar G3408 TA

Appendix C - Waukesha F11 GSI

Table C15: Nominal Test Points - Waukesha F11 GSI

Test Number	Speed [rpm]	Suction Pressure [kPa]	Bypass Valve [% Closed]	Slide Valve [% Closed]
1	1300	175	100	100
2	1450	175	100	100
3	1600	175	100	100
4	1450	200	100	100

Table C16: Fuel Gas Properties - Waukesha F11 GSI

Property	Pre-Audit	Post-Audit
Waukesha Knock Index	84.7	73.6
Density @ 101.3 kPa, 15.6 °C [kg/m^3]	0.747	0.794
Lower Heating Value [MJ/kg]	48.59	48.60

Table C17: Condition Analysis Measurement Results - Waukesha F11 GSI

Property	Pre-Audit	Post-Audit
Date [dd/mm/yyyy]	11/02/2010	27/10/2011
Panel Hours	NA	52901
Engine Run Hours – PTAC Study	NA	12198
Engine Run Hours – LHP Enabled	NA	4496
Cylinder 1 Compression [psig]	220	226
Cylinder 2 Compression [psig]	220	215.5
Cylinder 3 Compression [psig]	220	225
Cylinder 4 Compression [psig]	220	206
Cylinder 5 Compression [psig]	220	220
Cylinder 6 Compression [psig]	220	210
Crankcase Flow [cfm air]	0.8	1.2
Exhaust Back Pressure [“H_2O]	15	NA
Air Intake Restriction [“H_2O]	5	8
Turbo Air Inlet / Outlet Temperature [°C]	19 / 77	6 / 66
Intercooler Air Outlet Temperature [°C]	47	37
Intercooler Water Inlet / Outlet Temperature [°C]	24.6 / 27.2	25.2 / 29.7
Auxiliary Cooler Inlet / Outlet Temperature [°C]	28.4 / 24.0	NA / NA
Jacket Water Cooler Inlet / Outlet Temperature [°C]	80.5 / 42	66 / 45
Accutek Coil Test	Pass	Pass
Borescope	Completed	Completed

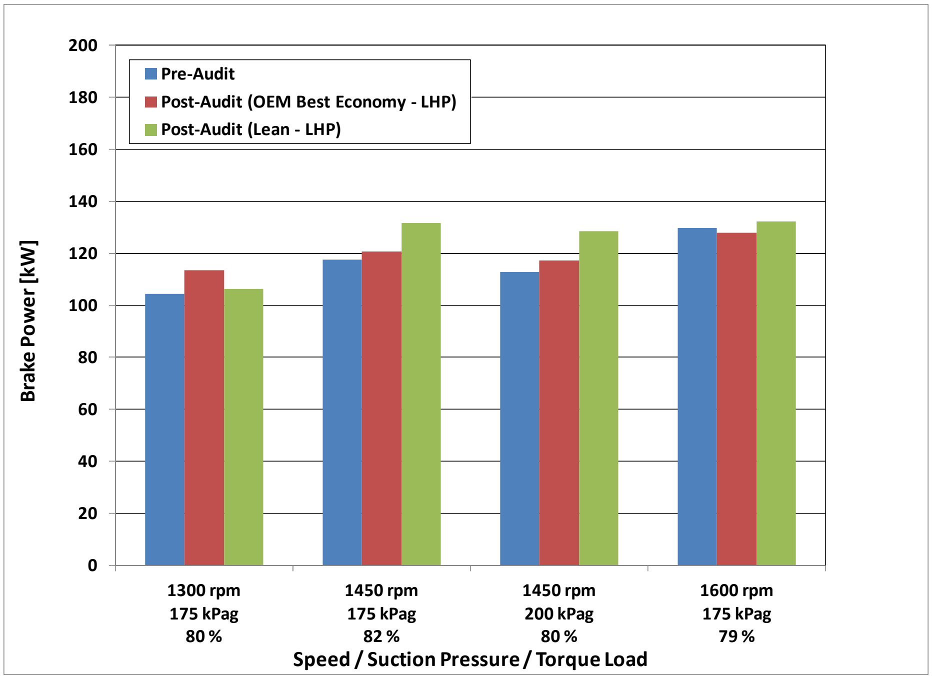

Figure C20: Brake Power - Waukesha F11 GSI

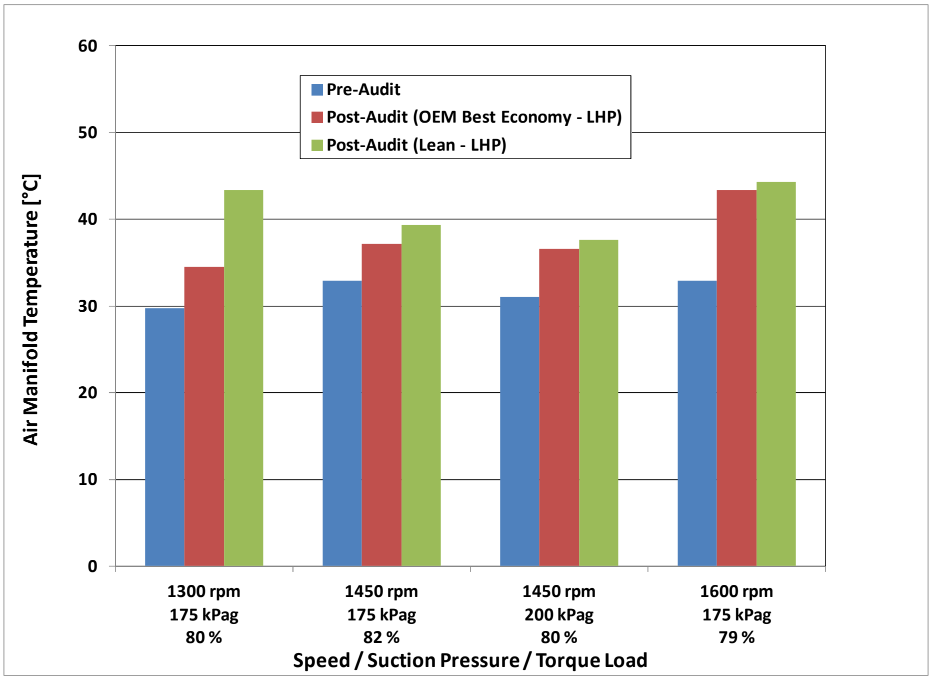

Figure C21: Air Manifold Temperature - Waukesha F11 GSI

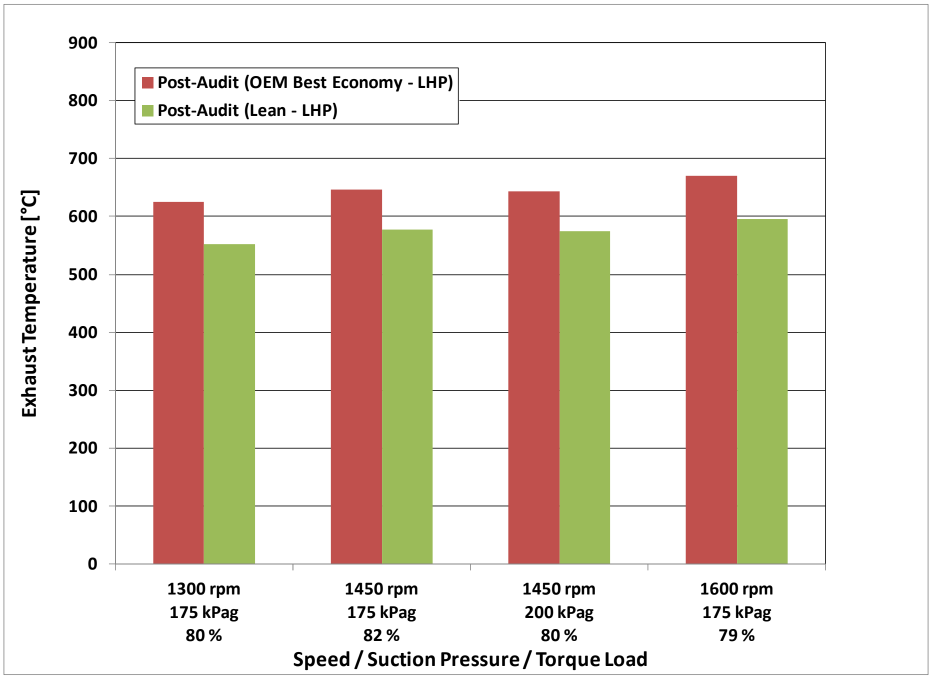

Figure C22: Exhaust Gas Temperature - Waukesha F11 GSI

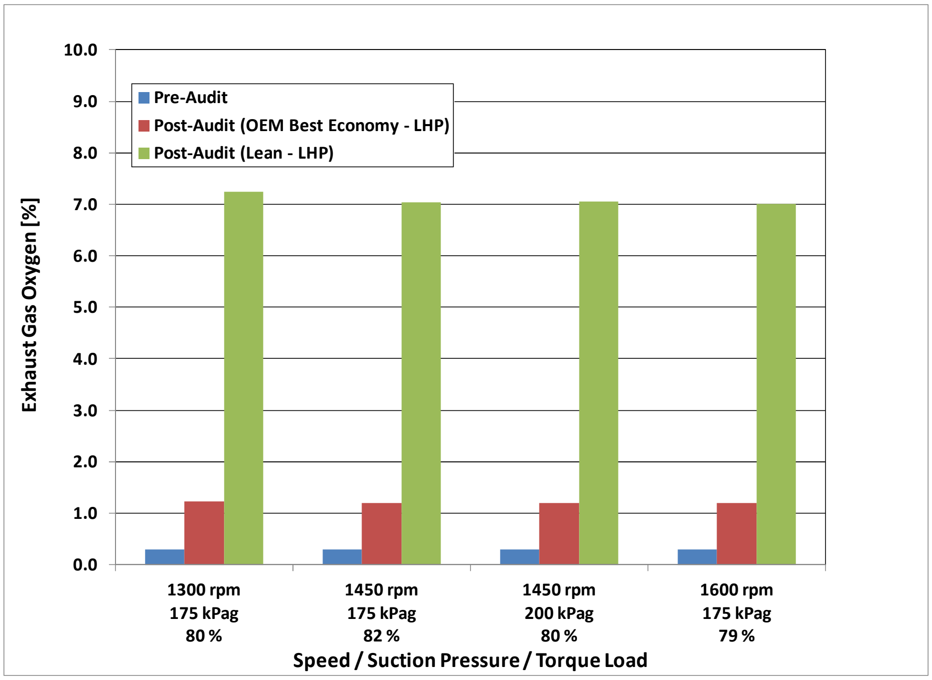

Figure C23: Exhaust Gas Oxygen - Waukesha F11 GSI

Appendix D - Waukesha H24 GL

Table D18: Nominal Test Points - Waukesha H24 GL

Test Number	Speed [rpm]	Suction Pressure [kPa]	Bypass Valve [% Closed]	Torque Load [%]
1	1400	175	100	63
2	1500	175	100	64
3	1600	175	100	65
4	1500	225	100	72
5	1600	275	100	82

Table D19: Fuel Gas Properties - Waukesha H24 GL

Property	Pre-Audit	Post-Audit
Waukesha Knock Index	76.4	76.1
Density @ 101.3 kPa, 15.6 °C [kg/m^3]	0.811	0.793
Lower Heating Value [MJ/kg]	46.81	47.70

Table D20: Condition Analysis Measurement Results - Waukesha H24 GL

Property	Pre-Audit	Post-Audit
Date [dd/mm/yyyy]	10/02/2010	23/10/2011
Unit Hours	19903	34076
Engine Run Hours – PTAC Study	NA	12770
Engine Run Hours – LHP Enabled	NA	11681
Cylinder 1 Compression [psig]	230	170
Cylinder 2 Compression [psig]	240	221
Cylinder 3 Compression [psig]	230	210
Cylinder 4 Compression [psig]	240	198
Cylinder 5 Compression [psig]	250	207
Cylinder 6 Compression [psig]	240	229.5
Cylinder 7 Compression [psig]	240	215
Cylinder 8 Compression [psig]	250	203
Crankcase Flow [cfm air]	2.0	1.8
Exhaust Back Pressure [“H_2O]	3	3
Air Intake Restriction [“H_2O]	2	4
Turbo Air Inlet / Outlet Temperature [°C]	25 / 100	12 / 83
Intercooler Air Outlet Temperature [°C]	45	47
Intercooler Water Inlet / Outlet Temperature [°C]	45 / 49.2	47.7 / 49.2
Auxiliary Cooler Inlet / Outlet Temperature [°C]	51.5 / 28.1	NA / NA
Jacket Water Cooler Inlet / Outlet Temperature [°C]	77.8 / 45.4	78.5/ 55.2
Accutek Coil Test	Pass	Pass
Borescope	Completed	Completed

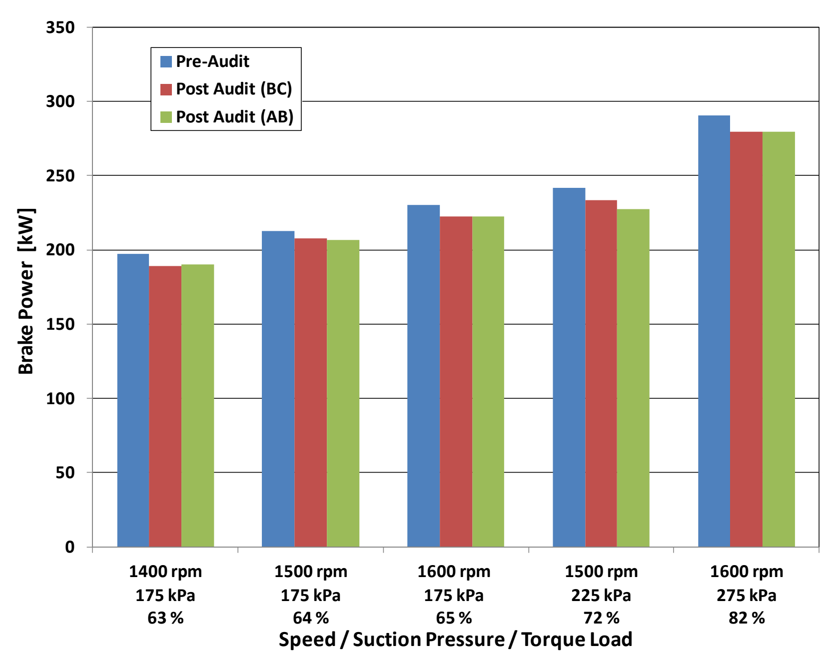

Figure D24: Brake Power - Waukesha H24 GL

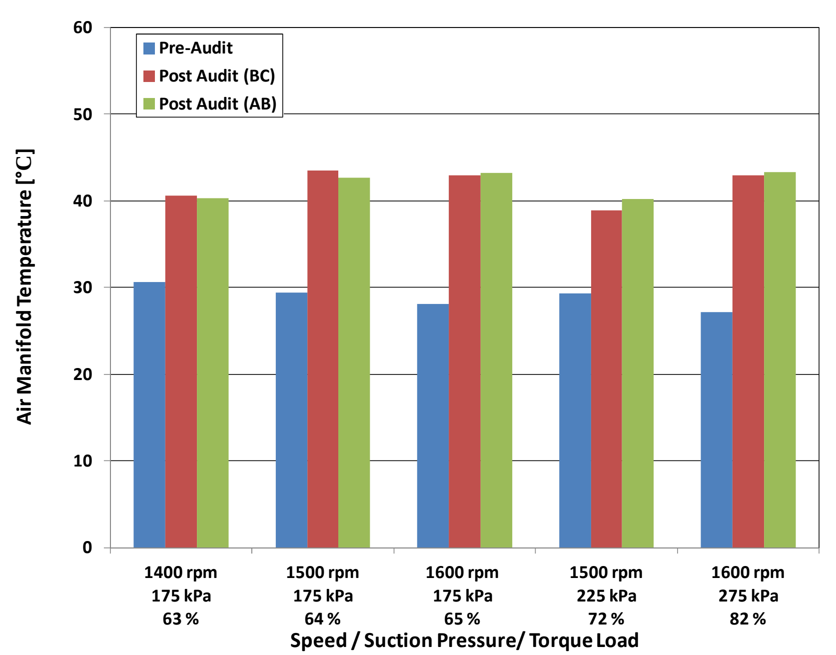

Figure D25: Air Manifold Temperature - Waukesha H24 GL

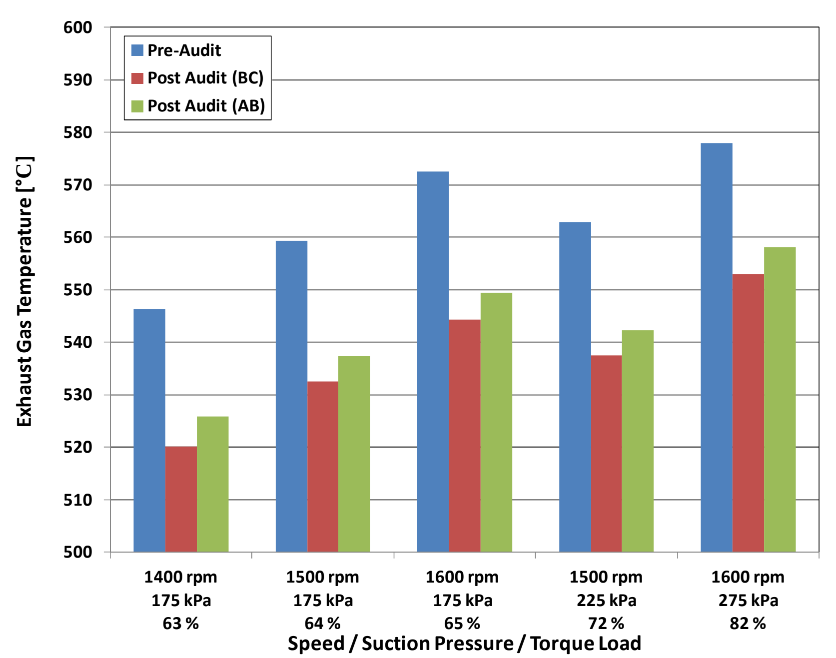

Figure D26: Exhaust Gas Temperature - Waukesha H24 GL

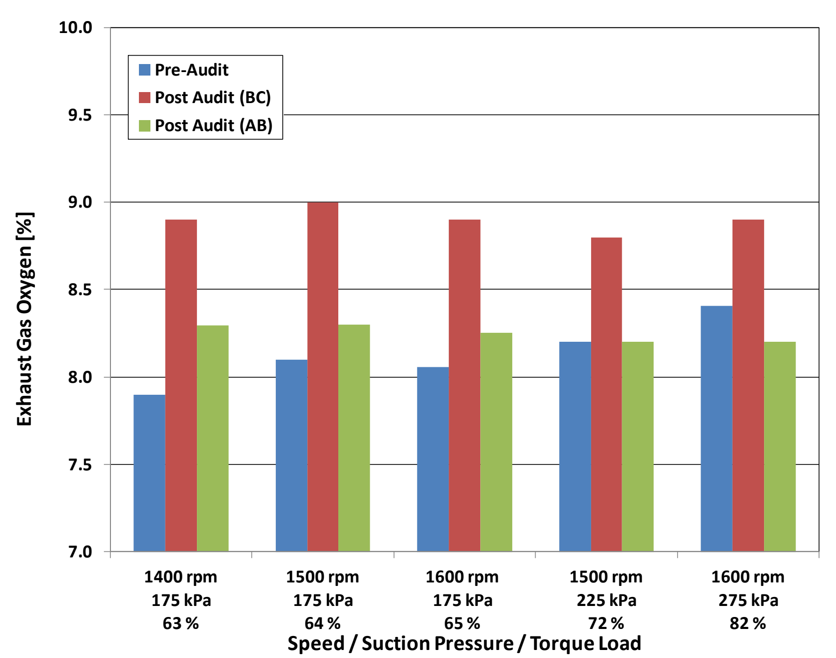

Figure D27: Exhaust Gas Oxygen - Waukesha H24 GL