TECHNICAL REPORT

STATIONARY ENGINES AIR EMISSIONS RESEARCH FINAL REPORT

PREPARED FOR

PTAC (Petroleum Technology Alliance Canada)
Suite 400, 500-5th Avenue S.W.
Calgary, Alberta T2P 3L5
Canada

Contact: Susie Shymko
Innovation and Technology Development Coordinator
Telephone: (403) 218-7708
E-mail: sshymco@ptac.org

PREPARED BY

Clearstone Engineering Ltd.
700, 900-6 Avenue S.W.
Calgary, Alberta, T2P 3K2
Canada

Contact: Don Colley, P.Eng
Telephone: 403 215 2647
Facsimile: 403 266 8871
E-mail: don.colley@clearstone.ca
Website: www.clearstone.ca

(Final)

April 19, 2012

DISCLAIMER

EXECUTIVE SUMMARY

Under contract to the Petroleum Technology Alliance of Canada (PTAC), Clearstone Engineering Ltd. conducted a study of natural gas fuelled internal combustion engines to better understand the relationship between NO_x and GHG emissions and fuel consumption. The study included a literature review and field studies of Waukesha VHP GSI engines operating in the upstream oil and gas industry.

Five Waukesha L7042GSI engines modified with the installation of REMVue air to fuel ratio control systems were tested to characterize fuel consumption and emissions during a series of tests at different Lambda values. Overall load values tested ranged from 750 bhp to 1366 bhp. The nominal rated power output of current L7042GSI engines is 1480 bhp at 1200 rpm. However, previous versions were rated at levels of 1100 bhp at 1000 rpm. The engines tested included those rated at both 1100 and 1400 bhp.

All engines were tested at condition that attempted to achieve NO_x emission levels of 2.0 g/bhp-h (2.7 g/kWh) and all were tested in the lean burn region of operation compatible with the application of REMVue AFR control technology. Lambda values were in the range of 1.22 to 1.59. One engine appeared to be turbo limited and could not achieve NO_x levels lower than about 4.0 g/bhp-h (5.4 g/kWh).

Based on the tests completed the following general conclusions are made:

- Engine operation over the Lambda ranges tested resulted in no shut downs for the reported test conditions. However, most test conditions were maintained for a few minutes and no conclusions should be drawn with respect to long term operation at any condition.
- Engine emission performance, and specifically the relationship between NO_x and CO_2e, has been demonstrated and, in general, AFR control technology in the lean burn region has the potential to reduce NO_x emissions to levels at or below 2 g/bhp-h (2.7 g/kWh). However, application of this technology does not guarantee that a specific engine can achieve such a criterion.
- Performance of any engine is engine specific based on physical setup, maintenance and other site specific conditions not studied and exact performance levels cannot be determined a priori.
- In general, all engines performed better than the average Industry Post-REMVue reference point and both above and below the OEM (Standard Economy) Waukesha BSFC reference point. These reference points are defined in Section 3.1 where it is noted that the Post-REMVue point is based on data contained in the Literature Review and the Waukesha points are from published company data sheets.
- All NO_x levels achieved were less than the OEM (Standard Economy) and OEM (3-Way Catalytic Converter) reference points.

Additional conclusions based on the five engines tested are:

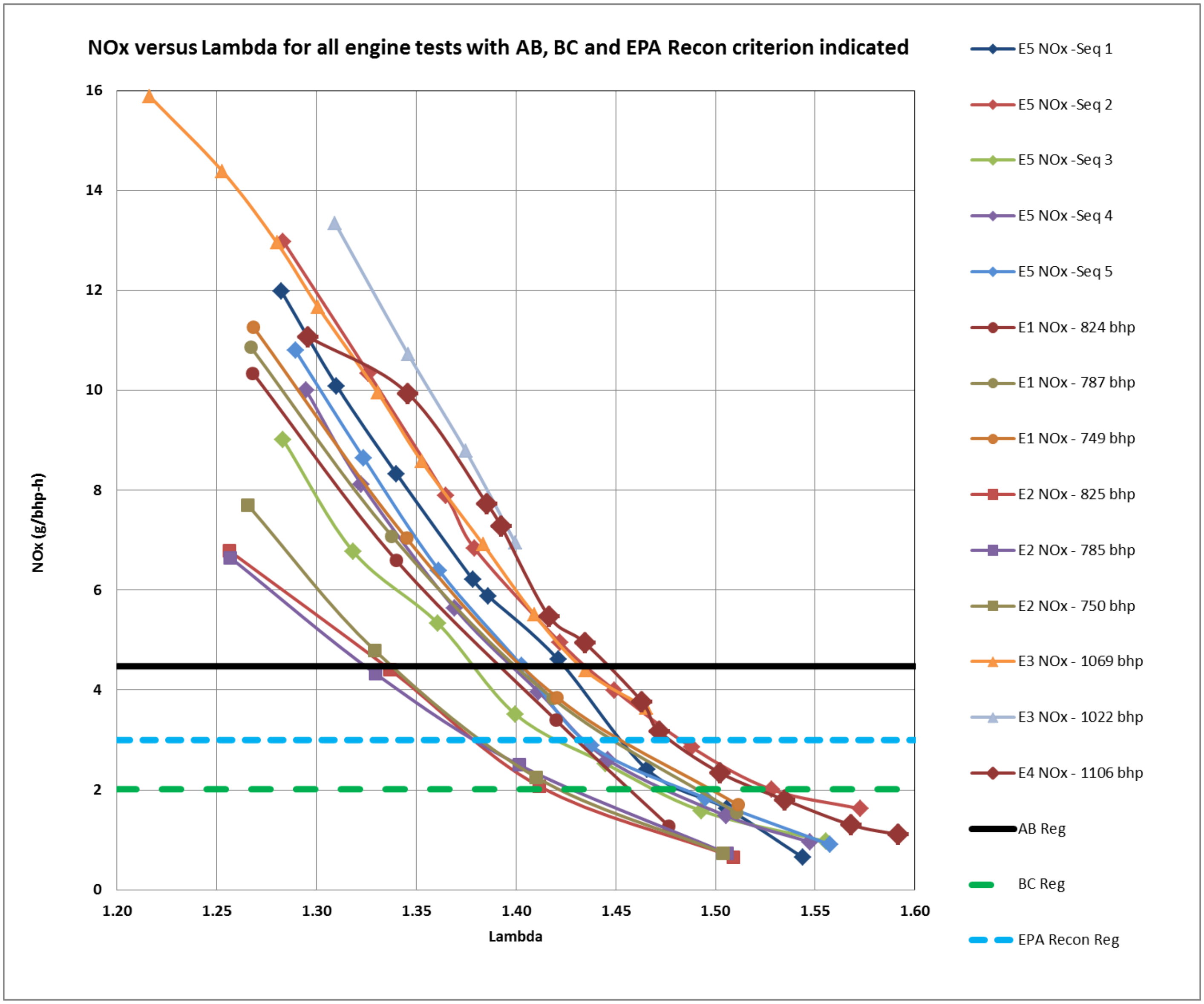
- Except for Engine 3, all engines were able to achieve NO_x emission levels of 2.0 g/bhp-h (2.7 g/kWh) or less. Maximum NO_x reductions from a baseline condition defined as the lowest Lambda tested were up to 90^+%. One test sequence on one engine achieved only 70^+%.

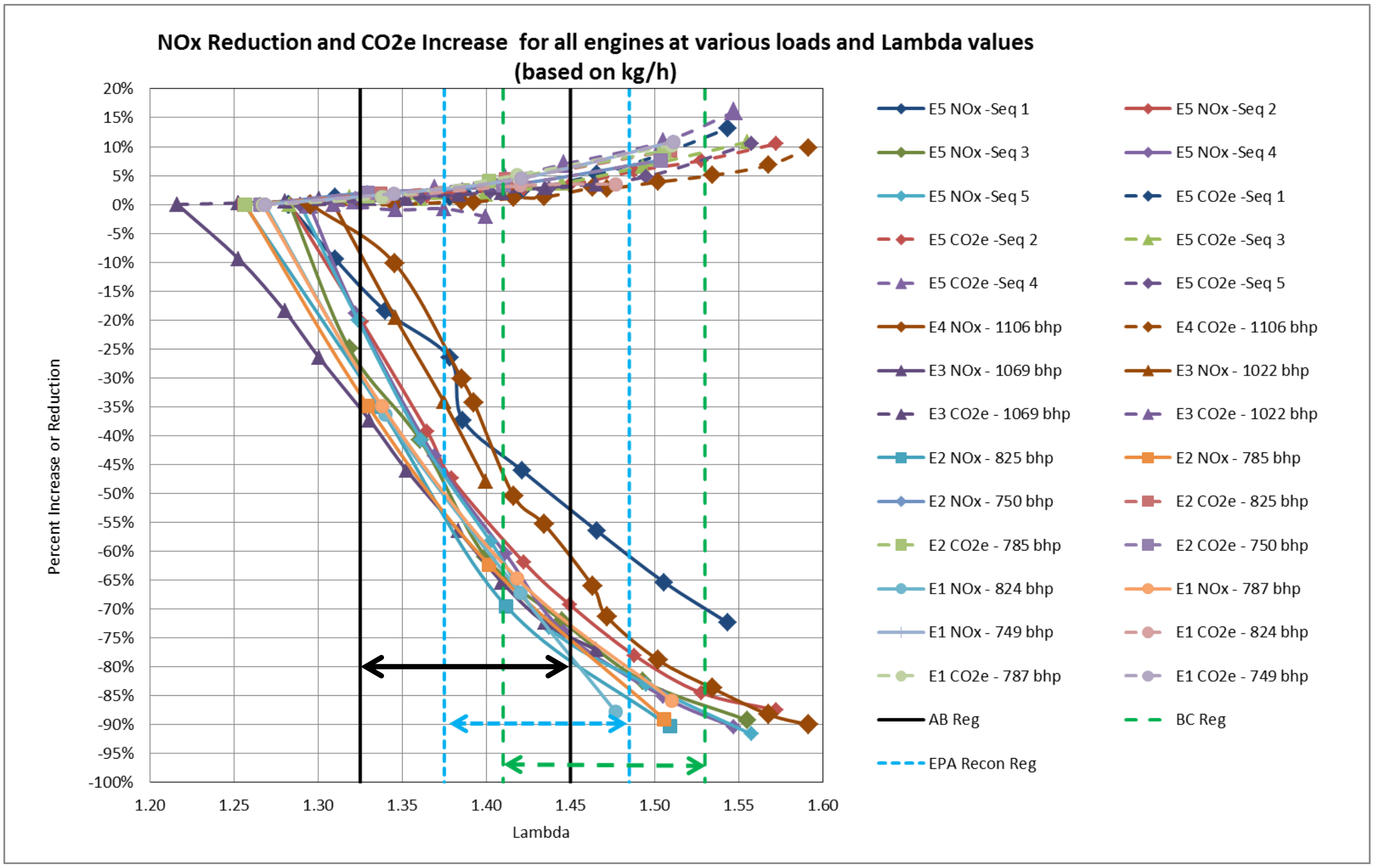
- CO_2e increased as NO_x emissions decreased. For the most part, this was due to an increase in fuel consumption required to heat additional combustion air. Maximum CO_2e increases, corresponding to the 90^+% NO_x reduction from the defined baseline were up to about 15^+%. For some engines, NO_x emission levels of less than 1.0 g/bhp-h were achieved.
- THC emissions increase as Lambda increases resulting in a small additional CO_2e emissions burden. Average increases in THC, as the engine moved from lowest to highest Lambda, were about 50%. THC emissions for each engine were different and ranged from a low of 2% to a high as 15% of total CO_2e. The reason for low or high THC emissions was not investigated as it was outside the scope of the project.
- Based on a compilation of all test results, a NO_x emissions criterion of 4.48 g/bhp-h (6.0 g/kWh) was achieved by the tested engines at Lambda values between 1.32 and 1.44. The CO_2e increase or penalty ranged from 1 of 4%. The increased operating cost for fuel only would be somewhat less.
- Based on a compilation of all test results, a NO_x emissions criterion of 3.0 g/bhp-h (4.0 g/kWh) was achieved by the tested engines at Lambda value between 1.38 and 1.48. The CO_2e increase or penalty ranged from 2 of 7%. The increased operating cost for fuel only would be somewhat less.
- Based on a compilation of all test results, a NO_x emissions criterion of 2.0 g/bhp-h (2.7 g/kWh) was achieved by the tested engines at Lambda value between 1.41 and 1.53. The CO_2e increase or penalty ranged from 4 to 10%. The increased operating cost for fuel only would be somewhat less.
- For engines that exhibit THC emissions greater than about 1000 ppm, the data suggest that increasing Lambda to reduce NO_x may lead to additional CO_2e emissions of up to 2% above those associated with the increase in BSFC. The extra CO_2e is associated with incremental increases in residual THC and CH_4 in the flue gases.
- Analyser bias was examined for O_2, THC and NO_x and is expressed relative to the ECOM data. O_2 bias is quite small and not considered to be significant. Likewise, bias in THC suggests that CO_2e may be marginally understated by as much as 20 g/bhp-h. NO_x bias appears to be a percent of actual NO_x values and NO_x emissions may be overstated by 0.2 g/bhp-h at low emission values of 1.0-2.0 g/bhp-h and overstated by as much as 1.8 g/bhp-h at high emission levels of 12-14 g/bhp-h. The effect of potential analyser bias is modest and does not negate conclusions regarding engine performance.
- Estimated uncertainties for AFR_{STOIC} (7.1%), AFR (9.3%), Lambda (16.0%), BSFC (7.7%), NO_x (kg/h 11.8%, g/bhp-h 12.8% and ng/J 13.1%) and CO_2e (kg/h 7.4%, g/bhp-h 8.9% and ng/J 9.4%) should be taken into consideration when the results of this study are applied. Based on other studies these uncertainties may not be conservative.

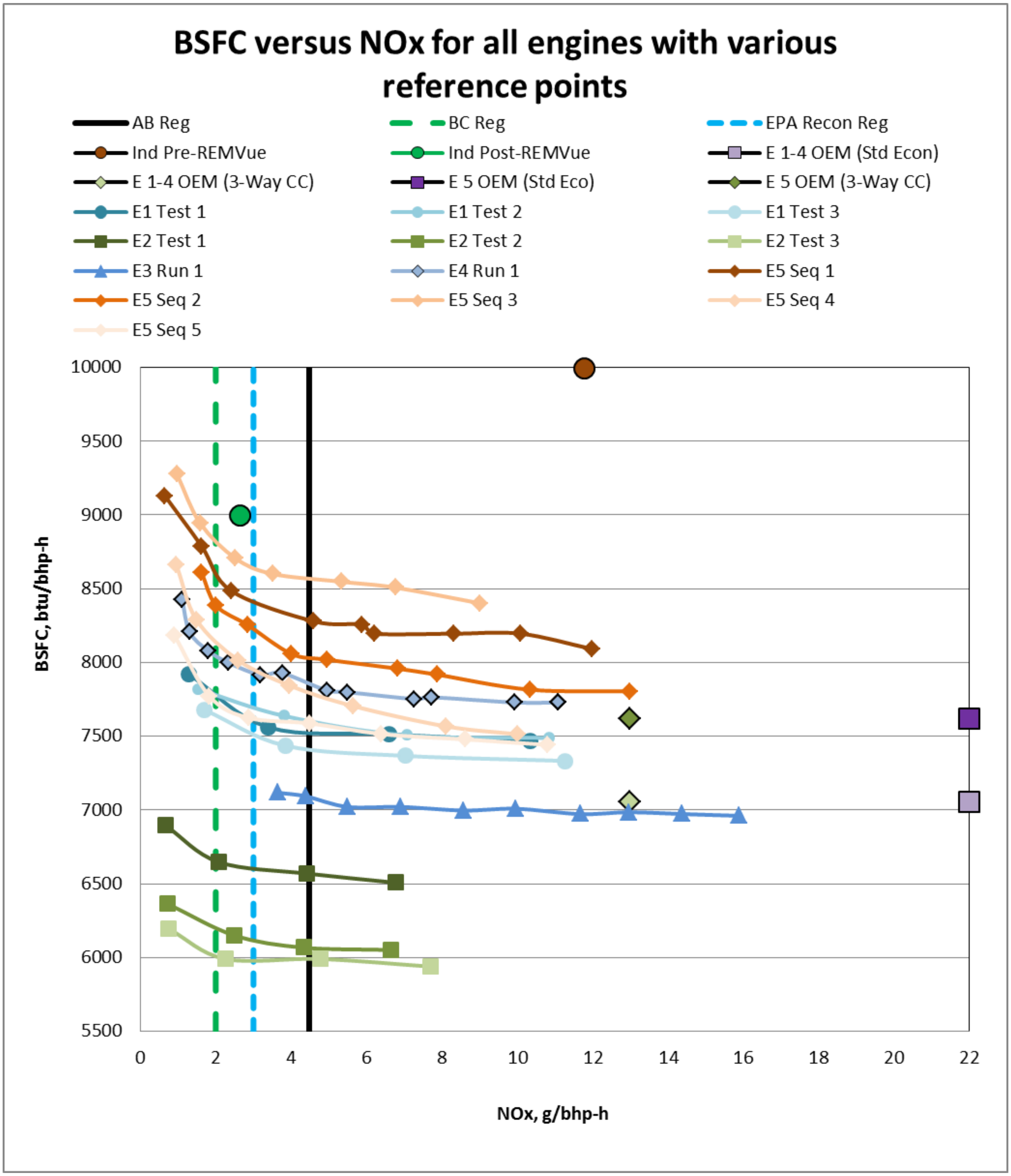
These key study conclusions are depicted in four graphs. The first shows NO_x emissions versus Lambda for all engine tests. The second shows NO_x emissions reductions from a baseline defined as the lowest Lambda and BSFC condition tested and the corresponding CO_2e emissions increase or penalty. The third shows the relationship between BSFC and NO_x emission levels and the fourth shows CO_2e emissions relative to CO_2e emissions at a NO_x emission rate of 8 g/bhp-h.

Engine performance is engine and load specific as indicated in the NO_x versus Lambda graph and the various criteria are achieved at different values of Lambda. Similarly, the CO_2e penalty is engine and load specific and on the graph depicting percent increase (CO_2e) or reduction

(NO_x) versus Lambda the general relationship is indicated. In general as indicated in the BSFC versus NO_x graph, BSFC increases marginally until NO_x emission levels of about 4 g/bhp-h are reached. Each engine exhibited a load specific profile with different inflection points. All, except engine 3, were able to achieve 2 g/bhp-h at which point BSFC increases became more pronounced. In the last graph, CO_2e emissions relative to the CO_2e emissions at a NO_x emission rate of 8 g/bhp-h (expressed in percent) increase more sharply as the NO_x emission rate decreases and approaches zero.




NOx Reduction and CO2e Increase for all engines at various loads and Lambda values
(based on kg/h)
Percent Increase or Reduction
20%
15%
10%
5%
0%
-5%
-10%
-15%
-20%
-25%
-30%
-35%
-40%
-45%
-50%
-55%
-60%
-65%
-70%
-75%
-80%
-85%
-90%
-95%
-100%
1.20
1.25
1.30
1.35
1.40
1.45
1.50
1.55
1.60
Lambda
E5 NOx -Seq 1
E5 NOx -Seq 2
E5 NOx -Seq 3
E5 NOx -Seq 4
E5 NOx -Seq 5
E5 CO2e -Seq 1
E5 CO2e -Seq 2
E5 CO2e -Seq 3
E5 CO2e -Seq 4
E5 CO2e -Seq 5
E4 NOx - 1106 bhp
E4 CO2e - 1106 bhp
E3 NOx - 1069 bhp
E3 NOx - 1022 bhp
E3 CO2e - 1069 bhp
E3 CO2e - 1022 bhp
E2 NOx - 825 bhp
E2 NOx - 785 bhp
E2 NOx - 750 bhp
E2 CO2e - 825 bhp
E2 CO2e - 785 bhp
E2 CO2e - 750 bhp
E1 NOx - 824 bhp
E1 NOx - 787 bhp
E1 NOx - 749 bhp
E1 CO2e - 824 bhp
E1 CO2e - 787 bhp
E1 CO2e - 749 bhp
AB Reg
BC Reg
EPA Recon Reg


BSFC versus NOx for all engines with various reference points
AB Reg
BC Reg
EPA Recon Reg
Ind Pre-REMVue
Ind Post-REMVue
E 1-4 OEM (Std Econ)
E 1-4 OEM (3-Way CC)
E 5 OEM (Std Eco)
E 5 OEM (3-Way CC)
E1 Test 1
E1 Test 2
E1 Test 3
E2 Test 1
E2 Test 2
E2 Test 3
E3 Run 1
E4 Run 1
E5 Seq 1
E5 Seq 2
E5 Seq 3
E5 Seq 4
E5 Seq 5
BSFC, btu/bhp-h
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
0
2
4
6
8
10
12
14
16
18
20
22
NOx, g/bhp-h

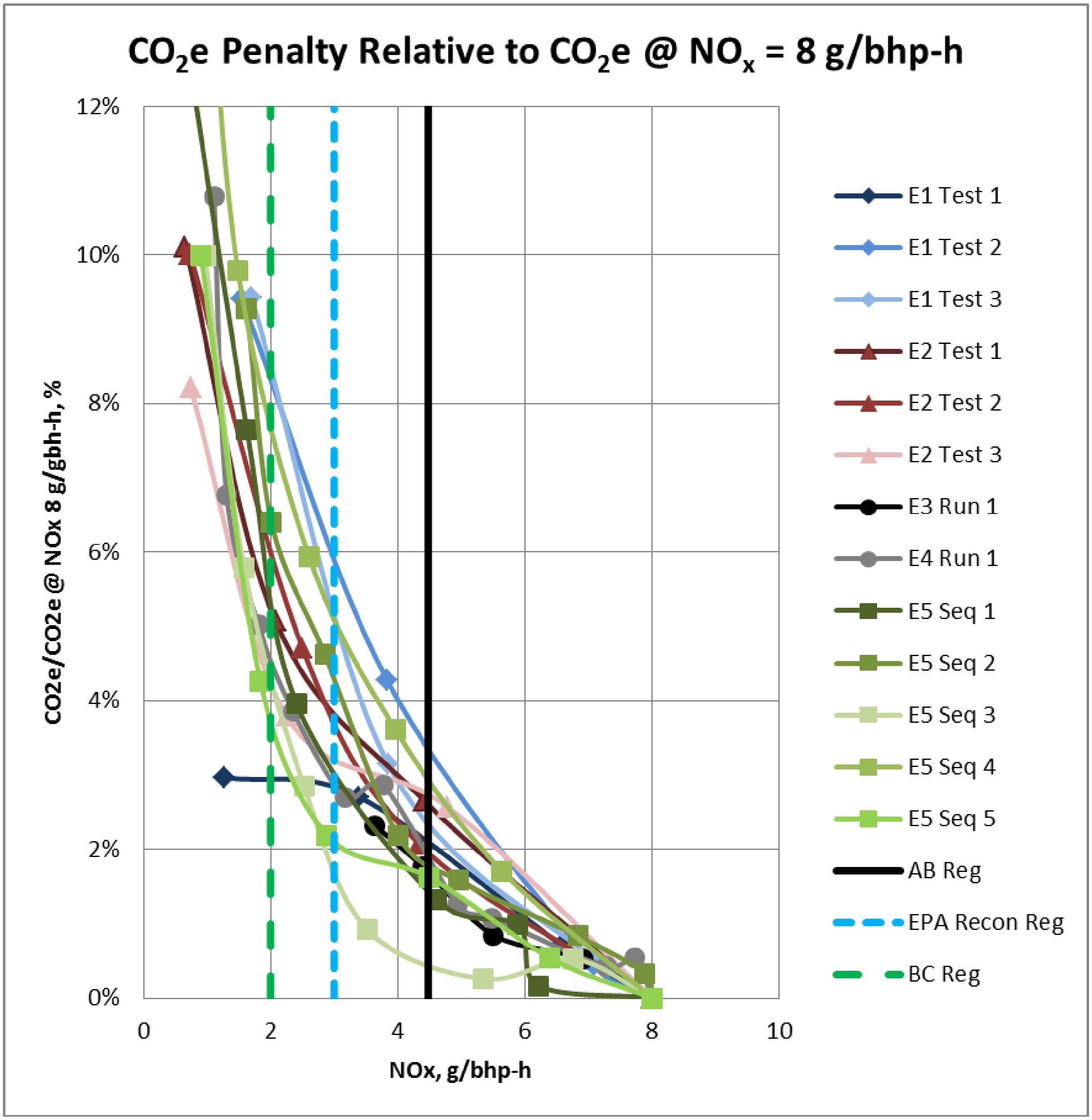
CO₂e Penalty Relative to CO₂e @ NOₓ = 8 g/bhp-h
CO2e/CO2e @ NOx 8 g/gbh-h, %
12%
10%
8%
6%
4%
2%
0%
0
2
4
6
8
10
NOx, g/bhp-h
E1 Test 1
E1 Test 2
E1 Test 3
E2 Test 1
E2 Test 2
E2 Test 3
E3 Run 1
E4 Run 1
E5 Seq 1
E5 Seq 2
E5 Seq 3
E5 Seq 4
E5 Seq 5
AB Reg
EPA Recon Reg
BC Reg

TABLE OF CONTENTS

DISCLAIMER .... **I**

EXECUTIVE SUMMARY .... **I**

TABLE OF CONTENTS .... **VII**

LIST OF TABLES .... **VIII**

LIST OF FIGURES .... **IX**

LIST OF ACRYNOMS .... **X**

ACKNOWLEDGEMENTS .... **XI**

1 INTRODUCTION **1**

2 METHODOLOGY **2**

- 2.1 TEST SUMMARIES 2
- 2.2 TEST MEASUREMENTS 4
  - *2.2.1 Brake Power Output 4*
  - *2.2.2 Engine Operation 4*
  - *2.2.3 Fuel Gas 4*
  - *2.2.4 Flue Gas Composition 5*
  - *2.2.5 Weather 6*
- 2.3 CALCULATION PROCEDURES 6
  - *2.3.1 Brake Power Output 6*
  - *2.3.2 Combustion Assessment 6*
- 2.4 UNCERTAINTY 7

3 RESULTS AND DISCUSSION **9**

- 3.1 REFERENCE POINTS 9
- 3.2 DATA CONSIDERATIONS 10
  - *3.2.1 Measurement Comparisons 10*
  - *3.2.2 CH_4 Component of THC 16*
- 3.3 INDIVIDUAL ENGINE RESULTS 16
  - *3.3.1 Test Engine 1 .... 16*
  - *3.3.2 Test Engine 2 .... 23*
  - *3.3.3 Test Engine 3 .... 29*
  - *3.3.4 Test Engine 4 .... 35*
  - *3.3.5 Test Engine 5 .... 41*
- 3.4 COMBINED TEST RESULTS 55
  - *3.4.1 Lambda Effect on THC, BSFC and CO_2e Emission Factor 55*
  - *3.4.2 NO_x and CO_2e Variations With Lambda 56*

4 CONCLUSIONS AND RECOMMENDATIONS **62**

5 REFERENCES CITED **64**

6 APPENDIX A - FIELD DATA **65**

- 6.1 COMBUSTION CALCULATION SOFTWARE 65
- 6.2 FUEL GAS ANALYSES 69
- 6.3 ENGINE SPECIFIC REMVUE INSTALLATION HISTORIES 70
- 6.4 ENGINE DATA 70

7 APPENDIX B - LITERATURE REVIEW **105**

LIST OF TABLES

Table 2-1: Testo 350 Combustible Gas Analyzer Specifications 5
Table 3-1: Pre and Post REMVue Lambda, NO_x and BSFC, and percent reduction in NO_x and BSFC. (From Table 3-2 of Literature Review excluding negative NO_x reduction data sets.) 9
Table 3-2: O_2 data analyses for Engine 5 test sequences 1 through 5[4] 11
Table 3-3: THC data analyses for Engine 5 test sequences 1 through 5[4] 13
Table 3-4: NO_X, NO, and NO_2 data analyses for Engine 5 sequences 1 through 5 14
Table 3-5: Summary of Test Engine 1 recorded operating data, measured operating and emission data and calculated results. 21
Table 3-6: Summary of Test Engine 2 recorded operating data, measured operating and emission data and calculated results. 27
Table 3-7: Summary of Test Engine 3 recorded operating data, measured operating and emission data and calculated results. 33
Table 3-8: Summary of Test Engine 4 recorded operating data, measured operating and emission data and calculated results. 39
Table 3-9: Summary of Test Engine 5 Sequence 1 recorded operating data, measured operating and emission data and calculated results. 46
Table 3-10: Summary of Test Engine 5 Sequence 2 recorded operating data, measured operating and emission data and calculated results. 47
Table 3-11: Summary of Test Engine 5 Sequence 3 recorded operating data, measured operating and emission data and calculated results. 49
Table 3-12: Summary of Test Engine 5 Sequence 4 recorded operating data, measured operating and emission data and calculated results. 51
Table 3-13: Summary of Test Engine 5 Sequence 5 recorded operating data, measured operating and emission data and calculated results. 53
Table 3-14: NO_x emission reduction and CO_2e penalty based on lowest lambda value tested for all engine tests achieving stated criteria. 57
Table 6-1: Summary of the applied fuel gas compositions for each engine studied. 69
Table 6-2: Engine 1 data collection sheet 70
Table 6-3: Engine 1 Test data at 985 RPM and 824 HP for various air-fuel ratios 72
Table 6-4: Engine 1 test data at 940 RPM and 787 HP for various air-fuel ratios 73
Table 6-5: Engine 1 test data at 900 RPM and 749 HP at various air-fuel ratio settings 74
Table 6-6: Engine 2 data collection sheet 77
Table 6-7: Engine 2 test data at 940 RPM and 824 HP at various air-fuel ratio settings 79
Table 6-8: Engine 2 test data at 860 RPM and 787 HP at various air-fuel ratio settings 80
Table 6-9: Engine 2 test data at 800 RPM and 749 HP at various air-fuel ratio settings 81
Table 6-10: Engine 3 data collection sheet 83
Table 6-11: Engine 3 test data at 900 RPM and 1069 HP at various air-fuel ratios – Set 1 85
Table 6-12: Engine 3 test data at 900 RPM and 1069 HP at various air-fuel ratios – Set 2 86
Table 6-13: Engine 3 test data at 900 RPM and 1069 HP at various air-fuel ratios – Set 3 87
Table 6-14: Engine 3 test data at 900 RPM and 1069 HP at various air-fuel ratios – Set 4 89
Table 6-15: Engine 3 test data at 850 RPM and 1022 HP at various air-fuel ratios - Set 1 90
Table 6-16: Engine 3 test data at 850 RPM and 1022 HP at various air-fuel ratio settings - Set 2 91
Table 6-17: Engine 4 data collection sheet 93
Table 6-18: Engine 4 test data at 1000 RPM and 1106 HP at various air-fuel ratio settings – Set 1 94
Table 6-19: Engine 4 test data at 1000 RPM an 1106 HP at various air-fuel ratio settings - Set 2 95
Table 6-20: Engine 5 data collection sheet 97
Table 6-21: Engine 5 test sequence 1 at 1200 RPM and 1340 HP 98
Table 6-22: Engine 5 test data sequence 2 at 1200 RPM and 1366 HP at various air-fuel ratios 99
Table 6-23: Engine 5 test data sequence 3 at 1200 RPM and 1049 HP at various air-fuel ratios 100
Table 6-24: Engine 5 test data sequence 4 at 1100 RPM and 1308 HP at various air-fuel ratios 101
Table 6-25: Engine 5 test data sequence 5 at 1000 RPM and 1145 HP at various air-fuel ratios 103

LIST OF FIGURES

Figure 3-1: Test Engine 1 NO_x and CO_2e emission in g/bhp-h at 749, 787 and 824 BHP vs. Lambda. 17
Figure 3-2: Test Engine 1 NO_x and CO_2e emissions in kg/h at 749, 787 and 824 BHP vs. Lambda. 18
Figure 3-3: Test Engine 1 NO_x and CO_2e emission factors in ng/J energy input at 749, 787 and 824 BHP vs. Lambda. 18
Figure 3-4: Test Engine 1 BSFC at 749, 787 and 824 BHP vs. Lambda. 19
Figure 3-5: Test Engine 1 NO_x reduction and CO_2e increase at 724, 787 and 824 BHP vs. Lambda. 19
Figure 3-6: Test Engine 1 BSFC versus NO_x at 724, 787 and 824 BHP for a range of Lambda. 20
Figure 3-7: Test Engine 2 NO_x and CO_2e emission in g/bhp-h at 750, 785 and 825 BHP vs. Lambda. 24
Figure 3-8: Test Engine 2 NO_x and CO_2e emissions in kg/h at 750, 785 and 825 BHP vs. Lambda. 24
Figure 3-9: Test Engine 2 NO_x and CO_2e emission factors in ng/J energy input at 750, 785 and 825 BHP vs. Lambda. 25
Figure 3-10: Test Engine 2 BSFC at 750, 785 and 825 BHP vs. Lambda. 25
Figure 3-11: Test Engine 2 NO_x reduction and CO_2e increase at 750, 785 and 825 BHP vs. Lambda. 26
Figure 3-12: Test Engine 2 BSFC versus NO_x for test run 1 to 3 at various values of Lambda. 26
Figure 3-13: Test Engine 3 NO_x and CO_2e emission in g/bhp-h at 1022 and 1069 BHP vs. Lambda. 30
Figure 3-14: Test Engine 3 NO_x and CO_2e emissions in kg/h at 1022 and 1069 BHP vs. Lambda. 30
Figure 3-15: Test Engine 3 NO_x and CO_2e emission factors in ng/J energy input at 1022 and 1069 BHP vs. Lambda. 31
Figure 3-16: Test Engine 3 BSFC at 1022 and 1069 BHP vs. Lambda. 31
Figure 3-17: Test Engine 3 NO_x reduction and CO_2e Increase at 1022 and 1069 BHP vs. Lambda. 32
Figure 3-18: Test Engine 3 BSFC versus NO_x for test 1 and 2 at various values of Lambda. 32
Figure 3-19: Test Engine 4 NO_x and CO_2e emission in g/bhp-h at 1106 BHP vs. Lambda. 35
Figure 3-20: Test Engine 4 NO_x and CO_2e emissions in kg/h at 1106 BHP vs. Lambda. 36
Figure 3-21: Test Engine 4 NO_x and CO_2e emission factors in ng/J energy input at 1106 BHP vs. Lambda. 36
Figure 3-22: Test Engine 4 BSFC at 1106 BHP vs. Lambda. 37
Figure 3-23: Test Engine 4 NO_x reduction and CO_2e Increase at 1106 BHP vs. Lambda 37
Figure 3-24: Test Engine 4 BSFC versus NO_x at various values of Lambda and noted reference points.38
Figure 3-25: Test Engine 5 NO_x and CO_2e emissions in g/bhp-h for Seq 1 (1340 bhp), Seq 2 (1366 bhp), Seq 3 (1049 bhp), Seg 4 (1308 bhp) and Seq 5 (1145 bhp) at various Lambda. 42
Figure 3-26: Test Engine 5 NO_x and CO_2e emissions in kg/h for Seq 1 (1340 bhp), Seq 2 (1366 bhp), Seq 3 (1049 bhp), Seg 4 (1308 bhp) and Seq 5 (1145 bhp) at various Lambda. 42
Figure 3-27: Test Engine 5 NO_x and CO_2e emission factors in ng/J energy input for Seq 1 (1340 bhp), Seq 2 (1366 bhp), Seq 3 (1049 bhp), Seg 4 (1308 bhp) and Seq 5 (1145 bhp) at various Lambda. 43
Figure 3-28: Test Engine 5 BSFC for Seq 1 (1340 bhp), Seq 2 (1366 bhp), Seq 3 (1049 bhp), Seg 4 (1308 bhp) and Seq 5 (1145 bhp) at various Lambda. 43
Figure 3-29: Test Engine 5 NO_x reduction and CO_2e Increase for Seq 1 (1340 bhp), Seq 2 (1366 bhp), Seq 3 (1049 bhp), Seg 4 (1308 bhp) and Seq 5 (1145 bhp) at various Lambda. 44
Figure 3-30: Test Engine 5 NO_x versus Inlet Manifold Air Temperature using Seq 1, 2 and 4 data with engine operating at 1200 RPM and for four values of Lambda. 44
Figure 3-31: Test Engine 5 BSFC versus NO_x for Sequences 1 to 5 at various values of Lambda. 45
Figure 3-32: NO_x and CO_2e emission factors based on ECOM and AI flue gas data for THC. 56
Figure 3-33: NO_x versus Lambda for all tests compared to NO_x emissions criteria of 2.0, 3.0 and 4.48 g/bhp-h and treating all engines tested as being a representative group of all existing Waukesha L7042GSI engines in upstream oil & gas industry service. 58
Figure 3-34: NO_x reduction versus CO_2e increase (penalty) versus Lambda for all tests and compared to NO_x emissions criteria of 2.0, 3.0 and 4.48 g/bhp-h and treating all engines tested as being a representative group of all existing Waukesha L7042GSI engines in upstream oil & gas industry service. 59
Figure 3-35: BSFC versus NO_x for all engine tests at various Lambda with reference points for emissions criteria of 2.0, 3.0 and 4.48 g/bhp-h, industry average and Waukesha OEM conditions included. 60
Figure 3-36: CO_2e penalty in percent based on CO_2e/CO_2e @ NO_x = 8 g/bhp-h versus NO_x for all engine tests at various Lambda with reference points for emissions criteria of 2.0, 3.0 and 4.48 g/bhp-h.61

LIST OF ACRYNOMS

AB	Alberta
AENV	Alberta Environment
AFR	Air to fuel ratio controller
AFR_{STOIC}	Stoichiometric AFR
AI	Alberta Innovates laboratory
BC	British Columbia
BLIERs	Base Level Industrial Emission Requirements
BSFC	Brake specific fuel consumption based on power output and LHV fuel input
CAMS	Comprehensive Air Management System
CH_4	methane with a GWP of 21
CxHy	Expression used for THC
CO	Carbon Monoxide and a product of incomplete combustion
CO_2	Carbon Dioxide with a GWP of 1
CO_2e	Carbon dioxide equivalent of all substances contributing to global warming
EF	Emission factor
GHG	Greenhouse Gas
GWP	Global warming potential of substances contribution to CO_2e
HAP	Hazardous Air Pollutant
HHV	Higher heating value of fuel
Lambda	Ratio of actual AFR/AFR_{stoic}
LHV	Lower heating value of fuel
NESHAP	National Emissions Standard for Hazardous Air Pollutants
NMHC	Non-Methane Hydrocarbons
N_2O	Nitrogen oxide with a GWP of 310
NO	Nitrous oxide a component of NO_x
NO_2	Nitrogen Dioxide a component of NO_x
NO_x	Oxides of Nitrogen
NSCR	Non-selective catalytic reduction
NSPS	New Source Performance Standards
O_2	Oxygen
PIC	Power Ignition and Controls Division of Spartan Controls
PTAC	Petroleum Technology Alliance Canada
SCR	Selective Catalytic Reduction
s m^3	standard cubic meters (15 deg C and 101.325 kPa)
SO_x	Sulphur Oxides
STDEV	Standard Deviation
THC	Total Hydrocarbons in flue gas resulting from incomplete combustion
RICE	Reciprocating Internal Combustion Engine
US EPA	Unites States Environmental Protection Agency
VOC	Volatile Organic Compound
2SLB	2-stroke lean-burn engine
4SLB	4-stroke lean-burn engine
4SRB	4-stroke rich-burn engine

ACKNOWLEDGEMENTS

Clearstone Engineering Ltd. gratefully acknowledges the financial funding provided by the project sponsors, the project coordination of PTAC staff, the participation and input of the PTAC project committee, the provision of engine test locations by PTAC member companies and the field assistance and data provided by Power Ignition and Controls staff.

1 INTRODUCTION

Under contract to the Petroleum Technology Alliance of Canada (PTAC), Clearstone Engineering Ltd. conducted a study of natural gas fuelled internal combustion engines to better understand the relationship between NO_x and GHG emissions and fuel consumption. The study included a literature review and field studies of working engines in the upstream oil and gas industry.

The literature review was previously reported and with updates based on client feedback is included as Appendix B (Section 7) in this report. The focus of the body of this report is the field test program, results, assessments, and conclusions.

The field test program examined and documented the performance of existing natural gas fuelled reciprocating internal combustion engines (RICE) with retrofit REMVue air fuel ratio (AFR) control technology. All candidate engines were initially rich burn and all were selected from potential sites offered by PTAC member and study participating companies. Overhaul, upgrade and REMVue installation details for the five engines are summarized in Section 6.2.

A total of five engines were included in the test program, and the field work was completed in the fall of 2011. All engines selected for testing were Waukesha L7042GSI with a nominal design rating of 1480 brake horsepower (bhp) @ 1200 rpm. It is noted that although Waukesha engines made up about 42% of the Alberta fleet in 2002, the fleet includes White Superior, Caterpillar, Cooper and others. In addition, rich burn engines represent only 76% of the total fleet. (AENV 2002)

The test program was designed to examine the relationship between NO_x and GHG emissions for engines with emission control technology over various operating conditions that were within a stable operating range. All tests were in the lean burn region with Lambda values ranging from about 1.22 to 1.59 and energy output ranged from about 750 to 1370 bhp. A few tests were used to examine the effect of inlet air temperature.

During the field tests, Clearstone staff worked with technicians from PIC Ignition and Controls division of Spartan Controls (REMVue technology providers) and with the facility site operators. PIC staff provided operating data compiled by each REMVue unit and the results of emission tests completed with ECOM flue gas analyzers. In addition, they provided RecipTrap (or alternate calculation method) power output data for each engine. Clearstone field staff completed flue gas analyses using a Testo 350 combustion analyzer and at one site collected flue gas samples for detailed laboratory analyses at Alberta Innovates. Fuel gas samples data was provided by the site operators.

The methodology section (Section 2) outlines the test program, test measurements, calculation procedures and uncertainty. The results and discussions section (Section 3) presents the individual and consolidated test results and the conclusion (Section 4) delineates the key results of the program and observations regarding engine test equipment.

2 METHODOLOGY

In general, all engines were tested following similar procedures. However, engine test were constrained by site specific conditions related to load, fuel gas composition, and engine settings and weather. Site operators and or PIC field technicians managed the engines throughout the test program. Clearstone staff collected relevant information, conducted flue gas analyses and where planned collected flue gas samples for subsequent analyses.

2.1 Test Summaries

For each of the five engines, several tests or series of tests were completed. Typically, these involved adjusting the AFR from very lean to a less lean condition. At each AFR, the engine was allowed time to equilibrate before measurements of exhaust gas composition, fuel consumption, or other engine operating parameters were made, and, if scheduled, flue gas samples were collected. In addition, appropriate operating data was manually recorded and is summarized in Appendix A (Section 6). Engine specific test summaries and input data collection histories are summarized below.

Engine 1 (October 18th)

- Three tests completed

Test Number	Load (HP)	Speed (rpm)	No. of AFR's
1	824	987	4
2	787	940	4
3	749	898	4

- Input Data
  - Weather data file
  - Fuel gas analysis
  - ECOM data (manually recorded)
  - Recip Trap data manually recorded at site

Engine 2 (October 19th)

- Three tests completed

Test Number	Load (HP)	Speed (rpm)	No. of AFR's
1	825	940	4
2	785	860	4
3	750	800	4

- Input Data
  - Weather data file
  - Fuel gas analysis
  - ECOM data (manually recorded)
  - REMVue data file
  - Engine horsepower calculated from compressor inlet/outlet pressures and temperatures which were provided by Spartan Controls.

Engine 3 (October 20th)

- Two tests completed

Test Number	Load(HP)	Speed (rpm)	No. of AFR’s
1	1069	897	10
2	1022	853	4

- Input Data
  - Weather data file
  - Fuel gas analysis
  - ECOM data (manually recorded)
  - REMVue data file
  - Recip Trap data file

Engine 4 (October 21tst)

- One test completed

Test Number	Load (HP)	Speed (rpm)	No. of AFR’s
1	1106	994	13

- Input Data
  - Weather data for October 20 and additional manually recorded data used.
  - Fuel gas analysis
  - ECOM data file
  - REMVue data file
  - Engine horsepower calculated from compressor inlet/outlet pressures and temperatures which were provided by Spartan Controls.

Engine 5 (November 2nd and 3rd)

- One test completed

Sequence Number	Load (HP)	Speed (rpm)	No. of AFR’s
1	1340	1205	9
2	1366	1208	9
3	1049	1208	7
4	1308	1105	7
5	1145	1005	7

- Input Data
  - Weather data file
  - Fuel gas analysis
  - ECOM data file
  - REMVue data file
  - Recip Trap data file

- Testo 350 data for tests 1 and 2.
- Flue gas laboratory analysis for Tests 1 and 2

2.2 Test Measurements

Test measurements, their uncertainty and their application are outlined.

2.2.1 Brake Power Output

Brake power output was determined following SGER 2009 Appendix C Section 4. Two determination procedures are allowed; Recip Trap and Compressor Calculation.

The Recip Trap method uses a Dynalco Controls Model RT9260 Recip Trap, or equivalent, and the uncertainty is noted to be 3%. The alternate compressor calculation procedure uses manufacturer's procedures and the uncertainty is noted to be 5%. Both procedures include auxiliary power associated with the driven device and determine the actual brake power output of the driver. For uncertainty estimates in Section 2.4, the maximum value of 5% was used.

A Dynalco Controls RT9260 was used for engines 1, 3 and 5, and the compressor calculation method was used for engines 2 and 4.

One power output determination was conducted per test sequence. Engine load was maintained constant for the entire sequence by controlling engine speed.

2.2.2 Engine Operation

The installed REMVue control device captures a multitude of engine operating parameters including fuel flow, speed, inlet manifold and exhaust temperatures, manifold pressures and other data not pertinent to these tests. The device records data sets at prescribed time intervals and these ranged from every second to every minute depending on location. Data was electronically downloaded and provided to Clearstone for extraction of appropriate data segments.

2.2.3 Fuel Gas

Fuel gas analyses were provided by plant site operators for each compressor location or the nearest representative location to the engine location and are summarized in Table 6-2 of Section 6. Fuel gas analyses were used in the combustion calculation to:

- Complete material balances
- Determine AFR_{STOIC}, AFR, Lambda and BSFC
- Allocate a portion of the THC as CH_4 based on fuel gas composition
- Determine emission factors for CO, CO_2, CH_4, C_2H_4, Total VOC, THC, NO, NO_2 and Total NO_x.

Fuel gas analyses are reported to have uncertainties of 5% for major constituents including CH_4 and C_2H_6 and C_3H_8. Uncertainty increases as concentration drops to zero. A fuel gas flow rate measurement uncertainty of 3% was used for all fuel flow rates reported by REMVue or the plant operator.

2.2.4 Flue Gas Composition

Hand held field analysers were used to measure flue or exhaust gas parameters. Depending on the analyser selected, measurements included some or all of Room Temperature (°F), Flue Gas Temperature (°F), O_2 (%), CO (ppm), NO (ppm), NO_2 (ppm), NO_x (ppm), C_xH_y (%), CO_2 (%), efficiency (%), Losses (%), Lambda and Sensor Temperature (°F).

Measurement uncertainties of the Testo 350 hand held field analyser are summarized in Table 2-1. The ECOM analyser has comparable specifications. The Testo and ECOM analysers were calibrated with zero and span gas in the office and the auto calibration feature was used in the field. The calibration procedure set up in the standard method ASTM D6522 was not followed and the calibration done in the field did not include zero and span gas checks before and after each test run. Based on the tests and calibrations completed it is not possible to evaluate the calibration drift and this adds uncertainty to the results.

Table 2-1: Testo 350 Combustible Gas Analyzer Specifications

Measurement Parameter	Measurement Range	Accuracy	Resolution	Response Time
O_2	0 - 25 vol%	+/- 0.2 vol. %	0.01 vol.%	< 20 sec
CO	0 - 10,000 ppm	+/- 10 ppm (0 -199 ppm) +/- 5 % of reading (200 – 2,000 ppm) +/- 10 % of reading (rest of range)	1 ppm	< 40 sec
CO_{low}	0 - 500 ppm	+/- 2 ppm (0 -40 ppm) +/- 5 % of reading (rest of range)	0.1 ppm	< 40 sec
NO	0 – 4,000 ppm	+/- 5 ppm (0 -99 ppm) +/- 5 % of reading (100 – 2,000 ppm) +/- 10 % of reading (rest of range)	1 ppm	< 30 sec
NO_{low}	0-300 ppm	+/- 2 ppm (0 - 40 ppm) +/- 5 % of reading (rest of range)	1 ppm	< 30 sec
NO_2	0 - 500 ppm	+/- 5 ppm (0 - 100 ppm) +/- 5 % of reading (rest of range)	0.1 ppm	< 40 sec
THC (Natural Gas)	100 – 40,000 ppm	+/- 400 ppm (100 - 4,000 ppm) +/- 10 % of reading (rest of range)	10 ppm	< 40 sec
Exhaust Temp.	-40 – 1,200 C	+/- 18.8 deg C (above 200 deg C)	18.8 deg C	-
Flow Velocity	0 – 131 ft/sec	0.17 ft/sec	-	-

Measurement uncertainties of the hand held field analysers are reported to be 5% for most concentration determinations.

Eighteen flue gas samples were collected during the testing of Engine 5. These samples were subsequently analysed for fixed gases (N_2, O_2, CO_2, CO) and hydrocarbons (C_1 to C_4), a total of about 19 compounds. Uncertainty is 5% for all compounds.

It is noted that during the setup of the engine for each test, the ECOM flue gas analyser (used by PIC) sampled the right manifold while the Testo (used by Clearstone) sampled the combined flue gases after the turbo. When flue gas samples were extracted for AI analyses they were withdrawn from the left manifold port. These differences in sampling points may contribute to variations in the data as even though efforts were made to balance the engine, the performance of the left and right sides were not identical.

2.2.5 Weather

Weather monitored included temperature TP (°C), relative humidity RH (%) and barometric pressure BP (in Hg). Barometric pressure was corrected to site conditions using NovaLynx 2008.

Uncertainty estimates for these parameters was not determined or included in the determination of result uncertainty.

2.3 Calculation Procedures

2.3.1 Brake Power Output

PIC provided calculated Brake Power Output results for each test condition to Clearstone. PIC used a Recip Trap on engines 1, 3 and 5 and calculated the power based on engine data for engines 2 and 4.

2.3.2 Combustion Assessment

Clearstone used its proprietary combustion assessment software, described in section 6.1, to analyse each test condition. This program uses fuel gas flow, fuel temperature, fuel pressure, fuel heating value and composition, flue gas O_2 and CO concentration, inlet temperature and pressure and ambient air temperature, pressure and relative humidity to complete a mass balance for the engine. The results are based on rigorous equations for all components in the fuel gas. Measured flue gas data for THC and fuel gas composition are used to estimate residual CH_4 emissions assuming that the mass ratio of CH_4 to total THC in the flue gas is the same as in the fuel gas.

The combustion assessment program determines:

- Stoichiometric air to fuel ratio (AFR_{STOIC})
- Actual air to fuel ratio (AFR)
- Total flue gas (wet basis)
- Total flue gas composition (mole fraction dry basis) (Hydrocarbons listed in the Stack Gas (calculated on a dry basis) rows in tables 3-4 to 3-9 are based on compounds reported in fuel gas analysis and vary from site to site.), and

- Emission factors based on energy input (ng/J).

The key measurement data for these calculations is the O_2 concentration in the flue gas. Up to three values were available based on the use of three measurement devices: ECOM, Testo 350 and Laboratory Analysis. During preliminary assessment all of the data were used. However, the ECOM data provided by PIC was consistently available for all tests, thus in the final analyses the ECOM O_2 data was used for all combustion assessments. Variability in measurement results is discussed in Section 3.2

2.4 Uncertainty

Uncertainty is associated with each Lambda, BSFC, NO_x, and CO_2e determination. Uncertainty is related to measurement uncertainty; and consequently the uncertainty of each variable is related to the number of measurements required, and the way in which they are combined, to determine the numerical result of a parameter. The general method used for determining uncertainty is taken from CCEMC 2011 which references IPCC Good Practice Guidance on Uncertainty Management. The method has been adapted by CCEMC for projects instead of national GHG inventories. For this study the general principles have been applied but not detailed uncertainty calculations.

For sums and differences:

$$\delta q \leq ((\delta x)^2 + \cdots + (\delta z)^2)^{0.5}$$

For products and quotients:

$$\delta q \leq (\delta x/|x| + \cdots + \delta z/|z|)\ |q|$$

Where:

q	is the final calculated quantity
$x, \cdots, z$	are the various quantities used to calculate the final quantity
$\delta q, \cdots, \delta z$	are the uncertainties associated with the various quantities

In addition to the use of the above equations, uncertainty of determined results was assessed based on a parametric analysis. The parametric analysis was completed for AFR_{STOIC}, AFR and Lambda by determining the correct values using the combustion analyses material balance method and a set of Combustion Air O_2, Fuel CH_4 and Flue Gas O_2 values, and subsequently, the high and low deviations from the correct value by applying the plus and minus uncertainty values to Combustion Air O_2, Fuel CH_4, Flue Gas O_2. Care was taken to ensure that the maximum uncertainties resulting from additive affects were determined. The remaining result uncertainties were determined using the equations noted above and the parametric analysis values determine for AFR_{STOIC}, AFR and Lambda.

The estimated uncertainties are based on the fuel gas analyses reported for engine 2, 3 and 4 and the following measured parameter uncertainties:

Combustion Air O_2	2%
Fuel Flow rate	3%
Fuel CH_4	5%
Flue Gas O_2	0.2% (vol), about 5% of observed low values

- Flue gas NO_x	10%
- Flue gas THC	175 ppm, about 10% at observed high values
- Power output	5%

The following results were determined:

- AFRStoic is a function of fuel gas analyses uncertainty and combustion air analyses. Methane uncertainty is fuel gas is 5% and oxygen analysis for air was assumed to have an uncertainty of 2%. AFRStoic uncertainty was determined to be -7.1% to 6.8%.

- AFR is a function of fuel gas analyses, flue gas O_2 measurement and combustion air analyses. Flue gas oxygen uncertainty is 0.2% (vol), a maximum of 5% of the measured value observed during the engine tests. AFR uncertainty was determined to vary from -8.7% to 9.3% for the tests at low Lambda values to -9.4% to 10.2% at the higher Lambda values. AFR would have a maximum uncertainty of 10.2%.

- Lambda is a function of AFRStoic and AFR and was determined to have an uncertainty varying from -15.0% to 13.0% at low Lambda values to -16.0% to 13.7% at high Lambda values. Lambda would have a maximum uncertainty of 16.0%.

- NO_x emissions in kg/h are a function of flue gas flow and NO_x concentration determinations. Flue gas flow is equal to (1 + AFR) x Fuel Flow. Based on the above uncertainty for AFR and values of 3% and 5% for fuel flow and NO_x, the mass emission rate uncertainty was determined to be 11.8%. Mass emission per bhp-h includes the bhp measurement uncertainty of 5% (maximum value of the Recip Trap and manual method). The NO_x emission factor uncertainty for g/bhp-h is 12.8% and for ng/J is 13.1%.

- CO_2e emissions in kg/h are a function of fuel flow and fuel analyses and the contribution of THC and N_2O. CO_2 determined from fuel gas flow and analysis has an uncertainty of 5.8%. The maximum THC value measured was about 1750 ppm (Engine 1) with an uncertainty of 10% or 175 ppm. The parametric analyses indicate that at 175 ppm the potential impact on CO_2e is 1.65%. Using absolute values related to CO_2 uncertainty and CH_4 uncertainty, the maximum CO_2e mass emission rate uncertainty was determined to be 7.4%. The CO_2e emission factor uncertainty for g/bhp-h is 8.9% and for ng/J is 9.4%.

- Uncertainty of N_2O is not included in the estimate for CO_2e uncertainty. However, based on the emission factor used for N_2O, the contribution to total CO_2e is a maximum of about 1%. The same emission factor was applied for all tests and its uncertainty would not affect the trends indicated by the tests. N_2O was not determined by test at any of the sites. For calculation of CO_2e, the Environment Canada emission factor for N_2O was used (Environment Canada 2011). The reported value for natural gas consumption by producers is 0.06 g/m^3 equivalent to1.6 ng/J. The confidence limit is noted as O.M. meaning Order of Magnitude. This emission factor was applied for all tests to calculate CO_2e. Including an N2O uncertainty, would add an additional 1% to the above noted uncertainty of 7.4% for CO_2e resulting in a total uncertainty of 8.4%.

- BSFC was determined based on measurements of fuel flow, fuel composition, and brake power output and the uncertainty was determined to be 7.7%.

Assessment of uncertainty related to engine testing by others suggests that the above estimates may not be conservative if all factors are considered (Cudney 2005).

3 RESULTS AND DISCUSSION

Summary results for all engine tests are presented for each engine and as a group of engines. The validity of presenting them as a group may be debatable. Although all engines were Waukesha L7042GSI engines, there may be significant differences that are related to their date of manufacture, level of maintenance, and other factors not available in the test data or engine documentation.

3.1 Reference Points

As reference points for comparison and assessment of the engine test results three sets of data were applied. These were:

- Regulatory
    - Alberta 4.48 g/bhp-h (6 g/kWh)
    - BC 2.0 g/bhp-h (2.7 g/kWh)
    - US EPA Reconstructed Engines 3.0 g/bhp-h (4 g/kWh) (US EPA 2008)

- Waukesha L7042GSI OEM Standard Economy and OEM 3-Way Catalytic Converter specification values for NO_x (g/bhp-h) and BSFC (btu/bhp-h) (Waukesha 2010) as assessed by Clearstone using the fuel gas associated with each engine tested.
    - Engines 1-4 rated at 1100 bhp @1000 rpm
        - OEM (Std Econ): NO_x = 22 g/bhp-h at BSFC = 7058 btu/bhp-h
        - OEM (3-Way CC): NO_x = 13 g/bhp-h at BSFC = 7058 btu/bhp-h
    - Engine 5 rated at 1480 bhp @ 1200 rpm
        - OEM (Std Econ): NO_x = 22 g/bhp-h at BSFC = 7618 btu/bhp-h
        - OEM (3-Way CC): NO_x = 13 g/bhp-h at BSFC = 7618 btu/bhp-h

- Industry survey data for Pre and Post REMVue performance as contained in Appendix B - Literature Review Table 3-2 with negative NO_x reduction data sets removed. The remaining data is listed in Table 3-1 and includes average Pre and Post NO_x emission rates and corresponding BSFC values. Standard deviation values are included and indicated wide variation in performance.

Table 3-1: Pre and Post REMVue Lambda, NO_x and BSFC, and percent reduction in NO_x and BSFC. (From Table 3-2 of Literature Review excluding negative NO_x reduction data sets.)

	Pre-Retrofit			Post-Retrofit			Reduction	
	Lambda	NO_x Emission	BSFC	Lambda	NO_x Emission	BSFC	NOx	BSFC
		g/bhp-h	btu/bhp-h		g/bhp-h	btu/bhp-h	%	%
7042GSI	1.01	13.17	8507	1.52	4.06	7962	69%	7%
7042GSI	1.00	4.96	12045	1.63	2.06	9733	59%	24%
7042GSI	1.01	17.30	10215	1.63	1.77	9494	90%	8%

Table 3-1: Pre and Post REMVue Lambda, NO_x and BSFC, and percent reduction in NO_x and BSFC. (From Table 3-2 of Literature Review excluding negative NO_x reduction data sets.)

	Pre-Retrofit			Post-Retrofit			Reduction	
	Lambda	NO_x Emission	BSFC	Lambda	NO_x Emission	BSFC	NOx	BSFC
		g/bhp-h	btu/bhp-h		g/bhp-h	btu/bhp-h	%	%
7042GSI	1.02	19.26	11651	1.57	1.64	10407	92%	12%
7042GSI	1.00	10.71	9574	1.62	1.40	9034	87%	6%
7042GSI	1.01	12.09	9803	1.58	1.57	9425	87%	4%
7044GSI	1.01	13.74	9748	1.53	3.30	9024	76%	8%
7042GSI	1.34	9.12	9751	1.82	1.23	9423	86%	3%
3521GSI	1.00	8.84	10981	1.50	2.15	10543	76%	4%
7042GSI	1.00	9.49	9408	1.48	3.02	8617	68%	9%
7042GSI	1.00	7.42	10474	1.53	4.57	9100	38%	15%
7042GSI	1.02	13.75	9181	1.49	4.30	9253	69%	-1%
7042GSI	1.09	23.23	8238	1.50	4.02	8014	83%	3%
7042GSI	1.00	3.75	8692	1.50	3.67	7818	2%	11%
7042GSI	1.00	3.75	8720	1.55	3.15	8085	16%	8%
7042GSI	1.01	4.77	10441	1.49	4.31	8693	10%	20%
7042GSI	1.01	11.41	10778	1.45	2.90	9534	75%	13%
7042GSI	1.01	13.17	8203	1.62	1.54	8317	88%	-1%
7042GSI	1.01	10.85	8372	1.56	1.17	7952	89%	5%
7042GSI	1.01	25.10	15000	1.82	1.23	9423	95%	59%
Average	1.03	11.79	9989	1.57	2.65	8992	67.7%	10.9%
Std Dev	0.08	5.95	1620	0.10	1.20	799	28.5%	13.0%

All results should be viewed with due consideration of data and result uncertainty and other data source and application matters.

3.2 Data Considerations

Field data was collected by Clearstone and by PIC. However, the common data source for all tests was the REMVue engine data and the ECOM flue gas data. Consequently, these data sets were used to complete all of the combustion and emissions assessments reported in Section 3.3. PIC used the ECOM on all tests but the THC component failed during engine 4 tests. Clearstone used the Testo 350 analyser to measure flue gas parameters for engine 5. However, the THC component failed on a few occasions and as a result a complete set of ECOM and Testo data was not obtained. Only eighteen samples were collected during Engine 5 sequence 1 and 2 test and submitted for detailed gas analyses test by gas chromatographic methods at Alberta Innovates (AI).

3.2.1 Measurement Comparisons

A comparison of results from the ECOM, Testo and AI based on data obtained for Engine 5 sequences 1 through 5 is summarized in Table 3-2, Table 3-3, and Table 3-4. This analysis indicates that for:

- Oxygen: The ECOM consistently provides a slightly higher reading than the Testo with a bias of 0.0% to 0.3%. The SDTEVs are between 0.04 and 0.10 percentage points. The ECOM readings are consistently lower that the AI readings with a bias of -0.7% and -0.9% percentage points, respectively for sequences 1 and 2. The SDTEVs are 0.27 and 0.58 percentage points, respectively.

- THC: The ECOM typically provides a low reading compared to the Testo with a bias of -62 to -445 ppm. However, for sequence 4 the bias was +9. Sequences 2 and 4, with the lowest bias exhibited inconsistent bias results with a high standard deviation. Sequences 1, 3 and 5 exhibited relatively low standard deviations. The ECOM readings are consistently lower that the AI readings with a bias of 208 and 230 ppm, respectively for sequences 1 and 2. The SDTEVs are 45 and 39 ppm, respectively. This bias of -62 to -445 ppm is equivalent to a CH_4 emission 0.1 to 0.9 g/bhp-h and would result in minimal additional CO_2e if the Testo data were applied.

- NO_x: The ECOM consistently provides a high reading compared to the Testo with a bias of 12% to 17% of the actual reading. Bias is inconsistent at very low NO_x values with a negative bias observed for a few tests. With the negative bias results excluded (three data points), the standard deviations are very good. The above noted positive bias is equivalent to 0.2 g/bhp-h at low emissions levels of 1.0-2.0 g/bhp-h, and about 1.8 g/bhp-h at high emissions levels of 12.0-14.0 g/bhp-h. This shift includes the NO and NO_2 bias indicated below.

- NO: The ECOM consistently provides a high reading compared to the Testo with a bias of 5% to 14% of the actual reading.

- NO_2: The ECOM consistently provides a high reading compared to the Testo with a bias of 33% to 38% of actual reading.

Table 3-2: O_2 data analyses for Engine 5 test sequences 1 through 5[(4)]

Engine 5 Sequence 1	ECOM[1] O_2 (%)	Testo[2] O_2 (%)	AI O_2 (%)	ECOM - Testo Delta	ECOM - AI Delta
Test 1	8.0	7.8	8.5	0.2	-0.5
Test 2	7.6	7.4	8.7	0.2	-1.1
Test 3	7.2	7.0	7.9	0.2	-0.6
Test 4	6.7	6.3	7.3	0.4	-0.6
Test 5	6.3	6.0	7.1	0.3	-0.8
Test 6	6.2	5.9	6.8	0.3	-0.6
Test 7	5.7	5.5	6.7	0.2	-1.0
Test 8	5.3	5.2	5.5	0.1	-0.2
Test 9	4.9	ND	5.4	N/A	-0.5
			Average Delta	0.2	-0.7
			Standard Deviation	0.08	0.27
Engine 5 Sequence 2	**ECOM O_2 (%)**	**Testo O_2 (%)**	**AI O_2 (%)**	**ECOM - Testo Delta**	**ECOM - AI Delta**
Test 10	8.2	7.8	9.0	0.4	-0.8
Test 11	7.8	7.5	8.4	0.3	-0.6
Test 12	7.4	7.1	8.5	0.3	-1.1

Table 3-2: O_2 data analyses for Engine 5 test sequences 1 through 5(4)

Engine 5 Sequence 1	ECOM[1] O_2 (%)	Testo[2] O_2 (%)	AI O_2 (%)	ECOM - Testo Delta	ECOM - AI Delta
Test 13	7.0	6.7	7.3	0.3	-0.3
Test 14	6.7	6.4	8.1	0.3	-1.4
Test 15	6.2	5.9	8.0	0.3	-1.8
Test 16	6.0	5.7	7.1	0.4	-1.0
Test 17	5.5	5.2	6.4	0.3	-1.0
Test 18	4.9	ND	4.7	N/A	0.2
Average Delta				0.3	-0.9
Standard Deviation				0.04	0.58
Engine 5 Sequence 3	**ECOM O_2 (%)**	**Testo O_2 (%)**	**AI O_2 (%)**	**ECOM - Testo Delta**	**ECOM - AI Delta**
Test 19	8.1	7.7	ND	0.4	N/A
Test 20	7.5	7.2	ND	0.3	N/A
Test 21	7.0	6.5	ND	0.4	N/A
Test 22	6.5	6.1	ND	0.4	N/A
Test 23	6.0	5.6	ND	0.3	N/A
Test 24	5.5	5.4	ND	0.2	N/A
Test 25	5.0	4.8	ND	0.2	N/A
Average Delta				0.3	N/A
Standard Deviation				0.10	N/A
Engine 5 Sequence 4	**ECOM O_2 (%)**	**Testo O_2 (%)**	**AI O_2 (%)**	**ECOM - Testo Delta**	**ECOM - AI Delta**
Test 26	8.0	8.0	ND	0.0	N/A
Test 27	7.6	7.6	ND	0.0	N/A
Test 28	7.0	6.9	ND	0.1	N/A
Test 29	6.6	6.4	ND	0.1	N/A
Test 30	6.1	6.0	ND	0.1	N/A
Test 31	5.5	5.5	ND	0.0	N/A
Test 32	5.1	ND	ND	N/A	N/A
Average Delta				0.1	N/A
Standard Deviation				0.07	N/A
Engine 5 Sequence 5	**ECOM O_2 (%)**	**Testo O_2 (%)**	**AI O_2 (%)**	**ECOM - Testo Delta**	**ECOM - AI Delta**
Test 33	8.1	8.0	ND	0.1	N/A
Test 34	7.5	7.3	ND	0.1	N/A
Test 35	6.9	6.9	ND	0.0	N/A
Test 36	6.5	6.4	ND	0.1	N/A
Test 37	6.0	6.0	ND	0.0	N/A
Test 38	5.5	5.5	ND	0.0	N/A
Test 39	5.0	ND	ND	N/A	N/A
Average Delta				0.0	N/A
Standard Deviation				0.07	N/A

[1] Each data point is the average of 181 individual samples recorded by the ECOM.

[2] Each data point is the average of 8 individual samples recorded by the Testo.

[3] Each data point is the average of 1 sample analyses by AI.

[4] ND refers to no data available

Table 3-3: THC data analyses for Engine 5 test sequences 1 through 5(4)					
Engine 5 Sequence 1	**ECOM[1] THC (ppm)**	**Testo[2] THC (ppm)**	**AI (ppm)**	**ECOM - Testo Delta**	**ECOM - AI Delta**
Test 1	100	586	361	-486	-261
Test 2	100	459	367	-359	-267
Test 3	100	521	346	-421	-246
Test 4	90	495	243	-405	-153
Test 5	80	516	263	-436	-183
Test 6	60	555	290	-495	-230
Test 7	70	545	267	-475	-197
Test 8	60	544	239	-484	-179
Test 9	50	ND	202	N/A	-152
			Average Delta	-445.1	-207.6
			Standard Deviation	48.25	44.61
Engine 5 Sequence 2	**ECOM THC (ppm)**	**Testo THC (ppm)**	**AI (ppm)**	**ECOM - Testo Delta**	**ECOM - AI Delta**
Test 10	70	446	350	-376	-280
Test 11	60	63	355	-3	-295
Test 12	50	0	301	50	-251
Test 13	50	5	253	45	-203
Test 14	40	11	286	29	-246
Test 15	40	293	238	-253	-198
Test 16	40	49	238	-9	-198
Test 17	31	10	233	21	-203
Test 18	30	ND	227	N/A	-197
			Average Delta	-61.9	-229.9
			Standard Deviation	160.44	38.75
Engine 5 Sequence 3	**ECOM THC (ppm)**	**Testo THC (ppm)**	**AI (ppm)**	**ECOM - Testo Delta**	**ECOM - AI Delta**
Test 19	170.0	407.1	ND	-237.1	N/A
Test 20	160.0	460.0	ND	-300.0	N/A
Test 21	160.0	410.0	ND	-250.0	N/A
Test 22	150.0	378.0	ND	-228.0	N/A
Test 23	150.0	330.0	ND	-180.0	N/A
Test 24	150.0	310.0	ND	-160.0	N/A
Test 25	140.0	282.9	ND	-142.9	N/A
			Average Delta	-214.0	N/A
			Standard Deviation	55.61	N/A
Engine 5 Sequence 4	**ECOM THC (ppm)**	**Testo THC (ppm)**	**AI (ppm)**	**ECOM - Testo Delta**	**ECOM - AI Delta**
Test 26	245.4	515.7	ND	-270.3	N/A
Test 27	230.0	438.3	ND	-208.3	N/A
Test 28	220.0	186.7	ND	33.3	N/A
Test 29	210.0	65.0	ND	145.0	N/A
Test 30	200.0	26.7	ND	173.3	N/A

Table 3-3: THC data analyses for Engine 5 test sequences 1 through 5(4)

Engine 5 Sequence 1	ECOM[1] THC (ppm)	Testo[2] THC (ppm)	AI (ppm)	ECOM - Testo Delta	ECOM - AI Delta
Test 31	190.0	5.0	ND	185.0	N/A
Test 32	190.0	N/A	ND		
			Average Delta	9.7	N/A
			Standard Deviation	201.15	N/A
Engine 5 Sequence 4	**ECOM THC (ppm)**	**Testo THC (ppm)**	**AI (ppm)**	**ECOM - Testo Delta**	**ECOM - AI Delta**
Test 33	220.0	620.0	ND	-400.0	N/A
Test 34	210.0	531.7	ND	-321.7	N/A
Test 35	200.0	481.7	ND	-281.7	N/A
Test 36	190.0	435.7	ND	-245.7	N/A
Test 37	180.0	415.0	ND	-235.0	N/A
Test 38	180.0	397.1	ND	-217.1	N/A
Test 39	170.0	ND	ND	ND	N/A
			Average Delta	-283.5	N/A
			Standard Deviation	68.14	N/A

[1] Each data point is the average of 181 individual samples recorded by the ECOM.

[2] Each data point is the average of 8 individual samples recorded by the Testo.

[3] Each data point is the average of 1 sample analyses by AI.

[4] ND refers to no data available

Table 3-4: NO_X, NO, and NO_2 data analyses for Engine 5 sequences 1 through 5

Engine 5 Sequence 1	ECOM[1] NOx (ppm)	Testo[2] NOx (ppm)	ECOM - Testo NO_x Delta (%)	ECOM[1] NO (ppm)	Testo[2] NO (ppm)	ECOM - Testo NO Delta (%)	ECOM[1] NO_2 (ppm)	Testo[2] NO_2 (ppm)	ECOM - Testo NO_2 Delta (%)
Test 1	112	153	-36%	80	111	-39%	32	42	-30%
Test 2	288	255	12%	178	198	-11%	110	57	48%
Test 3	485	420	13%	363	352	3%	121	68	44%
Test 4	1035	914	12%	894	820	8%	141	93	34%
Test 5	1376	1185	14%	1225	1088	11%	152	96	36%
Test 6	1480	1284	13%	1324	1180	11%	156	105	33%
Test 7	2066	1845	11%	1887	1727	8%	179	118	34%
Test 8	2576	2320	10%	2376	2194	8%	200	126	37%
Test 9	3183	ND	N/A	2957	ND	N/A	226	ND	N/A
		Average Delta[3]	12%		Average Delta[4]	8%		Average Delta[3]	38%
		STDEV[3]	1%		STDEV[4]	3%		STDEV[3]	6%
Engine 5 Sequence 2	**ECOM NOx (ppm)**	**Testo NOx (ppm)**	**ECOM - Testo NO_xDelta**	**ECOM NO (ppm)**	**Testo NO (ppm)**	**ECOM - Testo NO Delta**	**ECOM NO_2 (ppm)**	**Testo NO_2 (ppm)**	**ECOM - Testo NO_2 Delta**
Test 10	273	226	17%	155	152	1%	119	74	38%
Test 11	377	319	15%	255	254	1%	122	79	35%
Test 12	584	505	14%	448	414	8%	136	91	33%
Test 13	892	771	14%	748	674	10%	144	97	32%
Test 14	1150	994	14%	998	889	11%	152	105	31%

Table 3-4: NO$_X$, NO, and NO$_2$ data analyses for Engine 5 sequences 1 through 5

Test 15	1676	1385	17%	1507	1280	15%	169	105	38%
Test 16	1982	1703	14%	1802	1590	12%	179	113	37%
Test 17	2734	2370	13%	2523	2249	11%	210	121	42%
Test 18	3572	ND	N/A	3327	ND	N/A	245	ND	N/A
Average Delta			14.8%	Average Delta		8.5%	Average Delta		35.8%
STDEV			1.7%	STDEV		5.1%	STDEV		3.8%
Engine 5 Sequence 3	**ECOM NOx (ppm)**	**Testo NOx (ppm)**	**ECOM - Testo NO$_x$Delta**	**ECOM NO (ppm)**	**Testo NO (ppm)**	**ECOM - Testo NO Delta**	**ECOM NO$_2$ (ppm)**	**Testo NO$_2$ (ppm)**	**ECOM - Testo NO$_2$ Delta**
Test 19	150	109	28%	76	77	-1%	74	31	58%
Test 20	282	213	24%	185	161	13%	97	52	46%
Test 21	507	465	8%	394	392	0%	113	72	36%
Test 22	760	708	7%	637	626	2%	123	82	33%
Test 23	1233	1108	10%	1098	1016	7%	135	92	32%
Test 24	1642	1421	13%	1496	1324	12%	145	97	33%
Test 25	2300	2086	9%	2137	1978	7%	163	108	34%
Average Delta			12.7%	Average Delta		5.7%	Average Delta		34.5%
STDEV			8.9%	STDEV		5.2%	STDEV		15.2%
Engine 5 Sequence 4	**ECOM NOx (ppm)**	**Testo NOx (ppm)**	**ECOM - Testo NO$_x$Delta**	**ECOM NO (ppm)**	**Testo NO (ppm)**	**ECOM - Testo NO Delta**	**ECOM NO$_2$ (ppm)**	**Testo NO$_2$ (ppm)**	**ECOM - Testo NO$_2$ Delta**
Test 26	155	128	17%	69	78	-14%	86	50	42%
Test 27	279	236	16%	173	169	2%	106	67	37%
Test 28	571	472	17%	443	391	12%	127	80	37%
Test 29	945	780	17%	804	690	14%	140	90	36%
Test 30	1438	1200	17%	1285	1101	14%	154	99	36%
Test 31	2220	1847	17%	2044	1743	15%	176	105	40%
Test 32	2841	ND	N/A	2652	ND	N/A	189	ND	N/A
Average Delta			15.7%	Average Delta		6.9%	Average Delta		34.9%
STDEV			3.1%	STDEV		10.4%	STDEV		9.0%
Engine 5 Sequence 5	**ECOM NOx (ppm)**	**Testo NOx (ppm)**	**ECOM - Testo NO$_x$Delta**	**ECOM NO (ppm)**	**Testo NO (ppm)**	**ECOM - Testo NO Delta**	**ECOM NO$_2$ (ppm)**	**Testo NO$_2$ (ppm)**	**ECOM - Testo NO$_2$ Delta**
Test 33	163	120	26%	96	85	11%	68	35	48%
Test 34	393	318	19%	293	259	12%	100	58	42%
Test 35	688	540	21%	574	465	19%	113	75	34%
Test 36	1132	921	19%	1009	836	17%	124	85	31%
Test 37	1707	1411	17%	1572	1321	16%	135	90	33%
Test 38	2409	2024	16%	2254	1922	15%	154	101	34%
Test 39	3133	ND	N/A	2973	ND	N/A	161	ND	N/A
Average Delta			17.4%	Average Delta		14%	Average Delta		33.0%
STDEV			7.2%	STDEV		3.3%	STDEV		12.0%

[1] Each data point is the average of 181 individual samples recorded by the ECOM.

[2] Each data point is the average of 8 samples recorded by the Testo.

[3] Average and STDEV exclude negative delta for test 1 of sequence 1.

[4] Average and STDEV exclude negative deltas for test 1 and 2 of sequence 1.

3.2.2 CH_4 Component of THC

Emissions of CH_4 were based on measured THC and the CH_4/THC ratio determined from the fuel gas analyses. The preferred procedure would be to use the flue gas CH_4/THC ratio or the actual CH4 emission concentration. However, the preferred data was not available for all tests. The potential implication of using the fuel gas ratio was assessed based on flue gas measurements completed by AI on Engine 5.

For engine 5, the CH_4/THC molar ratio in the fuel gas was 0.936. The CH_4/THC molar ratio determined from the results of 18 flue gas samples analysed by AI was 0.923 with a STDEV of 0.027. Using the fuel gas ratio, instead of the flue gas ratio, results in CH_4 being conservatively overstated by 1.38%.

3.3 Individual Engine Results

For each data set results were determined for:

- NO_x emissions in g/bhp-h vs Lambda at various bhp settings
- NO_x emissions in kg/h vs Lambda at various bhp settings
- CO_2e emissions in g/bhp-h vs Lambda at various bhp settings
- CO_2e emissions in kg/h vs Lambda at various bhp settings
- BSFC in btu/bhp-h at various bhp settings
- NO_x reduction versus CO_2e increase
- BSFC versus NO_x for each test run or sequence

Complete summary results are presented for each engine and additional field data files are contained in Section 6 (Appendix A). Condition at which specific emission criteria were met is based on smooth curve fit of data points (Excel option) and visual inspection.

3.3.1 Test Engine 1

This engine, rated at 1100 bhp @1000 rpm was tested at three loads with four Lambda settings for each load condition. Results are summarized in Figure 3-1 to Figure 3-6 and presented in Table 3-5.

This engine was tested over a narrow load range of 749 to 824 bhp and NO_x emission rates vary marginally with load and when plotted, as kg/h in Figure 3-2, are essentially identical except at the highest Lambda values. This engine meets the 4.48, 3 and 2 g/bhp-h emission levels at Lambda values of about 1.40, 1.45 and 1.50, respectively.

CO_2e results indicate the proper trend with respect to Lambda but are not consistent with respect to load suggesting some measurement error. Closer examination of the THC data suggest that the measured value of 870 ppm at Lambda 1.48 for the series at 824 rpm @ 987 bhp is in error and should be in the range of 1,750 to 2,000 ppm. A THC measurement error of 100% is indicated. The value of 1,380 ppm at Lambda 1.27 may also be in error by 5-10% (too high). Application of the estimated value of 1750 ppm removes the anomaly from this data set.

Except for one data point at Lambda 1.51 for the 787 bhp series, NO_x and CO_2e emission factors expressed in ng/J are reasonably consistent. For this engine, non-CO_2 CO_2e (associated with CH_4 and N_2O) accounts for 13.3%. (CH_4 = 12.4%) of total CO_2e with a STDEV of 2.5 percentage points. This data set has the low THC value noted above.

Figure 3-5 shows the potential CO_2e penalty (CO_2e % increase) as NO_x emissions (NO_x % Reduction) are reduced by increasing Lambda. The base case is the lowest Lambda tested (about 1.27) and achieving NOx emission levels of 4.48, 3 and 2 g/bhp-h resulted in maximum CO_2e penalties of about 4%, 7% and 10%, respectively.

Figure 3-6 shows BSFC verses NO_x in the context of regulatory, OEM and industry reference points. This engine exhibits a BSFC inflection point at about 4 g/bhp-h. It performs better than industry average reference points but operates at a higher BSFC than OEM reference points.

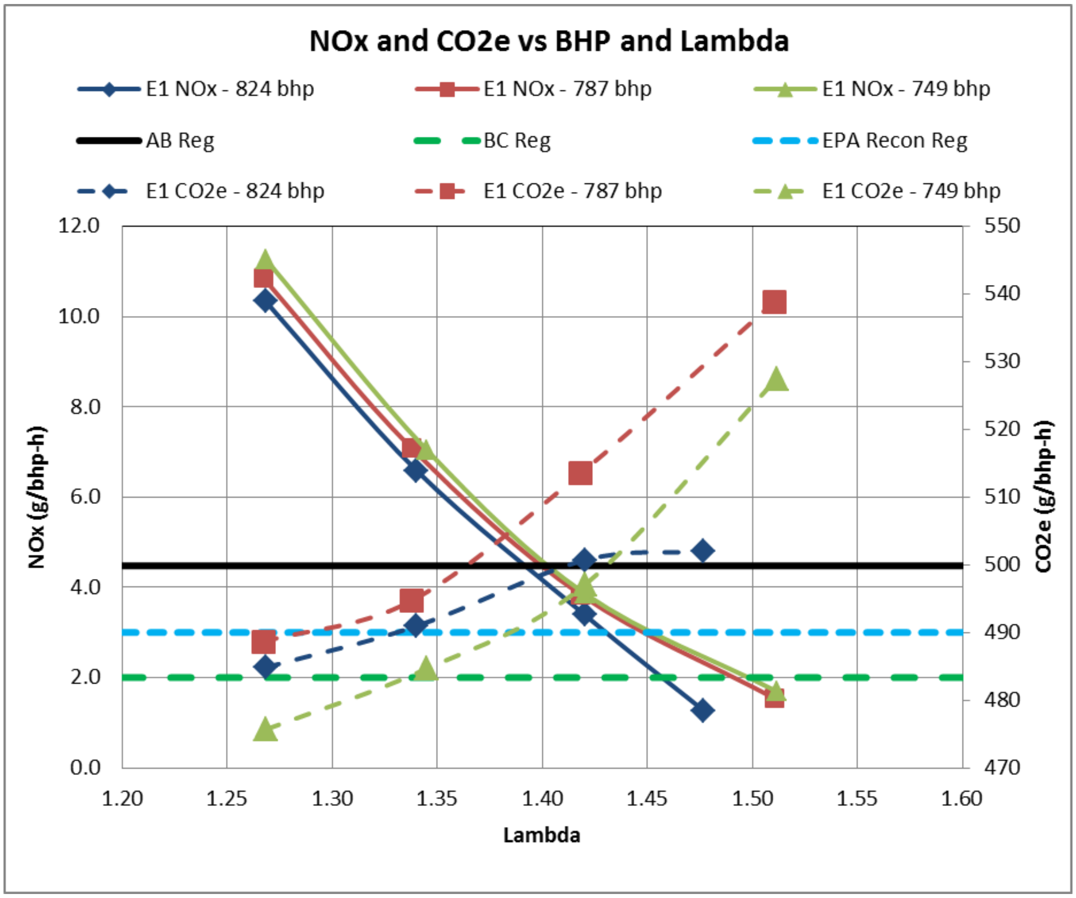


Figure 3-1: Test Engine 1 NO_x and CO_2e emission in g/bhp-h at 749, 787 and 824 BHP vs. Lambda.

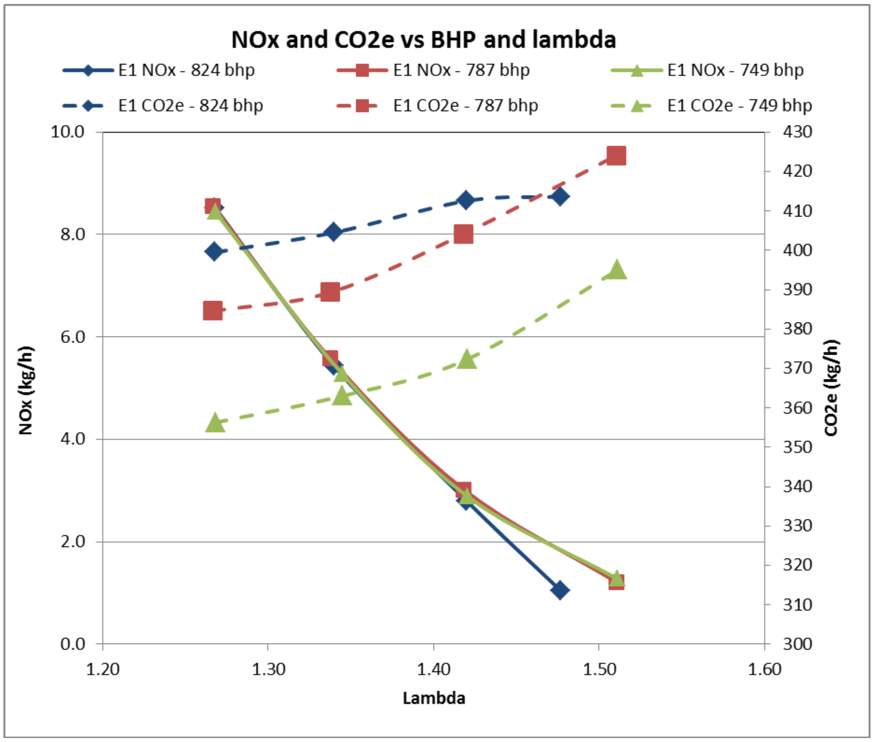


Figure 3-2: Test Engine 1 NO_x and CO_2e emissions in kg/h at 749, 787 and 824 BHP vs. Lambda.

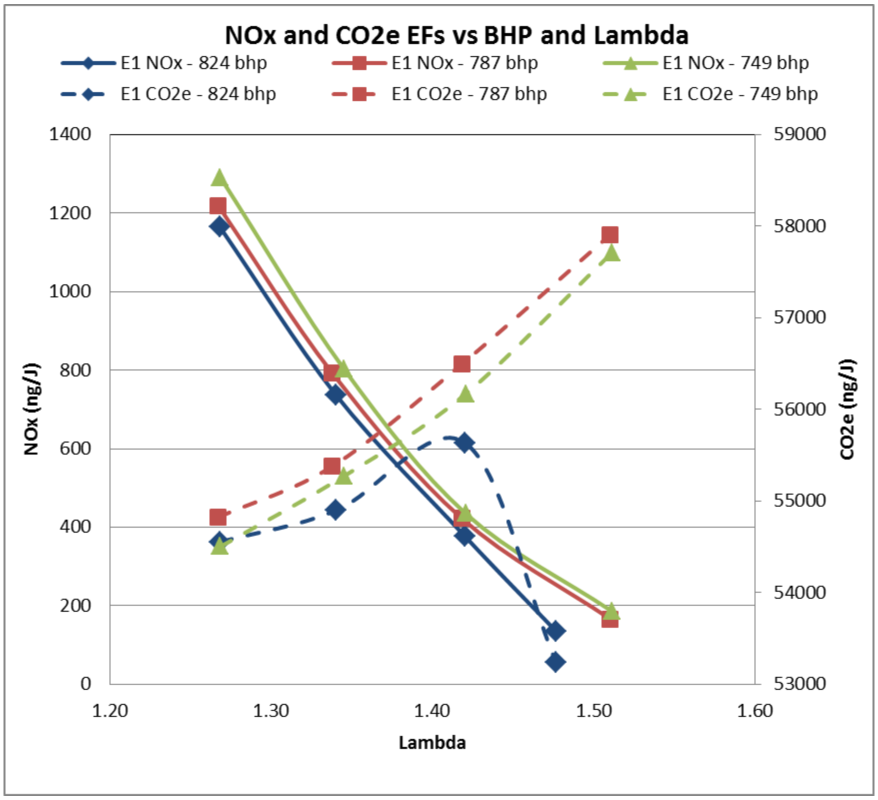


Figure 3-3: Test Engine 1 NO_x and CO_2e emission factors in ng/J energy input at 749, 787 and 824 BHP vs. Lambda.

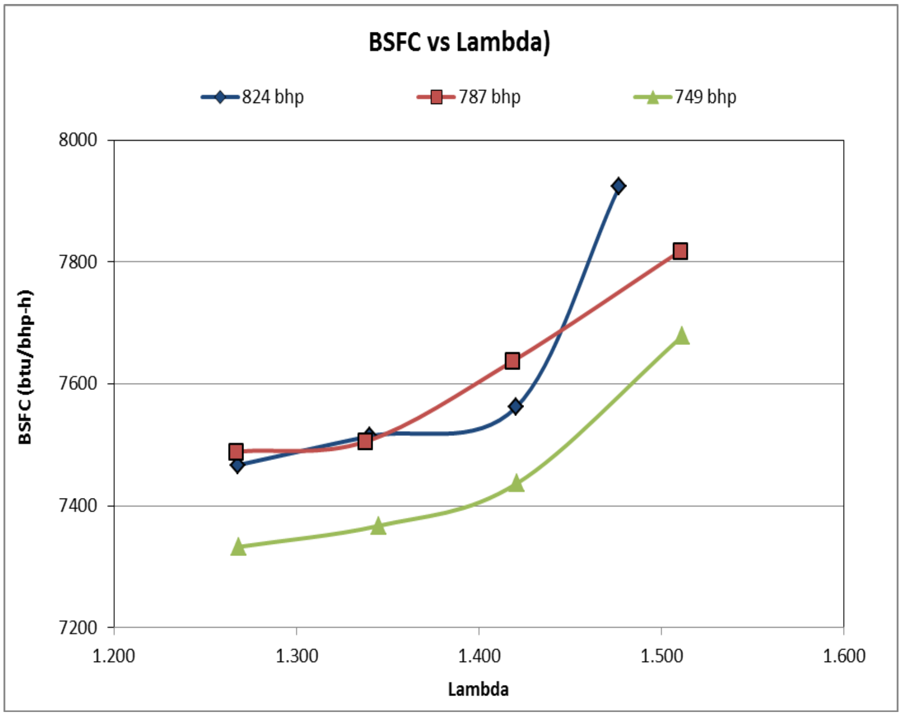


Figure 3-4: Test Engine 1 BSFC at 749, 787 and 824 BHP vs. Lambda.

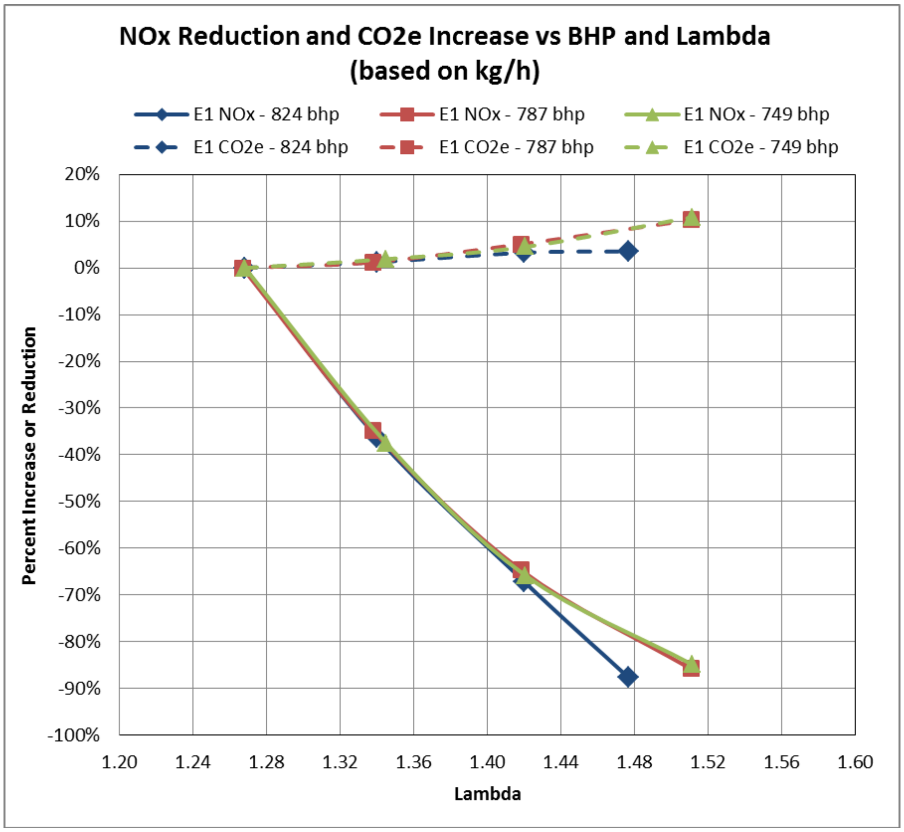


Figure 3-5: Test Engine 1 NO_x reduction and CO_2e increase at 724, 787 and 824 BHP vs. Lambda.

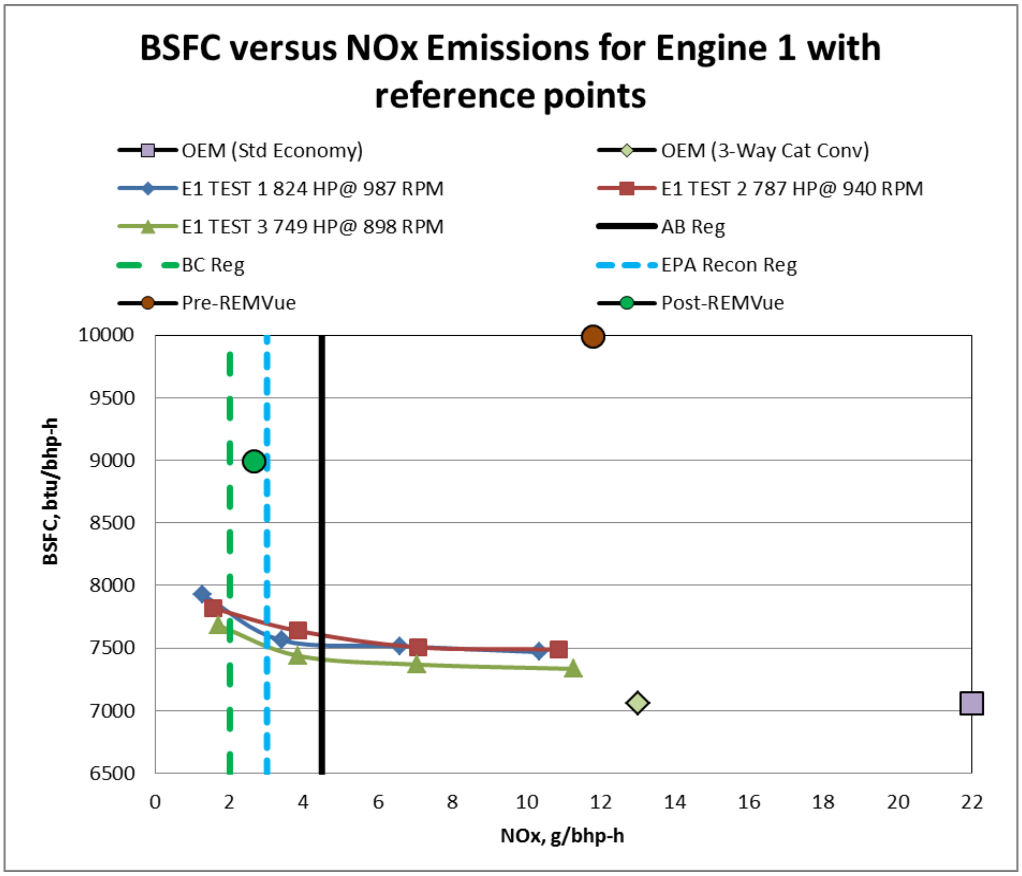


Figure 3-6: Test Engine 1 BSFC versus NO$_x$ at 724, 787 and 824 BHP for a range of Lambda.

Table 3-5: Summary of Test Engine 1 recorded operating data, measured operating and emission data and calculated results.

Test Engine 1	**Engine: Waukesha L7042GSI**			**Maximum Rated Power: 1100 bhp@1000rpm**									
TEST RUN		**TEST 1 824 HP@ 987 RPM**				**TEST 2 787 HP@ 940 RPM**				**TEST 3 749 HP@ 898 RPM**			
	Unit	**1A**	**1B**	**1C**	**1D**	**2A**	**2B**	**2C**	**2D**	**3A**	**3B**	**3C**	**3D**
Inlet Temp	C	38.2	37.7	37.9	37.6	40.2	38.8	39.2	39.0	42.4	41.9	40.1	38.9
Exhaust Temp	C	600.7	597.8	602.2	609.0	587.2	584.7	589.3	596.5	576.6	575.7	578.8	586.7
Manifold Pressure	PSI	3.35	1.95	0.95	0.30	3.10	1.70	0.85	0.20	2.90	1.60	0.75	0.10
Speed	RPM	985	985	989	987	940	940	940	940	900	900	900	900
Stack Gas (measured)													
Lambda	-	1.48	1.42	1.34	1.27	1.51	1.42	1.34	1.27	1.51	1.42	1.35	1.27
O_2	%	7.5	7.0	6.0	5.0	8.0	7.0	6.0	5.0	8.0	7.0	6.1	5.0
CO	ppm	262	283	256	262	246	278	271	237	245	273	264	219
Total Combustible	ppm	870	1490	1390	1380	1910	1700	1520	1450	1860	1620	1480	1360
Unburnt Fuel	ppm	870	1490	1390	1380	1910	1700	1520	1450	1860	1620	1480	1360
NO	ppm	203	712	1592	2747	241	810	1732	2890	278	840	1750	3042
NO_2	ppm	67	116	172	239	83	123	174	241	87	124	170	264
Fuel Mol. Wt.	-	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4	16.4
Fuel	e3 sm3/d	5.04	4.81	4.78	4.75	4.75	4.64	4.56	4.55	4.44	4.30	4.26	4.24
Air	e3 sm3/d	69.96	64.21	60.21	56.62	67.44	61.86	57.34	54.19	63.08	57.42	53.86	50.55
Stack Gas (Wet Basis)	e3 sm3/d	75.02	69.03	65.01	61.39	72.21	66.52	61.91	58.75	67.54	61.73	58.12	54.79
Excess Air (%)	%	48.3	42.6	34.4	27.2	51.5	42.3	34.3	27.2	51.6	42.4	35.2	27.4
Exhaust MW	-	27.9	27.9	27.9	27.8	28.0	27.9	27.9	27.8	28.0	27.9	27.9	27.8
Dew Point Temp	°C	51.1	51.5	52.7	53.8	50.3	51.6	52.7	53.7	50.4	51.6	52.5	53.7
Emission Factors													
CO	ng/J	108	112	95	91	104	110	100	83	103	108	98	77
CO_2	ng/J	48454	48084	48226	48284	47754	47959	48143	48260	47787	48010	48163	48318
CO_2e	ng/J	53234	55636	54896	54555	57910	56498	55380	54825	57712	56171	55274	54505
Methane	ng/J	204	336	294	275	460	383	321	289	449	365	315	271
Ethane	ng/J	0.0	1.0	1.0	1.0	2.0	1.0	1.0	1.0	2.0	1.0	1.0	1.0
Total VOC	ng/J	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Hydrocarbons	ng/J	206	338	296	277	463	385	323	291	451	367	317	273
N_2O	ng/J	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
NO	ng/J	89	301	632	1027	109	342	687	1080	126	355	699	1139
NO_2	ng/J	45	75	105	137	58	80	106	138	60	80	104	152
Total Oxides of Nitrogen	ng/J	135	377	737	1164	166	422	793	1219	186	435	803	1291
Non-CO_2 CO_2e	%	9.0%	13.6%	12.2%	11.5%	17.5%	15.1%	13.1%	12.0%	17.2%	14.5%	12.9%	11.4%
Stack Gas (calculated on dry basis)													
CO_2	mole frac.	0.07495	0.07748	0.08282	0.08805	0.07203	0.07743	0.08276	0.08802	0.07202	0.07744	0.08221	0.08799
N_2	mole frac.	0.84865	0.84992	0.85377	0.85733	0.84549	0.84966	0.85355	0.85717	0.84551	0.84971	0.85313	0.85713
O_2	mole frac.	0.07500	0.07000	0.06000	0.05000	0.08000	0.07000	0.06000	0.05000	0.08000	0.07000	0.06100	0.05000
CO	mole frac.	0.00026	0.00028	0.00026	0.00026	0.00025	0.00028	0.00027	0.00024	0.00025	0.00027	0.00026	0.00022
NO	mole frac.	0.00020	0.00071	0.00159	0.00275	0.00024	0.00081	0.00173	0.00289	0.00028	0.00084	0.00175	0.00304
NO_2	mole frac.	0.00007	0.00012	0.00017	0.00024	0.00008	0.00012	0.00017	0.00024	0.00009	0.00012	0.00017	0.00026
Methane	mole frac.	0.00087	0.00149	0.00139	0.00138	0.00191	0.00170	0.00152	0.00145	0.00186	0.00162	0.00148	0.00136

Table 3-5: Summary of Test Engine 1 recorded operating data, measured operating and emission data and calculated results.

Test Engine 1	Engine: Waukesha L7042GSI	Maximum Rated Power: 1100 bhp@1000rpm											
TEST RUN		TEST 1 824 HP@ 987 RPM				TEST 2 787 HP@ 940 RPM				TEST 3 749 HP@ 898 RPM			
	Unit	1A	1B	1C	1D	2A	2B	2C	2D	3A	3B	3C	3D
Ethane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00001	0.00000	0.00000	0.00000	0.00001	0.00000	0.00000	0.00000
Propane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Isobutane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Output Values													
BHP	hp	824	824	824	824	787	787	787	787	749	749	749	749
AFR	-	13.88	13.35	12.60	11.92	14.20	13.33	12.57	11.91	14.21	13.35	12.64	11.92
AFR$_{STOIC}$	-	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4
Lambda	-	1.48	1.42	1.34	1.27	1.51	1.42	1.34	1.27	1.51	1.42	1.35	1.27
BSFC (LHV)	btu/bhph	7923	7561	7514	7467	7818	7637	7505	7489	7679	7437	7367	7333
NO$_x$	(g/bhp-h)	1.3	3.4	6.6	10.3	1.5	3.8	7.1	10.9	1.7	3.9	7.0	11.3
CO$_2$	(g/bhp-h)	457	433	431	429	444	436	430	430	437	425	422	422
CH$_4$	(g/bhp-h)	1.9	3.0	2.6	2.4	4.3	3.5	2.9	2.6	4.1	3.2	2.8	2.4
N$_2$O	(g/bhp-h)	0.015	0.014	0.014	0.014	0.015	0.015	0.014	0.014	0.015	0.014	0.014	0.014
CO$_2$e	(g/bhp-h)	502.0	500.7	490.9	484.8	538.8	513.5	494.7	488.7	527.4	497.2	484.7	475.7
Methane (% of total CO$_2$e)	%	8.0%	12.7%	11.2%	10.6%	16.7%	14.2%	12.2%	11.1%	16.3%	13.6%	12.0%	10.4%
Fuel HHV	MJ/m3	37.0											
Fuel LHV	MJ/m3	32.8											
Emissions													
CO$_2$	(kg/h)	376.5	356.6	355.4	353.6	349.7	343.1	338.4	338.5	327.1	318.3	316.3	315.8
CH$_4$	(kg/h)	1.59	2.49	2.17	2.01	3.37	2.74	2.26	2.03	3.07	2.42	2.07	1.77
N$_2$O	(kg/h)	0.012	0.012	0.012	0.012	0.012	0.011	0.011	0.011	0.011	0.011	0.011	0.010
CO$_2$e	(kg/h)	413.6	412.6	404.5	399.5	424.1	404.1	389.3	384.6	395.0	372.4	363.0	356.3
NO	(kg/h)	0.69	2.23	4.66	7.52	0.80	2.45	4.83	7.58	0.86	2.35	4.59	7.45
NO$_2$	(kg/h)	0.35	0.56	0.77	1.00	0.42	0.57	0.75	0.97	0.41	0.53	0.68	0.99
NO$_x$	(kg/h)	1.05	2.80	5.43	8.52	1.22	3.02	5.57	8.55	1.27	2.88	5.27	8.44
CO	(kg/h)	0.84	0.83	0.70	0.67	0.76	0.79	0.70	0.58	0.71	0.72	0.64	0.50

Note: Shaded Test 1 A1 Total Combustibles and Unburned Fuel data is suspect

3.3.2 Test Engine 2

This engine, rated at 1100 bhp @ 1000 rpm, was tested over a narrow load range of 749 to 824 bhp at three loads and four Lambda settings for each load condition. This engine results are summarized in Figure 3-7 to Figure 3-12 and presented in Table 3-6. NO_x emission rates vary marginally with load and when plotted, as kg/h vs Lambda in Figure 3-8, are essentially identical except at the lowest Lambda values where emission rates appear to be weakly but inconsistently influenced by load. This inconsistency could also be attributed to data uncertainty.

CO_2e results indicate the proper trend with respect to Lambda but the results at 750 bhp are not as consistent suggesting some small measurement errors. Data points for 750 bhp at Lambda values of 1.27 and 1.33 in Figure 3-9 appear to be slightly high indicating the reported fuel values may be high. THC and CO values appear to be in line with expected values for both conditions. This engine meets the 4.48, 3.0 and 2.0 g/bhp-h emission levels at Lambda values of about 1.33, 1.38 and 1.43, respectively.

NO_x and CO_2e emission factors expressed in ng/J are reasonably consistent for all tests. For this engine, non-CO_2 CO_2e (associated with CH_4 and N_2O) accounts for 13.9%. (CH_4 = 13.0%) of total CO_2e with a STDEV of 1.5 percentage points.

Figure 3-11 shows the potential CO_2e penalty (CO_2e % increase) as NO_x emissions (NO_x % Reduction) are reduced by increasing Lambda. The base case is the lowest Lambda tested (about 1.25) and achieving NO_x emission levels of 4.48, 3.0 and 2.0 g/bhp-h resulted in maximum CO_2e penalties of about 2%, 3% and 5.5%, respectively.

Figure 3-12 shows BSFC verses NO_x in the context of regulatory, OEM and industry reference points. This engine exhibits a BSFC inflection point between 2 – 3 g/bhp-h and preforms better than OEM and industry average reference points.

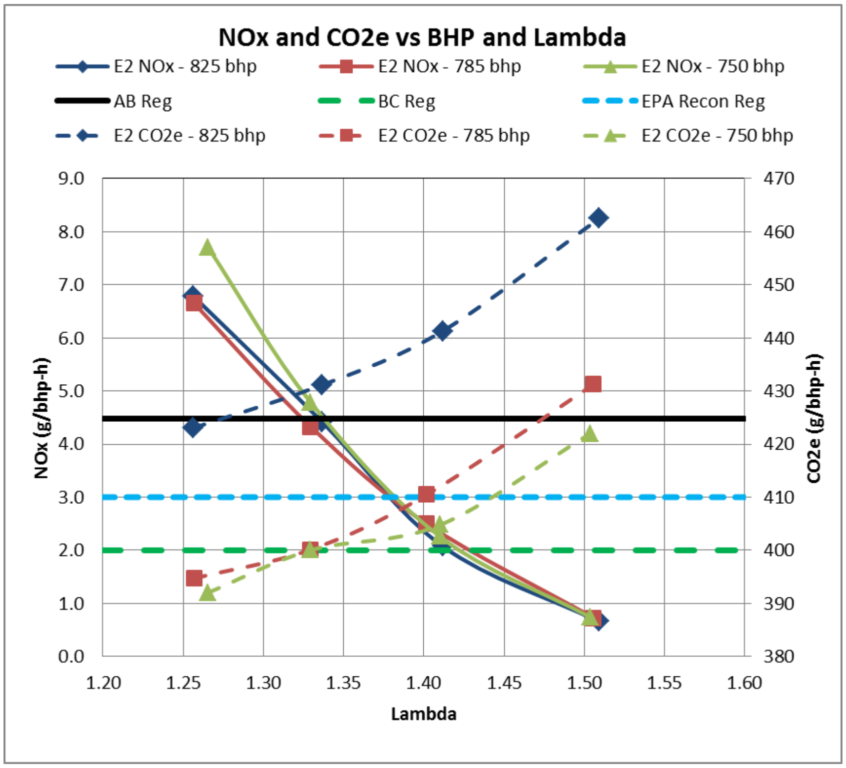


Figure 3-7: Test Engine 2 NO_x and CO_2e emission in g/bhp-h at 750, 785 and 825 BHP vs. Lambda.

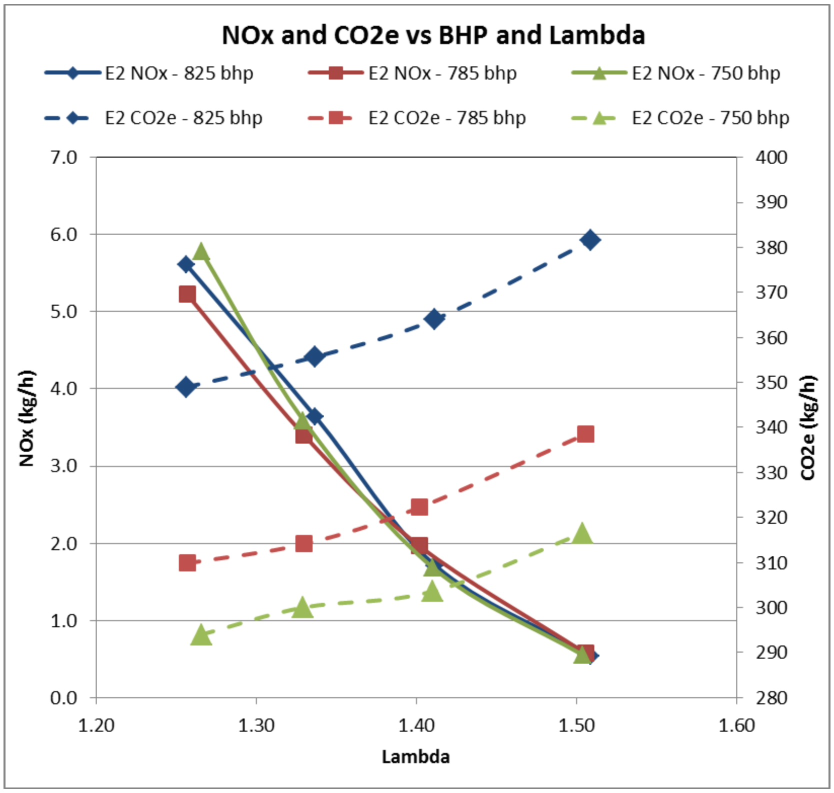


Figure 3-8: Test Engine 2 NO_x and CO_2e emissions in kg/h at 750, 785 and 825 BHP vs. Lambda.

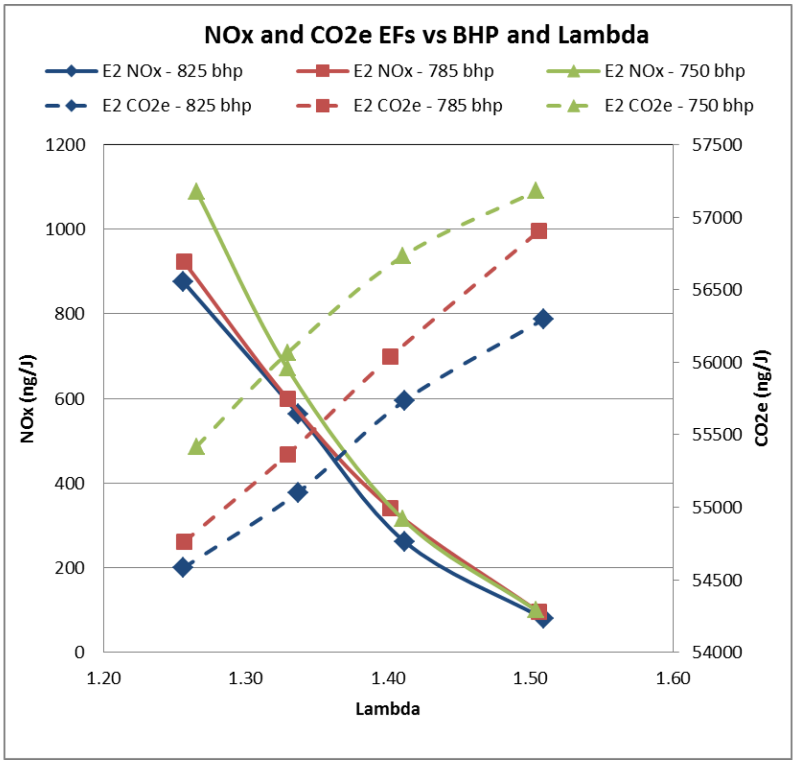


Figure 3-9: Test Engine 2 NO_x and CO_2e emission factors in ng/J energy input at 750, 785 and 825 BHP vs. Lambda.

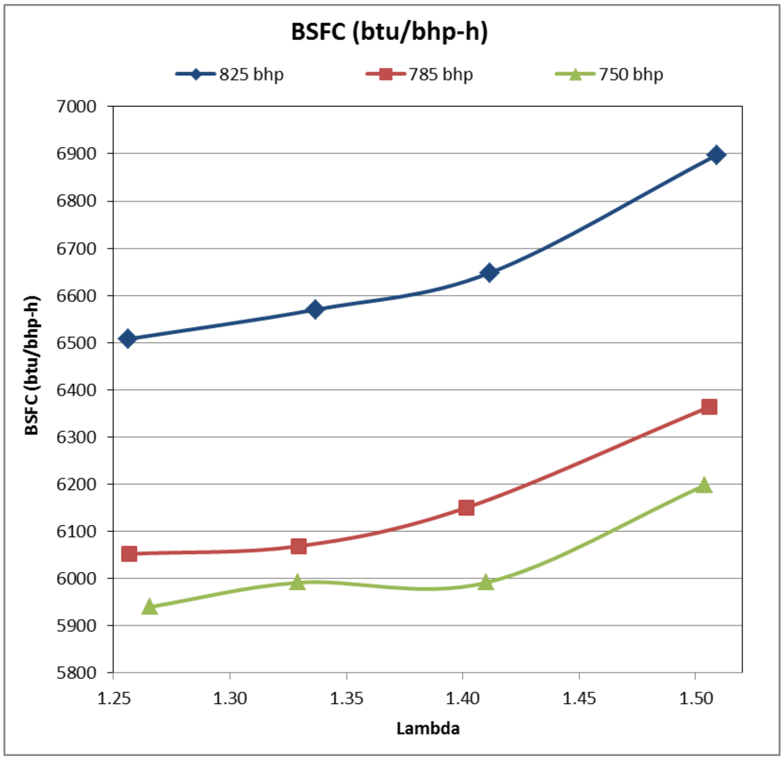


Figure 3-10: Test Engine 2 BSFC at 750, 785 and 825 BHP vs. Lambda.

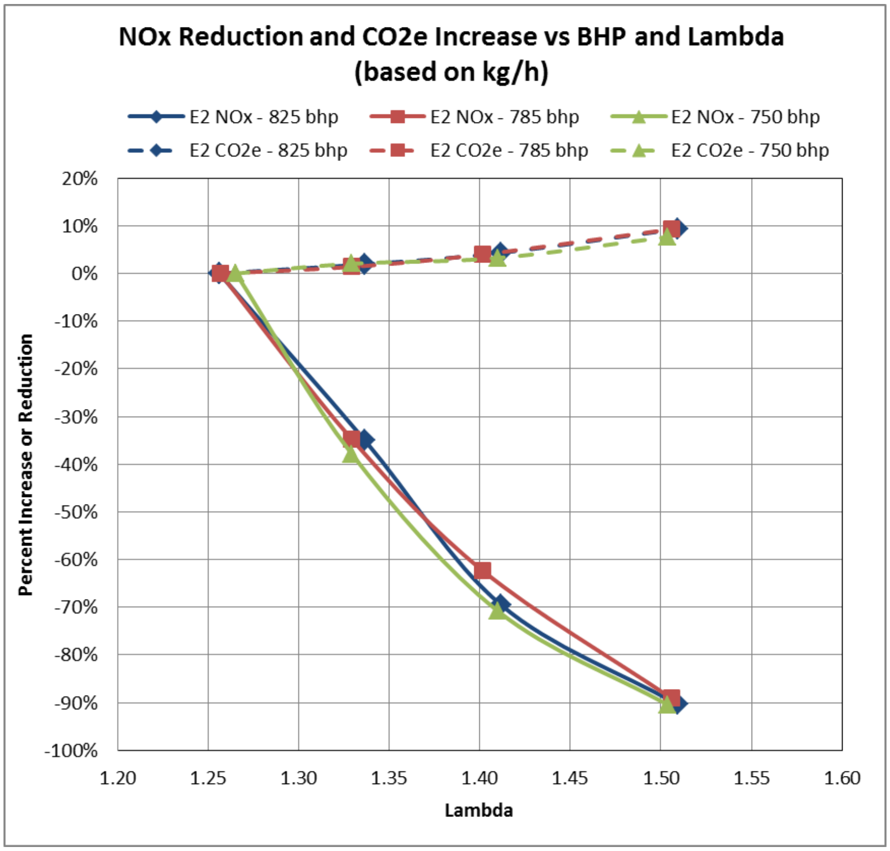


Figure 3-11: Test Engine 2 NO_x reduction and CO_2e increase at 750, 785 and 825 BHP vs. Lambda.

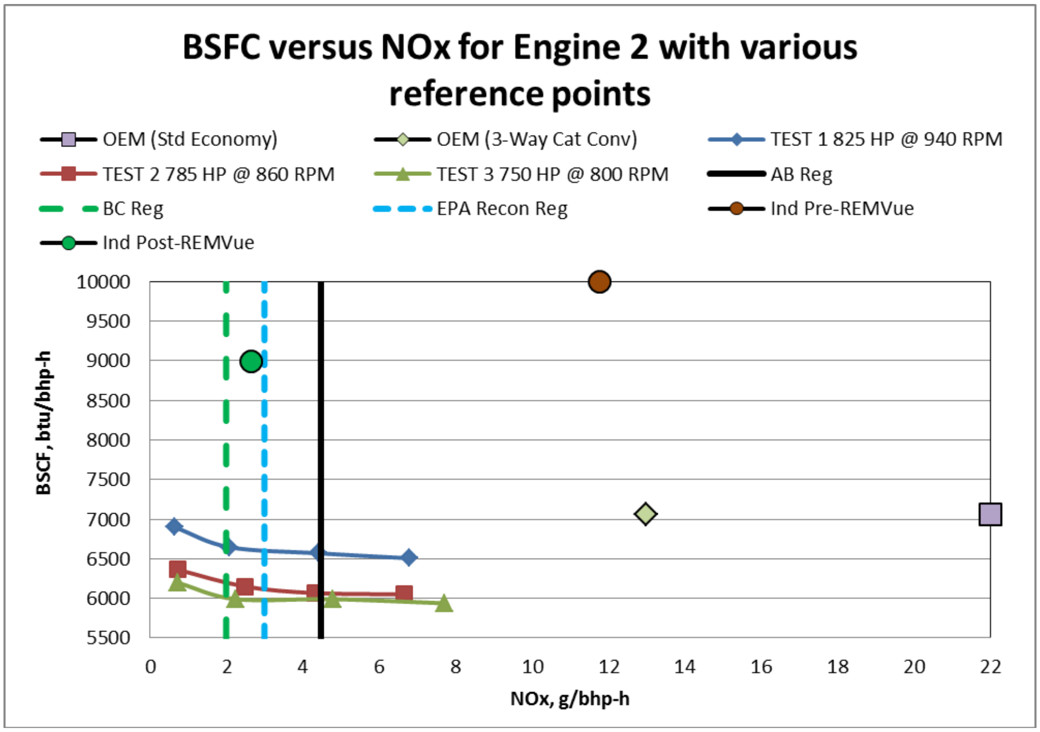


Figure 3-12: Test Engine 2 BSFC versus NO_x for test run 1 to 3 at various values of Lambda.

Table 3-6: Summary of Test Engine 2 recorded operating data, measured operating and emission data and calculated results.

Test Engine 2	**Engine: Waukesha L7042GSI**			**Maximum Rated Power: 1100 bhp @ 1000 rpm**									
TEST RUN		**TEST 1 825 HP @ 940 RPM**				**TEST 2 785 HP @ 860 RPM**				**TEST 3 750 HP @ 800 RPM**			
	Unit	**1A**	**1B**	**1C**	**1D**	**2A**	**2B**	**2C**	**2D**	**3A**	**3B**	**3C**	**3D**
Inlet Temp	C	35.65	34.80	33.65	33.50	35.25	34.10	33.55	33.95	35.60	34.60	33.80	33.60
Exhaust Temp	C	577.7	574.4	575.4	582.0	559.7	552.9	554.1	560.0	546.6	540.8	539.0	546.0
Manifold Pressure	PSI	2.40	1.00	0.10	-0.40	1.80	0.40	-0.30	-0.75	1.90	0.70	-0.10	-0.55
Speed	RPM	940	940	940	940	860	860	860	860	800	800	800	800
Flue Gas (measured)													
Lambda	-	1.51	1.41	1.34	1.26	1.51	1.40	1.33	1.26	1.50	1.41	1.33	1.27
O_2	%	8.0	7.0	6.1	5.0	8.0	6.9	6.0	5.0	8.0	7.0	6.0	5.1
CO	ppm	213	247	256	260	208	236	245	231	203	238	239	229
Total Combustible	ppm	1530	1510	1435	1385	1665	1590	1510	1430	1730	1750	1690	1603
Unburnt Fuel	ppm	1530	1510	1435	1385	1665	1590	1510	1430	1730	1750	1690	1603
NO	ppm	123	528	1293	2188	146	709	1364	2289	152	645	1541	2665
NO_2	ppm	34	60	79	104	43	68	97	121	45	67	101	154
Fuel Mol. Wt.	-	16.48	16.48	16.48	16.48	16.48	16.48	16.48	16.48	16.48	16.48	16.48	16.48
Fuel	e3 sm3/d	4.42	4.26	4.21	4.17	3.88	3.75	3.70	3.69	3.61	3.49	3.49	3.46
Air	e3 sm3/d	62.7	56.5	52.9	49.2	54.9	49.4	46.2	43.6	51.0	46.3	43.6	41.2
Stack Gas (Wet Basis)	e3 sm3/d	67.1	60.8	57.1	53.4	58.8	53.2	50.0	47.3	54.7	49.8	47.1	44.6
Excess Air (%)	%	52.2	42.4	35.0	26.9	51.9	41.5	34.1	26.9	51.8	42.1	33.9	27.6
Exhaust MW	-	28.0	27.9	27.9	27.8	28.0	27.9	27.9	27.8	28.0	27.9	27.9	27.8
Dew Point Temp	°C	50.0	51.2	52.2	53.4	49.9	51.3	52.3	53.3	49.9	51.1	52.3	53.1
Emission Factors (based of HHV)													
CO	ng/J	90	98	95	91	88	92	91	80	86	94	88	80
CO_2	ng/J	48030	48101	48202	48291	47945	48067	48171	48282	47906	47960	48071	48183
CO_2e	ng/J	56296	55737	55103	54583	56904	56039	55366	54763	57180	56730	56064	55420
Methane	ng/J	370	340	305	276	403	356	319	285	418	394	357	321
Ethane	ng/J	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Total VOC	ng/J	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Hydrocarbons	ng/J	372	342	307	277	405	358	321	286	420	396	359	323
N_2O	ng/J	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
NO	ng/J	56	223	516	817	66	298	541	854	69	272	610	1000
NO_2	ng/J	24	39	48	60	30	44	59	69	31	43	61	89
Total Oxides of Nitrogen	ng/J	80	262	564	876	96	341	599	923	100	316	671	1089
Non-CO_2 CO_2e	%	0.14683	0.137	0.12524	0.11527	0.15744	0.14226	0.12995	0.11835	0.16219	0.15459	0.14257	0.13058
Stack Gas (calculated on dry basis)													
CO_2	mole frac.	0.0721	0.0776	0.0824	0.0882	0.0721	0.0781	0.0829	0.0882	0.0721	0.0775	0.0828	0.0875
N_2	mole frac.	0.8460	0.8501	0.8536	0.8578	0.8458	0.8503	0.8539	0.8577	0.8458	0.8498	0.8536	0.8568
O_2	mole frac.	0.0800	0.0700	0.0610	0.0500	0.0800	0.0690	0.0600	0.0500	0.0800	0.0700	0.0600	0.0510
CO	mole frac.	0.0002	0.0002	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
NO	mole frac.	0.0001	0.0005	0.0013	0.0022	0.0001	0.0007	0.0014	0.0023	0.0002	0.0006	0.0015	0.0027
NO_2	mole frac.	0.0000	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001	0.0001	0.0000	0.0001	0.0001	0.0002
Methane	mole frac.	0.0015	0.0015	0.0014	0.0014	0.0017	0.0016	0.0015	0.0014	0.0017	0.0017	0.0017	0.0016
Ethane	mole frac.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 3-6: Summary of Test Engine 2 recorded operating data, measured operating and emission data and calculated results.

Test Engine 2	**Engine: Waukesha L7042GSI**			**Maximum Rated Power: 1100 bhp @ 1000 rpm**									
TEST RUN		**TEST 1 825 HP @ 940 RPM**				**TEST 2 785 HP @ 860 RPM**				**TEST 3 750 HP @ 800 RPM**			
	Unit	**1A**	**1B**	**1C**	**1D**	**2A**	**2B**	**2C**	**2D**	**3A**	**3B**	**3C**	**3D**
Propane	mole frac.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Output Values													
BHP	hp	825	825	825	825	785	785	785	785	750	750	750	750
AFR	-	14.19	13.27	12.57	11.81	14.15	13.18	12.50	11.81	14.14	13.26	12.50	11.90
AFR_{STOIC}	-	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40
Lambda	-	1.51	1.41	1.34	1.26	1.51	1.40	1.33	1.26	1.50	1.41	1.33	1.27
BSFC (LHV)	btu/bhp-h	6898	6648	6570	6507	6363	6150	6068	6052	6197	5991	5991	5939
NO_x	(g/bhp-h)	0.66	2.07	4.41	6.79	0.73	2.50	4.33	6.65	0.74	2.25	4.79	7.70
CO_2	(g/bhp-h)	395	381	377	374	363	352	348	348	354	342	343	341
CH_4	(g/bhp-h)	3.04	2.69	2.39	2.14	3.05	2.61	2.31	2.05	3.09	2.81	2.55	2.27
N_2O	(g/bhp-h)	0.013	0.013	0.013	0.012	0.012	0.012	0.012	0.012	0.012	0.011	0.011	0.011
CO_2e	(g/bhp-h)	462.5	441.3	431.2	423.0	431.3	410.5	400.1	394.7	422.0	404.8	400.0	392.0
Methane (% of total CO_2e)	%	13.8%	12.8%	11.6%	10.6%	14.9%	13.3%	12.1%	10.9%	15.4%	14.6%	13.4%	12.2%
Fuel HHV	MJ/m3	36.8											
Fuel LHV	MJ/m3	32.6											
Emissions													
CO_2	kg/h	325.5	314.2	311.2	308.8	285.2	276.4	273.3	273.2	265.2	256.6	257.2	255.6
CH_4	kg/h	2.51	2.22	1.97	1.76	2.40	2.05	1.81	1.61	2.31	2.11	1.91	1.70
N_2O	kg/h	0.011	0.010	0.010	0.010	0.010	0.009	0.009	0.009	0.009	0.009	0.009	0.008
CO_2e	kg/h	381.5	364.1	355.7	349.0	338.5	322.2	314.1	309.8	316.5	303.6	300.0	294.0
NO	kg/h	0.38	1.46	3.33	5.22	0.39	1.71	3.07	4.83	0.38	1.46	3.26	5.31
NO_2	kg/h	0.16	0.25	0.31	0.38	0.18	0.25	0.33	0.39	0.17	0.23	0.33	0.47
NO_x	kg/h	0.54	1.71	3.64	5.61	0.57	1.97	3.40	5.22	0.55	1.69	3.59	5.78
CO	kg/h	0.16	0.25	0.31	0.38	0.18	0.25	0.33	0.39	0.17	0.23	0.33	0.47

3.3.3 Test Engine 3

This engine was tested at load conditions of 1069 to 1022 bhp, the first at ten Lambda values and the second at four Lambda values. Results are summarized in Figure 3-13 to Figure 3-18 based on results presented in Table 3-7. NO_x results for both tests appear to be acceptable but the CO_2e results at 1022 bhp appear to be inconsistent and should be viewed with caution.

NO_x emission rates vary with load as expected, even for the tests at 1022 bhp. CO_2e results are inconsistent. The proper trend is indicated by the tests at 1069 bhp but the results at 1022 bhp are inconsistent suggesting some measurement errors or operational problem related to turbo limitations and high values of Lambda. Test results at 1022 bhp should be ignored. THC and CO values appear to be in line with expected values for both conditions. This engine meets the 4.48 g/bhp-h emission levels at a Lambda value of about 1.43 and did not achieve NO_x levels less than about 4 g/bhp-h.

NO_x and CO_2e emission factors expressed in ng/J are not consistent for this engine. The test series at 1069 bhp appears to be okay but the series at 1022 bhp indicates an erratic and incorrect trend. A review of the data and discussions with the field personnel including PIC and the site operator did not identify the problem with the CO_2e results for this test.

For this engine, non-CO_2 CO_2e (associated with CH_4 and N_2O) accounts for 12.3%. (CH_4 = 11.4%) of total CO_2e with a STDEV of 0.9 percentage points.

Figure 3-17 shows the potential CO_2e penalty (CO_2e % increase) as NO_x emissions (NO_x % Reduction) are reduced by increasing Lambda. The base case is the lowest Lambda tested (about 1.22) and achieving a NO_x emission level of 4.48 g/bhp-h resulted in a CO_2e penalty of about 3%.

Figure 3-18 shows BSFC verses NO_x in the context of regulatory, OEM and industry reference points. This engine did not seem to exhibit a BSFC inflection point most likely due to the inability of the turbos to push enough air to reach higher values of Lambda and meet NO_x emission levels much below 4 g/bhp-h. Engine performance is comparable to OEM and better than industry average reference points.

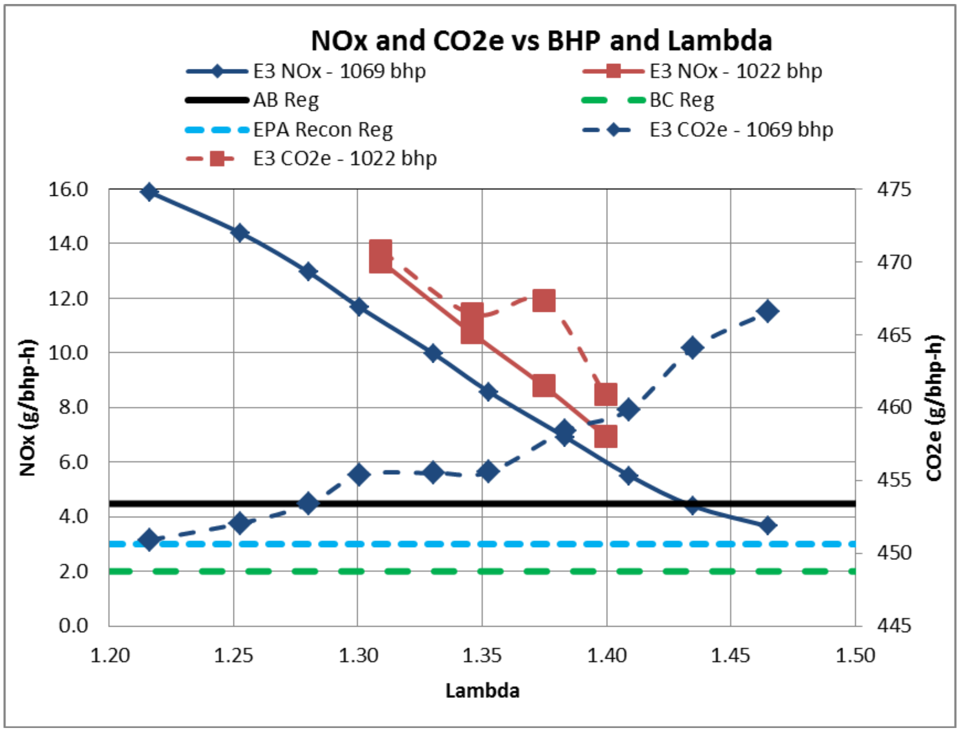


Figure 3-13: Test Engine 3 NO_x and CO_2e emission in g/bhp-h at 1022 and 1069 BHP vs. Lambda.

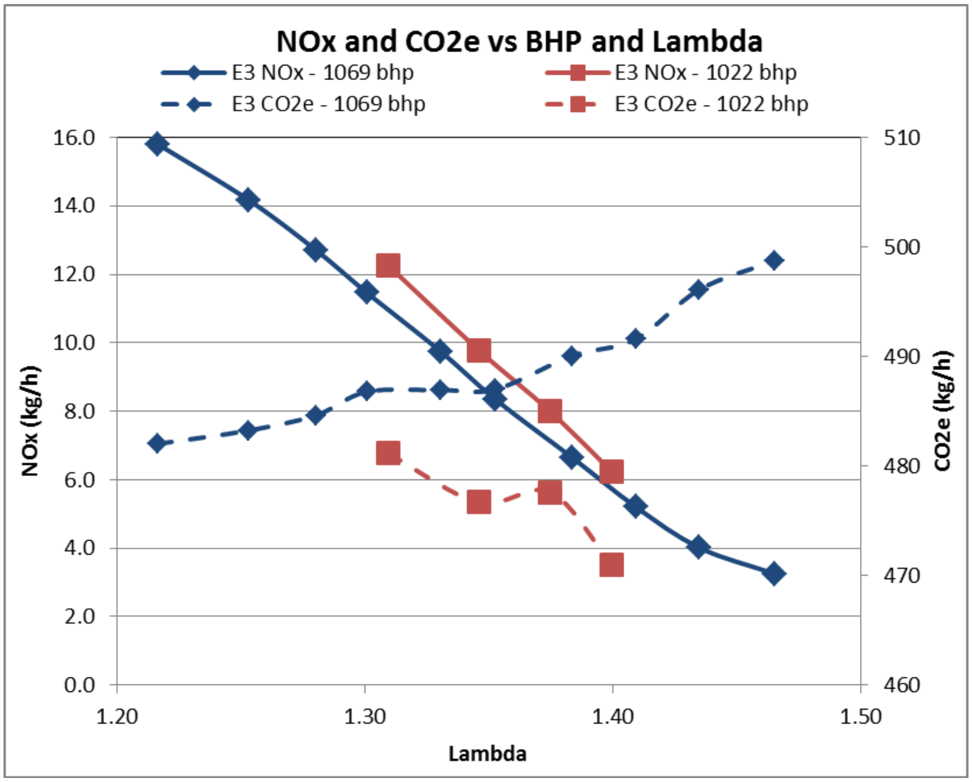


Figure 3-14: Test Engine 3 NO_x and CO_2e emissions in kg/h at 1022 and 1069 BHP vs. Lambda.

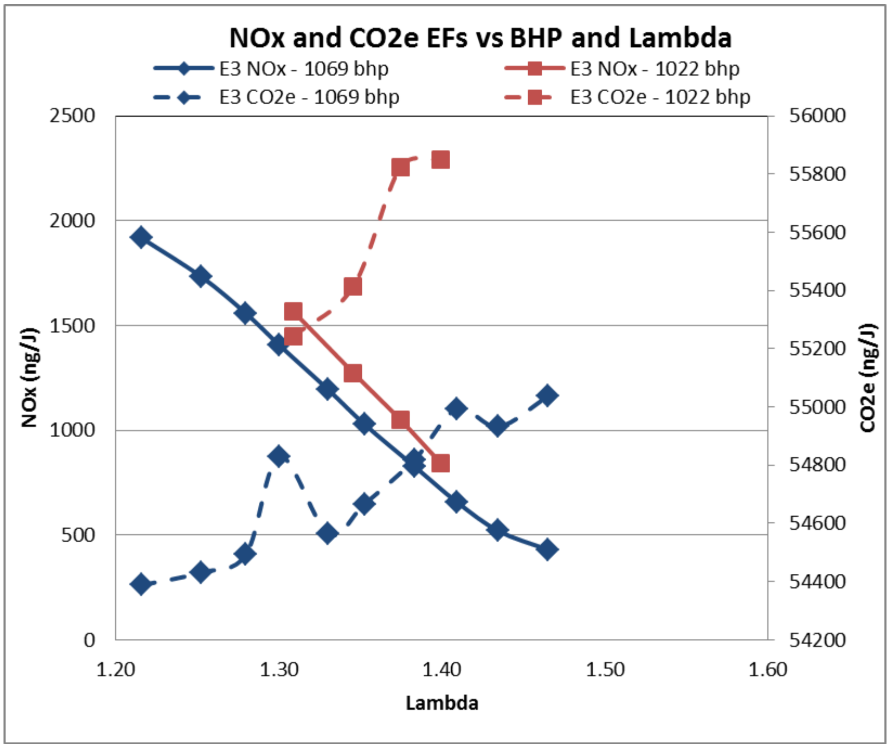


Figure 3-15: Test Engine 3 NO$_x$ and CO$_2$e emission factors in ng/J energy input at 1022 and 1069 BHP vs. Lambda.

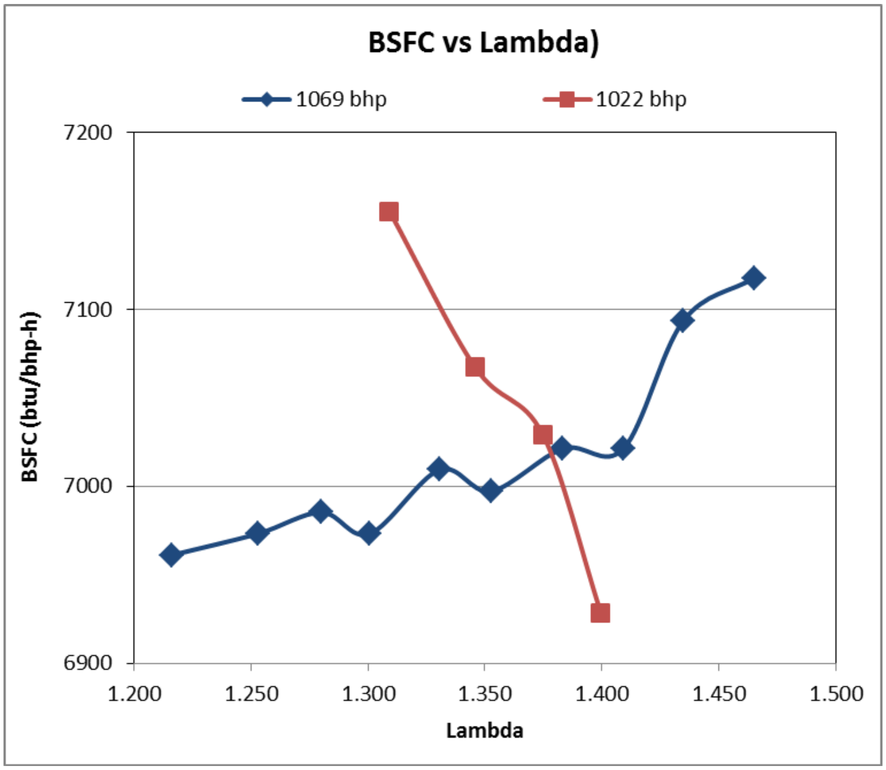


Figure 3-16: Test Engine 3 BSFC at 1022 and 1069 BHP vs. Lambda.

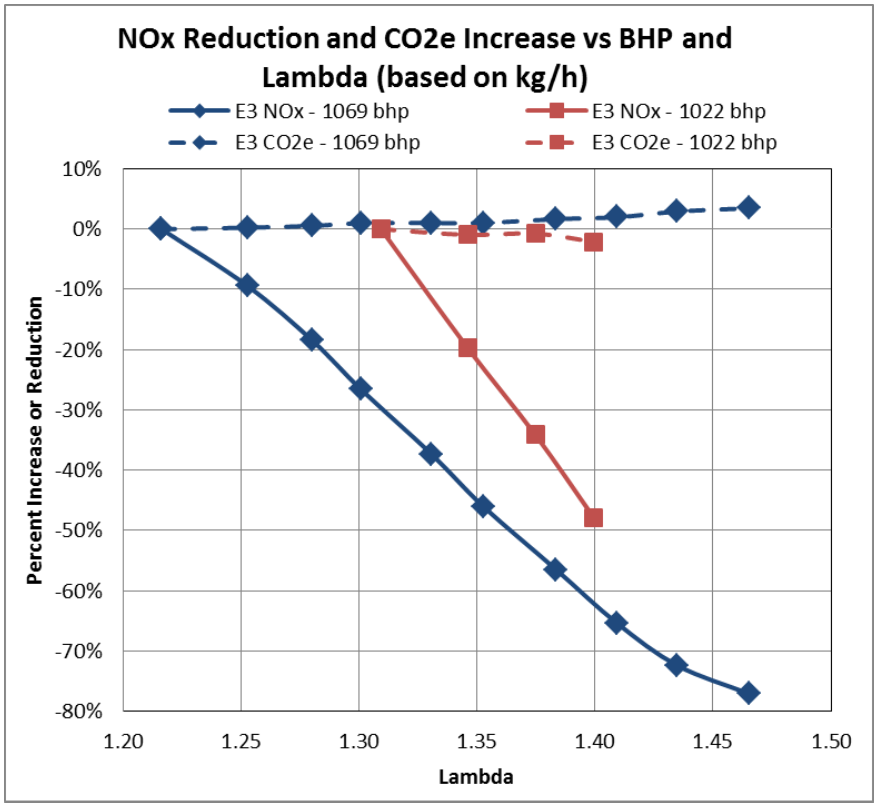


Figure 3-17: Test Engine 3 NO_x reduction and CO_2e Increase at 1022 and 1069 BHP vs. Lambda.

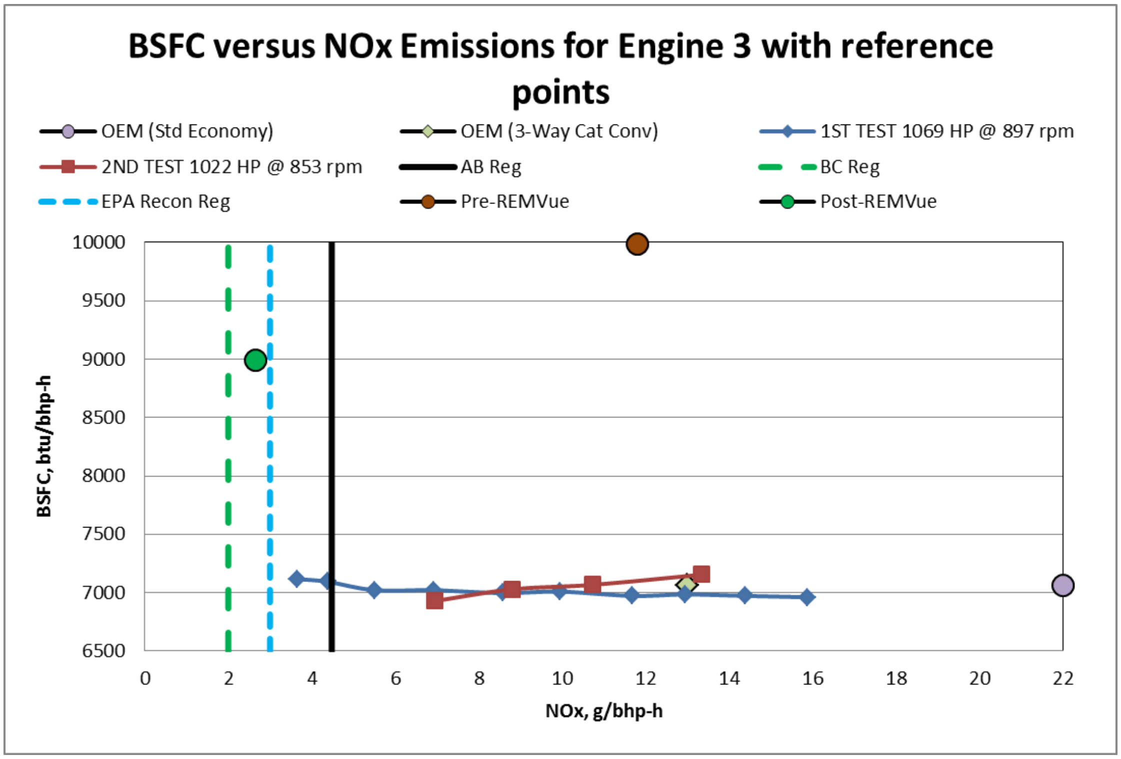


Figure 3-18: Test Engine 3 BSFC versus NO_x for test 1 and 2 at various values of Lambda.

Table 3-7: Summary of Test Engine 3 recorded operating data, measured operating and emission data and calculated results.

Test Engine 3	**Engine: Waukesha L7042GSI**	**Maximum Rated Power: 1100 bhp @ 1000 rpm**													
TEST RUN		**1ST TEST 1069 HP @ 897 rpm**										**2ND TEST 1022 HP @ 853 rpm**			
	Unit	**1A**	**1B**	**1C**	**1D**	**1E**	**1F**	**1G**	**1H**	**1J**	**1K**	**2A**	**2B**	**2C**	**2D**
Inlet Temp	C	60.00	60.30	59.90	59.30	58.50	57.60	57.20	56.90	56.25	55.75	57.80	58.90	58.90	59.00
Exhaust Temp	C	598.9	600.1	601.5	604.3	606.7	608.9	612.7	615.4	619.7	626.7	589.6	593.8	597.7	603.4
Manifold Pressure	PSI	8.15	7.75	7.50	6.85	6.45	6.15	5.65	5.45	5.15	4.65	7.00	6.95	6.65	6.30
Speed	RPM	898	894	895	894	898	900	898	897	899	899	853	852	850	851
Flue Gas (measured)															
Lambda	-	1.47	1.43	1.41	1.38	1.35	1.33	1.30	1.28	1.25	1.22	1.40	1.37	1.35	1.31
O_2	%	7.3	7.0	6.7	6.4	6.0	5.7	5.3	5.0	4.6	4.0	6.6	6.3	5.9	5.4
CO	ppm	342	341	340	330	321	309	300	285	275	263	311.0	302.0	289.0	275.0
Total Combustible	ppm	1320	1320	1360	1340	1330	1330	1430	1360	1370	1400	1580.0	1600.0	1530.0	1530.0
Unburnt Fuel	ppm	1320	1320	1360	1340	1330	1330	1430	1360	1370	1400	1580.0	1600.0	1530.0	1530.0
NO	ppm	828	1045	1398	1821	2349	2789	3382	3808	4352	5030	1790.0	2305.0	2873.0	3665.0
NO_2	ppm	107	115	119	133	152	170	195	221	241	245	163.0	186.0	225.0	268.0
Fuel Mol. Wt.	-	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
Fuel	e3 sm3/d	5.91	5.89	5.83	5.83	5.81	5.82	5.79	5.80	5.79	5.78	5.5	5.6	5.6	5.7
Air	e3 sm3/d	80.53	78.6	76.41	75.01	73.09	72.02	70.04	69.05	67.46	65.38	71.6	71.3	70.2	69.2
Stack Gas (Wet Basis)	e3 sm3/d	86.46	84.5	82.26	80.85	78.91	77.86	75.85	74.86	73.25	71.17	77.1	76.9	75.8	74.9
Excess Air (%)	%	45.8	43.0	40.4	38.0	34.8	32.6	29.6	27.6	25.0	21.1	39.3	36.9	34.0	30.4
Exhaust MW	-	27.9	27.9	27.9	27.9	27.9	27.8	27.8	27.8	27.8	27.8	27.9	27.9	27.8	27.8
Dew Point Temp	°C	51.1	51.4	51.7	52.1	52.3	52.8	53.1	53.4	53.8	54.4	51.8	52.2	52.6	53.0
Emission Factors															
CO	ng/J	138	135	132	126	119	113	107	100	94	87	120	114	107	99
CO_2	ng/J	48135	48157	48154	48191	48227	48251	48223	48286	48307	48327	48046	48060	48135	48174
CO_2e	ng/J	55036	54932	54992	54819	54666	54564	54830	54494	54431	54388	55850	55822	55414	55243
Methane	ng/J	305	299	302	292	283	277	291	272	268	265	348	346	323	313
Ethane	ng/J	1.4	1.4	1.4	1.4	1.3	1.3	1.4	1.3	1.2	1.2	1.6	1.6	1.5	1.5
Total VOC	ng/J	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Hydrocarbons	ng/J	307	300	303	293	284	279	293	274	269	266	350	348	325	315
N_2O	ng/J	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
NO	ng/J	359	444	582	744	936	1091	1291	1429	1597	1783	739	934	1137	1408
NO_2	ng/J	71	75	76	83	93	102	114	127	136	133	103	116	137	158
Total Oxides of Nitrogen	ng/J	430	519	658	827	1029	1193	1405	1557	1732	1916	842	1050	1274	1566
Non-CO_2 CO_2e	%	12.5%	12.3%	12.4%	12.1%	11.8%	11.6%	12.0%	11.4%	11.3%	11.1%	14.0%	13.9%	13.1%	12.8%
Stack Gas (calculated on dry basis)															
CO_2	mole frac.	0.07572	0.07733	0.07890	0.08046	0.08254	0.08409	0.08614	0.08770	0.08978	0.09294	0.07932	0.08084	0.08292	0.08547
N_2	mole frac.	0.84868	0.84985	0.85089	0.85192	0.85331	0.85431	0.85555	0.85662	0.85798	0.86012	0.85084	0.85176	0.85317	0.85479
O_2	mole frac.	0.07300	0.07000	0.06700	0.06400	0.06000	0.05700	0.05300	0.05000	0.04600	0.04000	0.06600	0.06300	0.05900	0.05400
CO	mole frac.	0.00034	0.00034	0.00034	0.00033	0.00032	0.00031	0.00030	0.00029	0.00028	0.00026	0.00031	0.00030	0.00029	0.00028
NO	mole frac.	0.00083	0.00105	0.00140	0.00182	0.00235	0.00279	0.00338	0.00381	0.00435	0.00503	0.00179	0.00231	0.00287	0.00367
NO_2	mole frac.	0.00011	0.00012	0.00012	0.00013	0.00015	0.00017	0.00020	0.00022	0.00024	0.00025	0.00016	0.00019	0.00023	0.00027
Methane	mole frac.	0.00132	0.00132	0.00136	0.00134	0.00133	0.00133	0.00143	0.00136	0.00137	0.00140	0.00158	0.00160	0.00153	0.00153
Ethane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Propane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table 3-7: Summary of Test Engine 3 recorded operating data, measured operating and emission data and calculated results.

Test Engine 3	**Engine: Waukesha L7042GSI**		**Maximum Rated Power: 1100 bhp @ 1000 rpm**												
TEST RUN		**1ST TEST 1069 HP @ 897 rpm**										**2ND TEST 1022 HP @ 853 rpm**			
	Unit	**1A**	**1B**	**1C**	**1D**	**1E**	**1F**	**1G**	**1H**	**1J**	**1K**	**2A**	**2B**	**2C**	**2D**
Output Values															
BHP	hp	1069	1069	1069	1069	1069	1069	1069	1069	1069	1069	1022	1022	1022	1022
AFR	-	13.63	13.34	13.11	12.87	12.58	12.37	12.10	11.91	11.65	11.31	13.02	12.78	12.52	12.18
AFR_{STOIC}	-	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3
Lambda	-	1.47	1.43	1.41	1.38	1.35	1.33	1.30	1.28	1.25	1.22	1.40	1.37	1.35	1.31
BSFC (LHV)	btu/bhp-h	7118	7094	7021	7021	6997	7009	6973	6985	6973	6961	6929	7029	7067	7155
NOx	(g/bhp-h)	3.6	4.4	5.5	6.9	8.6	10.0	11.7	13.0	14.4	15.9	6.9	8.8	10.7	13.3
CO_2	(g/bhp-h)	408	407	403	403	402	403	400	402	401	401	396	402	405	411
CH_4	(g/bhp-h)	2.6	2.5	2.5	2.4	2.4	2.3	2.4	2.3	2.2	2.2	2.9	2.9	2.7	2.7
N_2O	(g/bhp-h)	0.014	0.014	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.014
CO_2e	(g/bhp-h)	466.5	464.1	459.9	458.4	455.6	455.5	455.4	453.4	452.0	450.9	460.9	467.3	466.4	470.8
Methane (% of total CO_2e)	%	11.6%	11.4%	11.5%	11.2%	10.9%	10.7%	11.1%	10.5%	10.3%	10.2%	13.1%	13.0%	12.2%	11.9%
Fuel HHV	MJ/m3	36.8													
Fuel LHV	MJ/m3	32.6													
Emissions															
CO_2	(kg/h)	436.2	434.9	430.5	430.8	429.6	430.6	428.1	429.4	428.9	428.3	405.2	411.2	414.1	419.6
CH_4	(kg/h)	2.76	2.70	2.70	2.61	2.52	2.47	2.58	2.42	2.38	2.35	2.93	2.96	2.78	2.73
N_2O	(kg/h)	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.013	0.014	0.014	0.014
CO_2e	(kg/h)	498.7	496.1	491.6	490.0	487.0	486.9	486.8	484.6	483.2	482.0	471.0	477.6	476.7	481.1
NO	(kg/h)	3.25	4.01	5.20	6.65	8.34	9.74	11.46	12.71	14.18	15.80	6.23	7.99	9.78	12.26
NO_2	(kg/h)	0.64	0.68	0.68	0.74	0.83	0.91	1.01	1.13	1.21	1.18	0.87	0.99	1.18	1.38
NO_x	(kg/h)	3.90	4.69	5.88	7.39	9.17	10.65	12.47	13.85	15.38	16.98	7.10	8.98	10.96	13.64
CO	(kg/h)	1.25	1.22	1.18	1.13	1.06	1.01	0.95	0.89	0.83	0.77	1.01	0.98	0.92	0.86

3.3.4 Test Engine 4

This engine was tested at 1106 bhp and thirteen Lambda values. Results are summarized in Figure 3-19 to Figure 3-24 and tabulated in Table 3-8.

NO_x results at Lambda 1.3 suggest that the engine may be in transition to its maximum NO_x condition. In general, the test results are consistent with expected trends. This engine meets the 4.48, 3.0 and 2.0 g/bhp-h emission levels at Lambda values of about 1.45, 1.48 and 1.52, respectively.

NO_x and CO_2e emission factors expressed in ng/J are reasonably consistent for all tests. For this engine, non-CO_2 CO_2e (associated with CH_4 and N_2O) accounts for 5.6%. (CH_4 = 4.7%) of total CO_2e with a STDEV of 0.3 percentage points. However, it is noted that the ECOM THC component failed and no THC data was available for test engine 4. A constant value of 500 ppm was applied when calculating results for all tests. The CO values appear to be in line with the rest of the data which shows no significant trend.

Figure 3-23 shows the potential CO_2e penalty (CO_2e % increase) as NO_x emissions (NO_x % Reduction) are reduced by increasing Lambda. The base case is the lowest Lambda tested (about 1.3) and achieving NO_x emission levels of 4.48, 3.0 and 2.0 g/bhp-h resulted in CO_2e penalties of about 2%, 3% and 4.5%, respectively.

Figure 3-24: shows BSFC verses NO_x in the context of regulatory, OEM and industry reference points. This engine exhibits a BSFC inflection point between 2 – 3 g/bhp-h and preforms better than industry average reference points. It operates at a higher BSFC than the OEM reference points

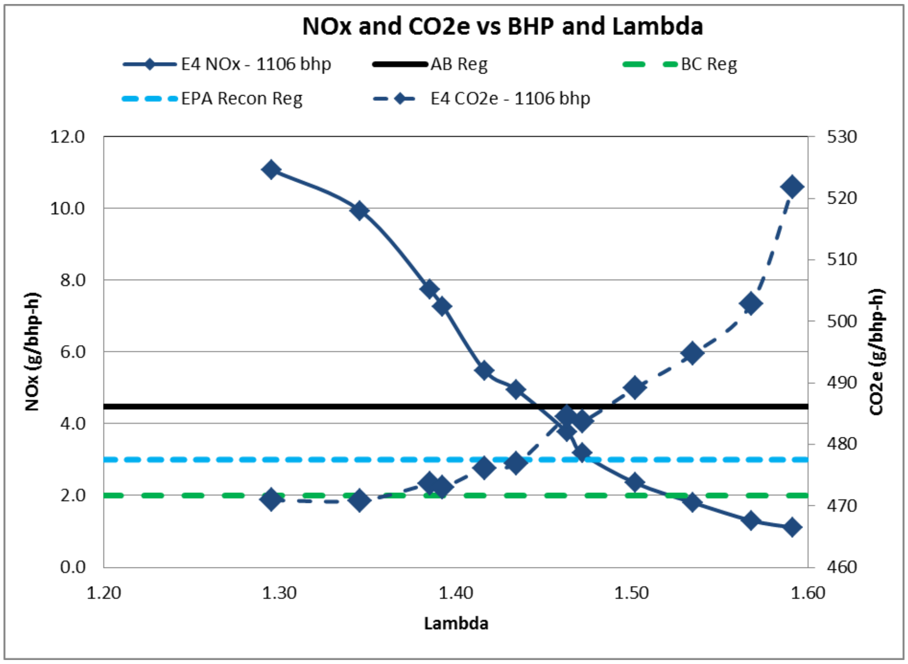


Figure 3-19: Test Engine 4 NO_x and CO_2e emission in g/bhp-h at 1106 BHP vs. Lambda.

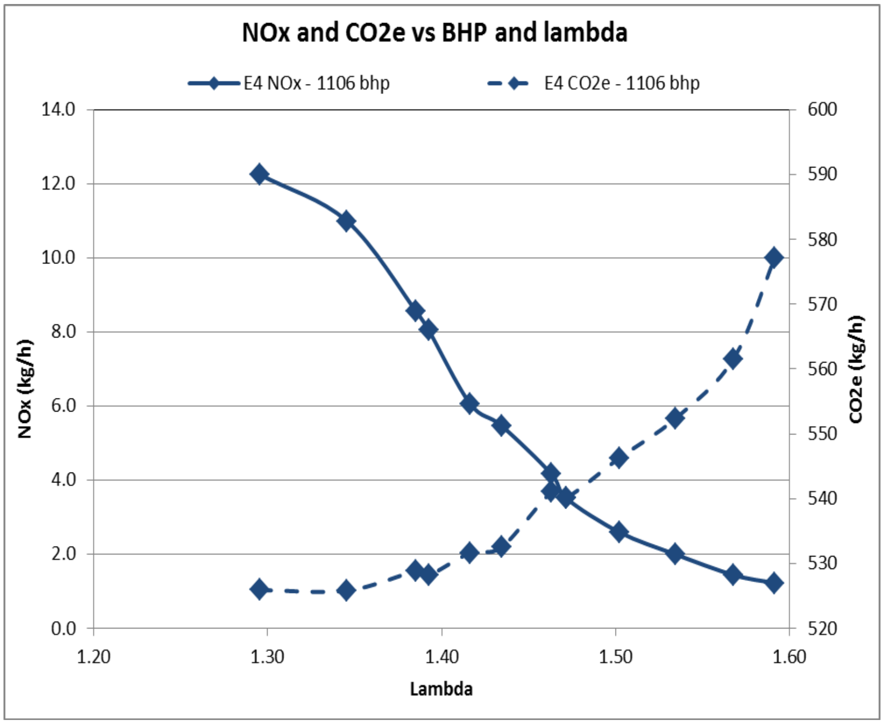


Figure 3-20: Test Engine 4 NO$_x$ and CO$_2$e emissions in kg/h at 1106 BHP vs. Lambda.

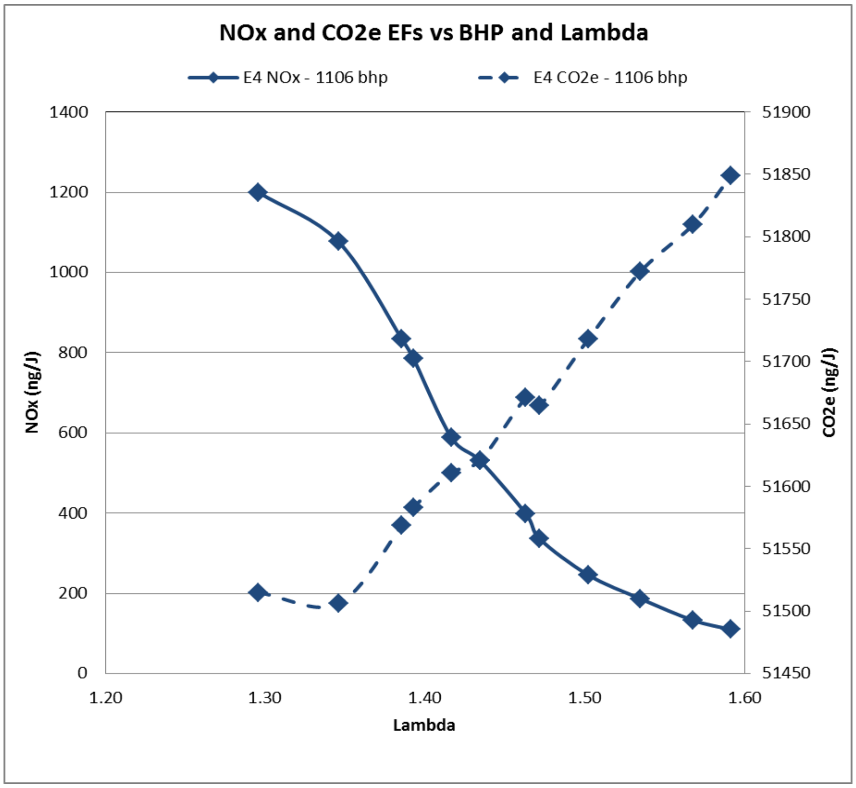


Figure 3-21: Test Engine 4 NO$_x$ and CO$_2$e emission factors in ng/J energy input at 1106 BHP vs. Lambda.

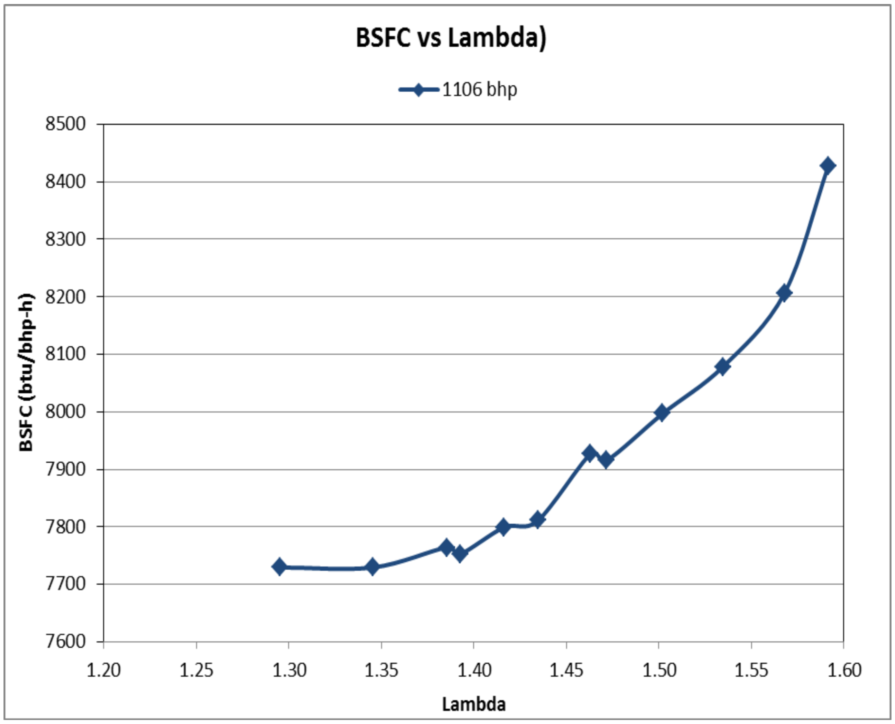


Figure 3-22: Test Engine 4 BSFC at 1106 BHP vs. Lambda.

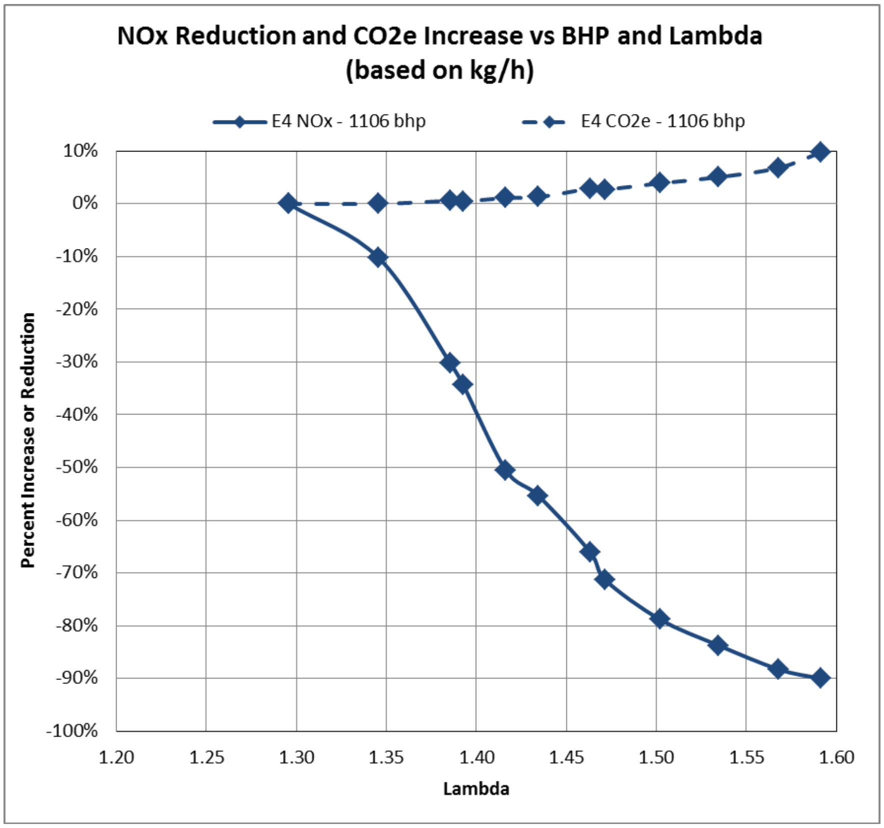


Figure 3-23: Test Engine 4 NO_x reduction and CO_2e Increase at 1106 BHP vs. Lambda

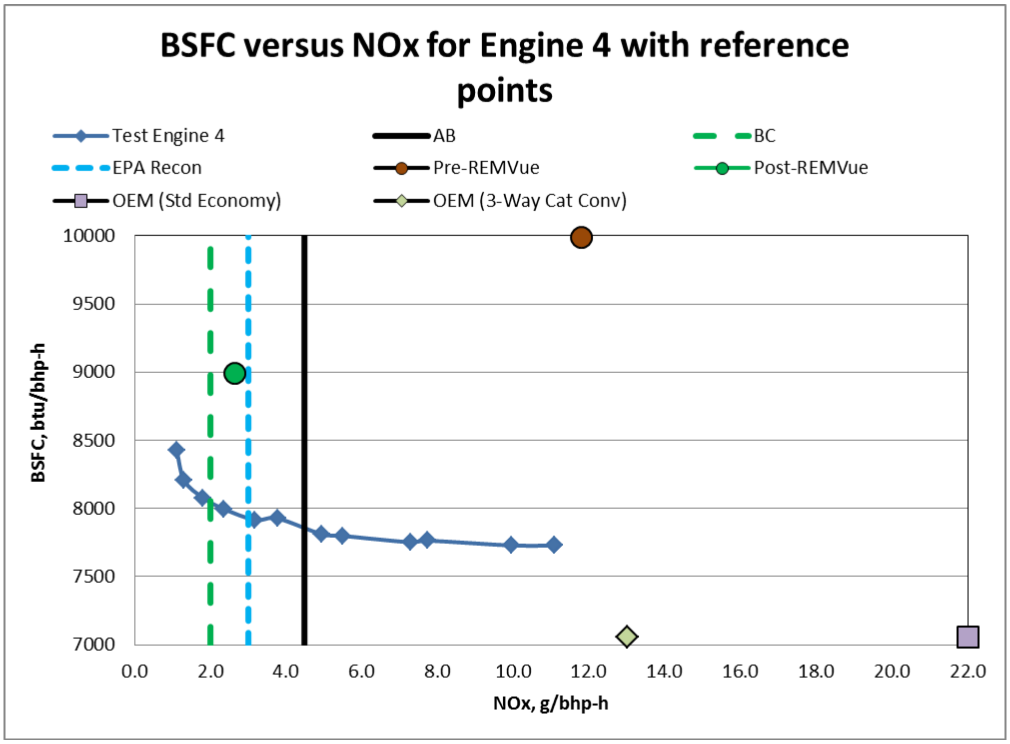


Figure 3-24: Test Engine 4 BSFC versus NO$_x$ at various values of Lambda and noted reference points.

Table 3-8: Summary of Test Engine 4 recorded operating data, measured operating and emission data and calculated results.

Test Engine 4	**Engine: Waukesha L7042GSI**			**Maximum Rated Power: 1100 bhp @ 1000 rpm**										
TEST RUN	**Unit**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Inlet Temp	C	56.95	54.85	53.00	51.75	51.10	50.80	50.00	49.90	49.50	50.20	49.90	49.65	49.35
Exhaust Temp	C	510.0	511.4	514.3	517.1	520.5	522.9	527.0	529.3	533.3	534.1	539.5	542.5	550.0
Manifold Pressure	PSI	12.16	11.21	10.12	9.44	8.96	8.72	8.12	7.86	7.37	7.29	6.80	6.73	6.45
Speed	RPM	995	995	992	999	993	994	992	995	997	996	990	992	997
Stack Gas (measured)														
Lambda	-	1.59	1.57	1.53	1.50	1.47	1.46	1.43	1.42	1.39	1.39	1.35	1.34	1.30
O_2	%	8.5	8.3	8.0	7.7	7.4	7.3	7.0	6.8	6.5	6.4	5.9	5.8	5.2
CO	ppm	202	209	219	221	221	217	211	203	193	186	173	161	153
Total Combustible	ppm	500	500	500	500	500	500	500	500	500	500	500	500	500
Unburnt Fuel	ppm	500	500	500	500	500	500	500	500	500	500	500	500	500
NO	ppm	168	213	319	449	657	806	1117	1259	1736	1839	2444	2727	3661
NO_2	ppm	41	46	57	64	69	68	78	88	104	120	165	191	249
Fuel Mol. Wt.	-	16.46	16.46	16.46	16.46	16.46	16.46	16.46	16.46	16.46	16.46	16.46	16.46	16.46
Fuel	e3 sm3/d	7.240	7.050	6.940	6.870	6.800	6.810	6.710	6.700	6.660	6.670	6.640	6.640	6.640
Air	e3 sm3/d	108.3	103.9	100.1	97	94.07	93.66	90.48	89.2	87.18	86.86	83.99	83.63	80.86
Stack Gas (Wet Basis)	e3 sm3/d	115.6	111	107.1	103.9	100.9	100.5	97.2	95.91	93.85	93.55	90.64	90.28	87.51
Excess Air (%)	%	60.0	57.7	54.4	51.2	48.2	47.3	44.5	42.7	40.2	39.4	35.4	34.7	30.4
Exhaust MW	-	28.0	28.0	28.0	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.8	27.8
Dew Point Temp	°C	49.7	49.9	50.2	50.6	50.9	51.1	51.4	51.6	52.0	52.1	52.6	52.7	53.3
Emission Factors (input HHV basis)														
CO	ng/J	90	92	94	93	91	89	84	80	75	72	65	60	55
CO_2	ng/J	48686	48689	48693	48702	48712	48718	48731	48742	48756	48763	48784	48793	48793
CO_2e	ng/J	51849	51810	51772	51718	51665	51671	51621	51611	51583	51569	51506	51515	51515
Methane	ng/J	127	125	123	120	117	117	114	113	111	110	106	106	106
Ethane	ng/J	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.5
Total VOC	ng/J	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Hydrocarbons	ng/J	128	126	123	121	118	117	115	113	111	110	107	106	106
N_2O	ng/J	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
NO	ng/J	80	100	147	202	289	353	479	532	720	758	976	1083	1083
NO_2	ng/J	30	33	40	44	47	46	51	57	66	76	101	116	116
Total Oxides of Nitrogen	ng/J	110	133	187	246	336	398	530	589	786	834	1077	1200	1200
Non-CO_2 CO_2e	%	6.1%	6.0%	5.9%	5.8%	5.7%	5.7%	5.6%	5.6%	5.5%	5.4%	5.3%	5.3%	5.3%
Stack Gas (calculated on dry basis)														
CO_2	mole frac.	0.0694	0.0705	0.0722	0.0738	0.0754	0.0759	0.0775	0.0786	0.0801	0.0807	0.0833	0.0837	0.0868
N_2	mole frac.	0.8447	0.8455	0.8467	0.8480	0.8491	0.8495	0.8506	0.8514	0.8523	0.8527	0.8545	0.8547	0.8566
O_2	mole frac.	0.0850	0.0830	0.0800	0.0770	0.0740	0.0730	0.0700	0.0680	0.0650	0.0640	0.0590	0.0580	0.0520
CO	mole frac.	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
NO	mole frac.	0.0002	0.0002	0.0003	0.0004	0.0007	0.0008	0.0011	0.0013	0.0017	0.0018	0.0024	0.0027	0.0037
NO_2	mole frac.	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0002	0.0002	0.0002
Methane	mole frac.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Ethane	mole frac.	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Propane	mole frac.	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 3-8: Summary of Test Engine 4 recorded operating data, measured operating and emission data and calculated results.

Test Engine 4	**Engine: Waukesha L7042GSI**			**Maximum Rated Power: 1100 bhp @ 1000 rpm**										
TEST RUN	**Unit**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Output Values														
BHP	hp	1106	1106	1106	1106	1106	1106	1106	1106	1106	1106	1106	1106	1106
AFR	-	14.96	14.74	14.43	14.12	13.83	13.75	13.48	13.31	13.09	13.02	12.65	12.59	12.18
AFR$_{STOIC}$	-	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4	9.4
Lambda	-	1.59	1.57	1.53	1.50	1.47	1.46	1.43	1.42	1.39	1.39	1.35	1.34	1.30
BSFC (LHV)	btu/bhp-h	8428	8207	8079	7997	7916	7927	7811	7799	7753	7764	7729	7729	7729
NO$_x$	(g/bhp-h)	1.1	1.3	1.8	2.3	3.2	3.8	4.9	5.5	7.3	7.7	9.9	11.1	11.1
CO$_2$	(g/bhp-h)	490.0	477.2	469.8	465.1	460.5	461.2	454.6	454.0	451.4	452.1	450.3	450.4	450.4
CH$_4$	(g/bhp-h)	1.28	1.23	1.19	1.15	1.11	1.11	1.06	1.05	1.03	1.02	0.98	0.98	0.98
N$_2$O	(g/bhp-h)	0.016	0.016	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015	0.015
CO$_2$e	(g/bhp-h)	521.8	502.9	494.7	489.2	483.7	484.5	476.9	476.1	473.0	473.6	470.9	470.9	470.9
Methane (% of total CO$_2$e)	%	5.1%	5.1%	5.0%	4.9%	4.8%	4.8%	4.7%	4.6%	4.6%	4.5%	4.4%	4.4%	4.4%
Fuel HHV	MJ/m3	36.9												
Fuel LHV	MJ/m3	32.6												
Emissions														
CO$_2$	kg/h	541.9	527.8	519.6	514.4	509.3	510.1	502.7	502.1	499.2	500.1	498.0	498.1	498.1
CH$_4$	kg/h	1.41	1.35	1.31	1.27	1.22	1.23	1.18	1.16	1.14	1.13	1.08	1.08	1.08
N$_2$O	(kg/h)	0.018	0.017	0.017	0.017	0.017	0.017	0.017	0.016	0.016	0.016	0.016	0.016	0.016
CO$_2$e	(kg/h)	577.2	561.6	552.4	546.3	540.2	541.0	532.6	531.7	528.2	528.8	525.8	525.9	525.9
NO	kg/h	0.89	1.08	1.57	2.13	3.02	3.70	4.94	5.48	7.37	7.77	9.96	11.06	11.06
NO$_2$	kg/h	0.33	0.36	0.43	0.46	0.49	0.48	0.53	0.59	0.68	0.78	1.03	1.18	1.18
NO$_x$	kg/h	1.22	1.44	2.00	2.60	3.51	4.17	5.47	6.07	8.05	8.55	11.00	12.25	12.25
CO	kg/h	1.00	1.00	1.00	0.98	0.95	0.93	0.87	0.82	0.77	0.74	0.66	0.61	0.56

3.3.5 **Test Engine 5**

This engine was tested over a load range of 1049 to 1366 bhp with five load conditions, the first two with nine Lambdas and the last three with seven Lambda values. Results are summarized in Figure 3-25 to Figure 3-31 and presented in Table 3-9 to Table 3-13.

As indicated by Figure 3-25 and Figure 3-26, NO_x and CO_2e emissions in g/bhp-h and kg/h are reasonable with respect to expected trends and behaviour. In Figure 3-27, NO_x emission factors trend well and are consistent. However, CO_2e emission factors, especially for Seq 2 and Seq 3, exhibit some erratic behaviour.

NO_x emission rates vary with load and temperatures and at very lean conditions trend to closer together as can be seen in and Figure 3-26. This engine meets the 4.48, 3.0 and 2.0 g/bhp-h emission levels at Lambda values between 1.38 and 1.43, 1.42 and 1.48 and 1.47 and 1.53, respectively.

NO_x and CO_2e emission factors expressed in ng/J are reasonably consistent for all tests except those for test sequence 3. It is noted that only one brake power load determination was made for each series so some undocumented variation is inherent in this data.

For this engine, non-CO_2 CO_2e (associated with CH_4 and N_2O) accounts for 2.1%. (CH_4 = 1.0%) of total CO_2e with a STDEV of 0.3 percentage points. These results are the average for all five test sequences.

Figure 3-28 shows that brake specific fuel consumption is not only a function of load but of inlet manifold air temperature. The effect of temperature is discussed later.

Figure 3-29 shows the potential CO_2e penalty (CO_2e % increase) as NO_x emissions (NO_x % Reduction) are reduced by increasing Lambda. The base case is the lowest Lambda tested (about 1.28). Achieving NO_x emission levels of 4.48, 3.0 and 2.0 g/bhp-h resulted in CO_2e penalties of about 1-4%, 2-6% and 4-9%, respectively.

In Figure 3-30, the influence of inlet manifold temperature on NO_x emissions is examined. The data sets were picked from test sequences 1, 2 and 4 where the engine was operating at approximately the same rpm (essentially constant) and load (varied from 1308 to 1366 bhp). The data suggest that increase manifold temperatures consistently result in higher NO_x production for each Lambda setting. As Lambda increases, the adverse influence of temperature appears to be more pronounced.

Figure 3-31 shows BSFC verses NO_x in the context of regulatory, OEM and industry reference points. This engine exhibits a BSFC inflection point at about 3 g/bhp-h and preforms better than industry average reference points. It appears to operate at a higher BSFC than the OEM reference points.

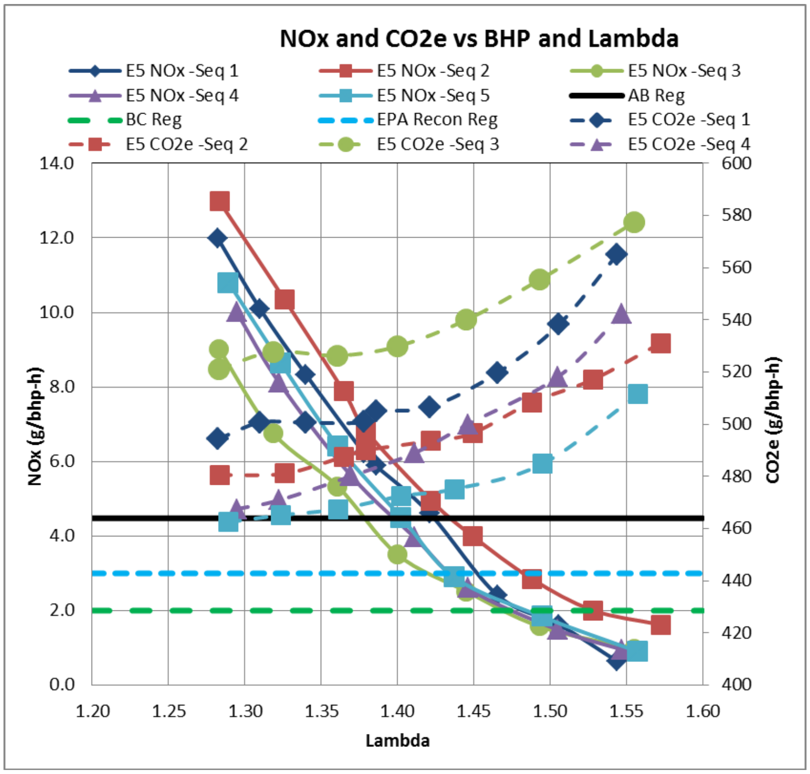


Figure 3-25: Test Engine 5 NO$_x$ and CO$_2$e emissions in g/bhp-h for Seq 1 (1340 bhp), Seq 2 (1366 bhp), Seq 3 (1049 bhp), Seg 4 (1308 bhp) and Seq 5 (1145 bhp) at various Lambda.

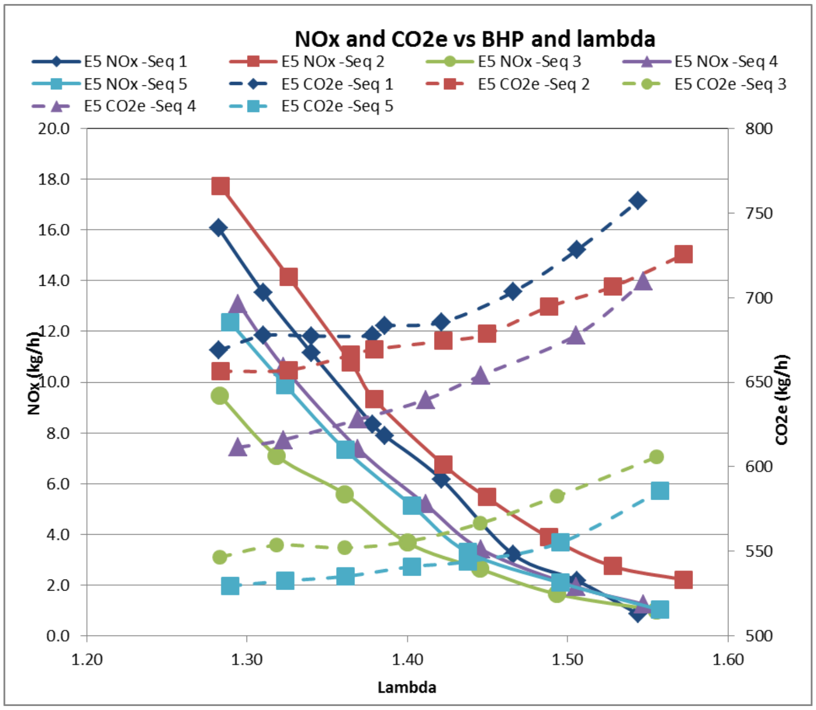


Figure 3-26: Test Engine 5 NO$_x$ and CO$_2$e emissions in kg/h for Seq 1 (1340 bhp), Seq 2 (1366 bhp), Seq 3 (1049 bhp), Seg 4 (1308 bhp) and Seq 5 (1145 bhp) at various Lambda.

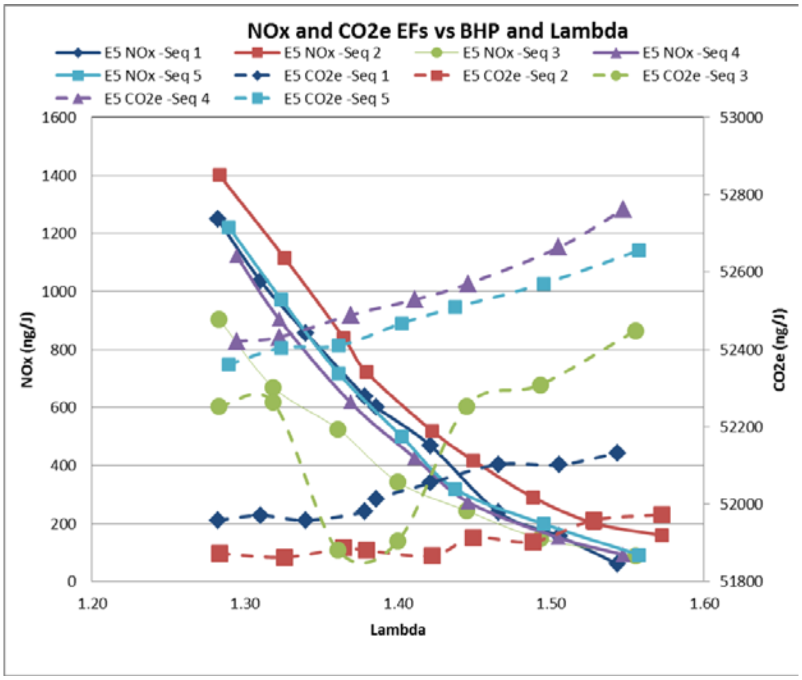


Figure 3-27: Test Engine 5 NO$_x$ and CO$_2$e emission factors in ng/J energy input for Seq 1 (1340 bhp), Seq 2 (1366 bhp), Seq 3 (1049 bhp), Seg 4 (1308 bhp) and Seq 5 (1145 bhp) at various Lambda.

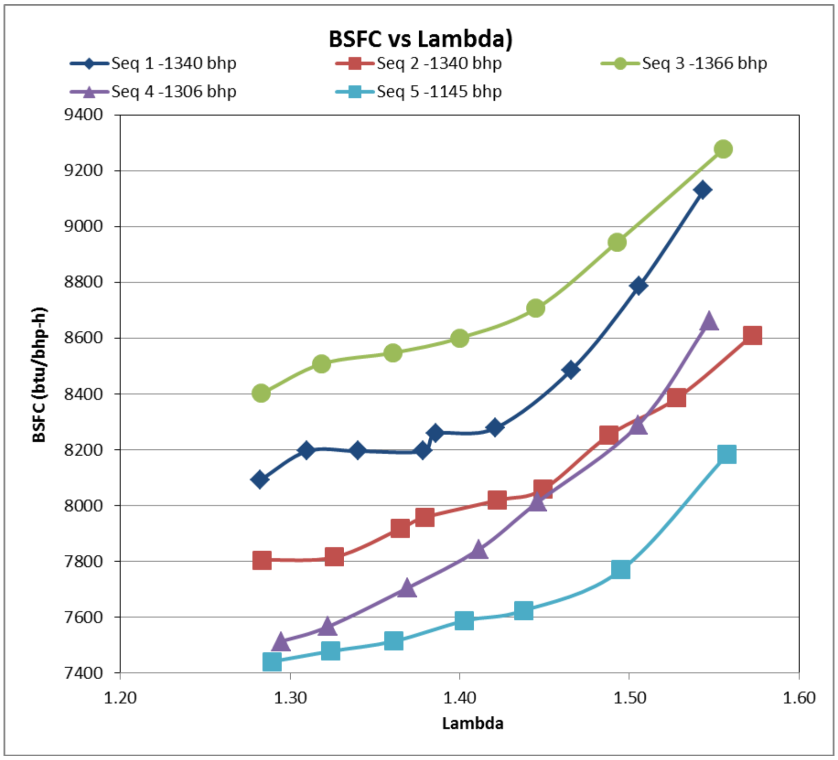


Figure 3-28: Test Engine 5 BSFC for Seq 1 (1340 bhp), Seq 2 (1366 bhp), Seq 3 (1049 bhp), Seg 4 (1308 bhp) and Seq 5 (1145 bhp) at various Lambda.

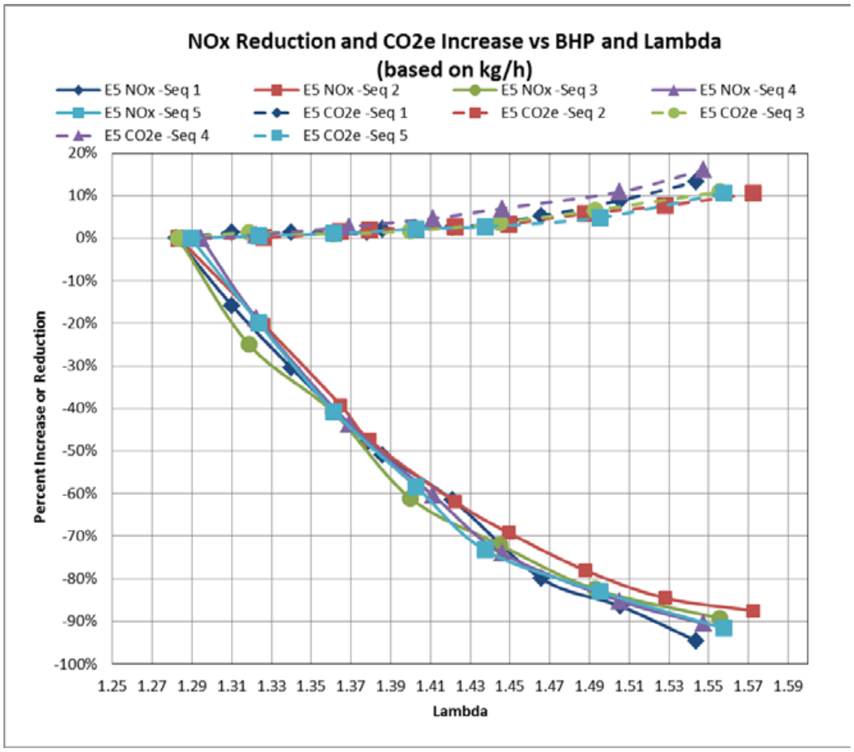


Figure 3-29: Test Engine 5 NO_x reduction and CO_2e Increase for Seq 1 (1340 bhp), Seq 2 (1366 bhp), Seq 3 (1049 bhp), Seg 4 (1308 bhp) and Seq 5 (1145 bhp) at various Lambda.

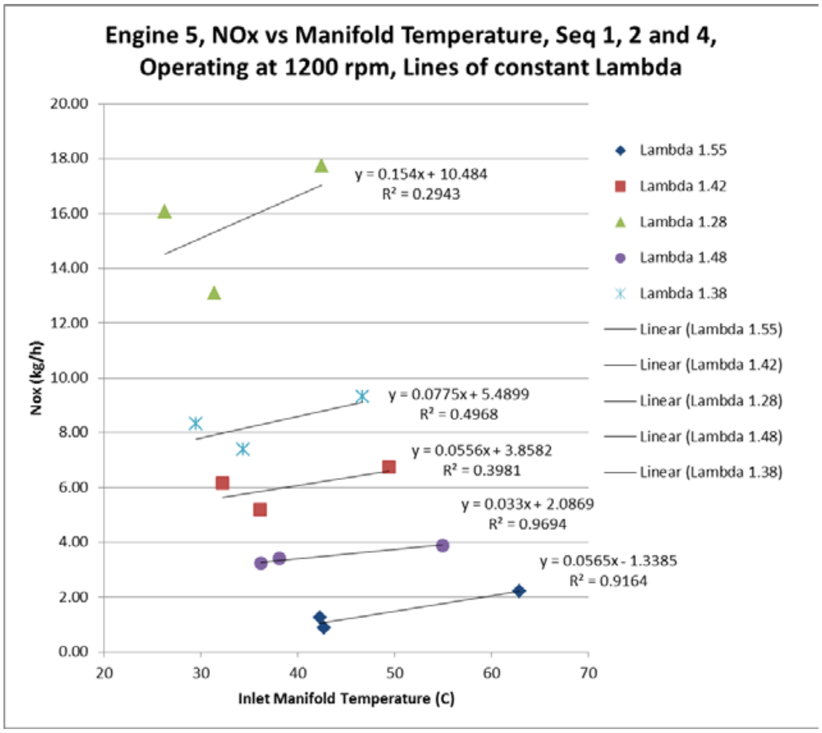


Figure 3-30: Test Engine 5 NO_x versus Inlet Manifold Air Temperature using Seq 1, 2 and 4 data with engine operating at 1200 RPM and for four values of Lambda.

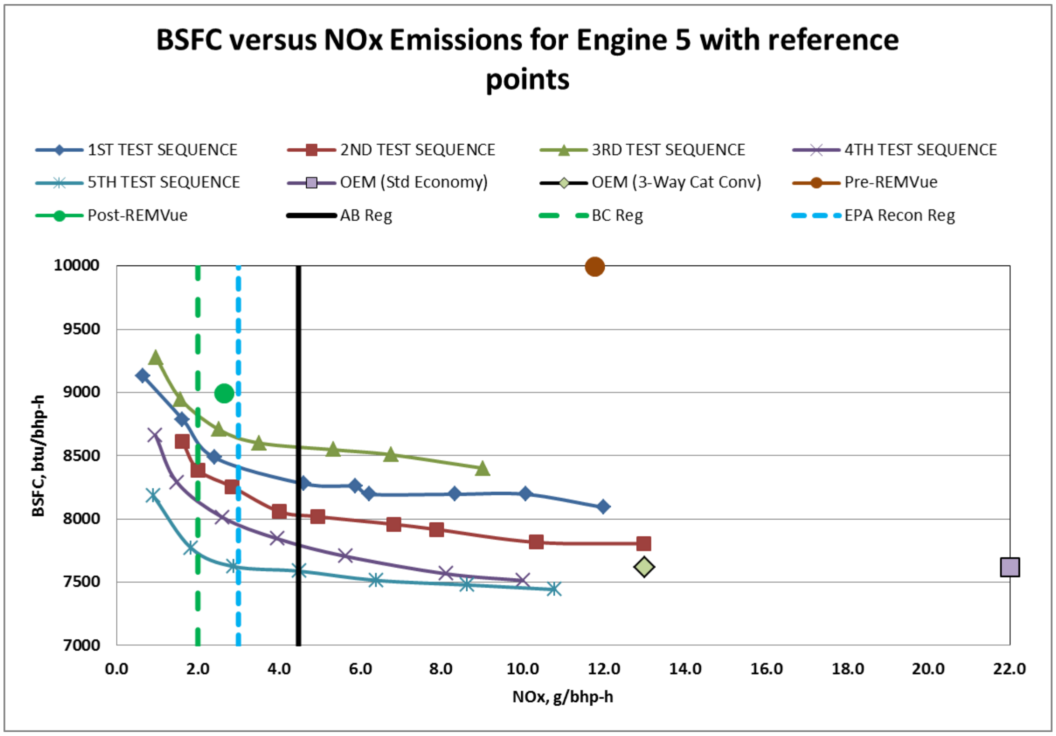


Figure 3-31: Test Engine 5 BSFC versus NO_x for Sequences 1 to 5 at various values of Lambda.

Table 3-9: Summary of Test Engine 5 Sequence 1 recorded operating data, measured operating and emission data and calculated results.

Test Engine 5	**Engine: Waukesha L7042GSI**			**Nominal Rated Power@1200 rpm: 1480 bhp**						
1ST TEST SEQUENCE	**Units**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Inlet Temp	C	42.7	38.6	36.2	32.2	30.7	29.5	28.8	27.9	26.3
Exhaust Temp	C	674.7	664.8	658.3	657.6	658.8	658.4	662	665	666.7
Manifold Pressure	PSI	13.79	11.82	10.08	8.47	7.98	7.66	7.22	6.79	6.18
Speed	RPM	1199	1200	1199	1199	1200	1199	1199	1199	1200
Stack Gas (measured)										
Lambda	-	1.54	1.51	1.47	1.42	1.39	1.38	1.34	1.31	1.28
O_2	%	8.0	7.6	7.2	6.7	6.3	6.2	5.7	5.3	4.9
CO	ppm	279	305	315	316	6.3	300	288	277	268
Total Combustible	ppm	100	100	100	90	6.2	70	60	60	60
Unburnt Fuel	ppm	100	100	100	90	80	70	60	60	60
NO	ppm	80	178	363	894	1225	1324	1887	2376	2957
NO_2	ppm	32	110	121	141	152	156	179	200	226
Fuel Mol. Wt.	-	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1
Fuel	e3 sm3/d	8.8	8.5	8.2	8.0	8.0	7.9	7.9	7.9	7.8
Air	e3 sm3/d	135.9	127.5	119.9	113.4	110.3	108.9	105.9	103.5	100.0
Stack Gas (wet basis)	e3 sm3/d	145.1	136.4	128.5	121.8	118.7	117.2	114.2	111.8	108.2
Excess Air (%)	%	54.6	50.9	46.9	42.4	39.0	38.2	34.2	31.3	28.5
Exhaust MW	-	28.1	28.1	28.1	28.0	28.0	28.0	28.0	28.0	28.0
Dew Point Temp	°C	48.5	48.9	49.4	50.0	50.5	50.6	51.1	51.5	51.9
Emission Factors										
CO	ng/J	120	128	128	125	117	114	106	100	94
CO_2	ng/J	51154	51144	51145	51160	51181	51191	51211	51223	51232
CO_2e	ng/J	52133	52102	52103	52055	52013	51981	51959	51971	51959
Methane	ng/J	23	22	22	19	16	14	12	12	11
Ethane	ng/J	2.0	2.0	1.9	1.7	1.4	1.2	1.0	1.0	1.0
Total VOC	ng/J	2.0	2.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0
Total Hydrocarbons	ng/J	27	26	25	22	19	17	14	13	13
N_2O	ng/J	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
NO	ng/J	37	80	158	377	504	541	747	919	1117
NO_2	ng/J	23	76	81	91	96	98	109	119	131
NO_x	ng/J	60	156	239	469	600	639	856	1037	1248
Non-CO_2 CO_2e	%	1.88%	1.84%	1.84%	1.72%	1.60%	1.52%	1.44%	1.44%	1.40%
Stack Gas (calculated dry basis)										
CO_2	mole frac.	0.07563	0.07761	0.07987	0.08261	0.08485	0.08540	0.08814	0.09033	0.09248
N_2	mole frac.	0.84433	0.84570	0.84724	0.84895	0.85039	0.85075	0.85244	0.85376	0.85501
O_2	mole frac.	0.07955	0.07600	0.07200	0.06700	0.06300	0.06200	0.05700	0.05300	0.04900
CO	mole frac.	0.00028	0.00031	0.00032	0.00032	0.00030	0.00030	0.00029	0.00028	0.00027
NO	mole frac.	0.00008	0.00018	0.00036	0.00089	0.00123	0.00132	0.00189	0.00238	0.00296
NO_2	mole frac.	0.00003	0.00011	0.00012	0.00014	0.00015	0.00016	0.00018	0.00020	0.00023
Methane	mole frac.	0.00009	0.00009	0.00009	0.00008	0.00008	0.00007	0.00006	0.00006	0.00006
Ethane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000

Table 3-9: Summary of Test Engine 5 Sequence 1 recorded operating data, measured operating and emission data and calculated results.

Test Engine 5	**Engine: Waukesha L7042GSI**			**Nominal Rated Power@1200 rpm: 1480 bhp**						
1ST TEST SEQUENCE	**Units**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Propane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Butane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Isobutane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Output Values										
BHP	hp	1340	1340	1340	1340	1340	1340	1340	1340	1340
AFR	-	15.44	15.06	14.66	14.21	13.86	13.78	13.40	13.10	12.82
AFR_{STOIC}	-	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Lambda	-	1.54	1.51	1.47	1.42	1.39	1.38	1.34	1.31	1.28
BSFC (LHV)	btu/bhp-h	9129	8787	8486	8279	8258	8196	8196	8196	8092
NO_x	(g/bhp-h)	0.7	1.6	2.4	4.6	5.9	6.2	8.3	10.1	12.0
CO_2	(g/bhp-h)	554	533	515	503	502	498	498	498	492
CH_4	(g/bhp-h)	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
N_2O	(g/bhp-h)	0.017	0.017	0.016	0.016	0.016	0.016	0.016	0.016	0.015
CO_2e	(g/bhp-h)	564.9	538	520	507	505	501	501	501	494
Methane (% of total CO_2e)	%	0.9%	0.9%	0.9%	0.8%	0.7%	0.6%	0.5%	0.5%	0.4%
Fuel HHV	MJ/m3	39.6								
Fuel LHV	MJ/m3	35.2								
Emissions										
CO_2	(kg/h)	743	715	690	674	672	667	668	668	659
CH_4	(kg/h)	0.33	0.31	0.30	0.25	0.21	0.18	0.16	0.16	0.14
N_2O	(kg/h)	0.023	0.022	0.022	0.021	0.021	0.021	0.021	0.021	0.021
CO_2e	(kg/h)	757.0	728.2	703.2	685.4	683.1	677.6	677.3	677.4	668.7
NO	(kg/h)	0.5	1.1	2.1	5.0	6.6	7.1	9.7	12.0	14.4
NO_2	(kg/h)	0.3	1.1	1.1	1.2	1.3	1.3	1.4	1.6	1.7
NO_x	(kg/h)	0.9	2.2	3.2	6.2	7.9	8.3	11.2	13.5	16.1
CO	(kg/h)	1.7	1.8	1.7	1.6	1.5	1.5	1.4	1.3	1.2

Table 3-10: Summary of Test Engine 5 Sequence 2 recorded operating data, measured operating and emission data and calculated results.

Test Engine 5	**Engine: Waukesha L7042GSI**			**Rated Power@1200 rpm: 1480 bhp**						
2ND TEST SEQUENCE	**Unit**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Inlet Temp	C	62.9	59.3	54.9	51.5	49.4	46.7	45.5	43.6	42.5
Exhaust Temp	C	665.4	660.4	658.3	656.9	658	658.7	659.9	662.2	668.5
Manifold Pressure	PSI	13.56	12.08	10.89	9.66	9.01	8.17	7.79	6.99	6.48
Speed	RPM	1199	1200	1199	1199	1199	1200	1198	1200	1199
Stack Gas (measured)										
Lambda	-	1.57	1.53	1.49	1.45	1.42	1.38	1.36	1.33	1.28
O_2	%	8.2	7.8	7.4	7.0	6.7	6.2	6.0	5.5	4.9
CO	ppm	323	305	315	308	6.7	289	283	272	265
Total Combustible	ppm	70	60	50	50	6.2	40	40	31	31
Unburnt Fuel	ppm	70	60	50	50	40	40	40	31	31

Table 3-10: Summary of Test Engine 5 Sequence 2 recorded operating data, measured operating and emission data and calculated results.

Test Engine 5	**Engine: Waukesha L7042GSI**			**Rated Power@1200 rpm: 1480 bhp**						
2ND TEST SEQUENCE	**Unit**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
NO	ppm	155	255	448	748	998	1507	1802	2523	3327
NO_2	ppm	119	122	136	144	152	169	179	210	245
Fuel MW	-	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1	18.1
Fuel	e3 sm3/d	8.46	8.24	8.11	7.92	7.88	7.82	7.78	7.68	7.67
Air	e3 sm3/d	133.0	125.9	120.7	114.8	112.1	107.9	106.2	101.8	98.4
Stack Gas	e3 sm3/d	141.9	134.6	129.2	123.1	120.3	116.1	114.3	109.9	106.5
Excess Air (%)	%	57.6	53.2	49.1	45.3	42.6	38.3	36.7	33.0	28.7
Exhaust MW	-	28.1	28.1	28.1	28.0	28.0	28.0	28.0	28.0	28.0
Dew Point Temp	°C	48.2	48.7	49.2	49.7	50.0	50.6	50.8	51.3	51.9
Emission Factors										
CO	ng/J	142	130	130	124	119	110	107	100	94
CO_2	ng/J	51141	51169	51176	51187	51203	51217	51223	51241	51251
CO_2e	ng/J	51973	51959	51903	51914	51867	51881	51887	51863	51873
Methane	ng/J	16	14	11	11	8	8	8	6	6
Ethane	ng/J	1.4	1.2	1	0.9	0.7	0.7	0.7	0.5	0.5
Total VOC	ng/J	1	1	1	1	1	1	1	0	0
Total Hydrocarbons	ng/J	19	16	13	13	10	10	9	7	7
N_2O	ng/J	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
NO	ng/J	73	116	199	323	422	617	728	989	1259
NO_2	ng/J	86	85	92	95	99	106	111	126	142
Total Oxides of Nitrogen	ng/J	159	202	291	418	520	723	839	1115	1401
Non-CO_2 CO_2e	%	1.60%	1.52%	1.40%	1.40%	1.28%	1.28%	1.28%	1.20%	1.20%
Stack Gas (calculated)										
CO_2	mole frac.	0.07411	0.07642	0.07868	0.08092	0.08259	0.08535	0.08643	0.08912	0.09237
N_2	mole frac.	0.84323	0.84484	0.84638	0.84783	0.84892	0.85064	0.85127	0.85284	0.85477
O_2	mole frac.	0.08200	0.07800	0.07400	0.07000	0.06700	0.06200	0.06000	0.05500	0.04900
CO	mole frac.	0.00032	0.00031	0.00032	0.00031	0.00030	0.00029	0.00028	0.00027	0.00027
NO	mole frac.	0.00016	0.00026	0.00045	0.00075	0.00100	0.00151	0.00180	0.00252	0.00333
NO_2	mole frac.	0.00012	0.00012	0.00014	0.00014	0.00015	0.00017	0.00018	0.00021	0.00025
Methane	mole frac.	0.00007	0.00006	0.00005	0.00005	0.00004	0.00004	0.00004	0.00003	0.00003
Ethane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Propane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Butane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Isobutane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Output Values										
BHP	hp	1366	1366	1366	1366	1366	1366	1366	1366	1366
AFR	-	15.72	15.28	14.88163	14.49	14.22	13.79	13.65	13.26	12.83
AFRSTOIC	-	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Lambda	-	1.57	1.53	1.49	1.45	1.42	1.38	1.36	1.33	1.28
BSFC (LHV)	btu/bhp-h	8609	8386	8253	8060	8019	7958	7917	7816	7805
NO_x	(g/bhp-h)	1.6	2.0	2.9	4.0	4.9	6.8	7.9	10.3	13.0

Table 3-10: Summary of Test Engine 5 Sequence 2 recorded operating data, measured operating and emission data and calculated results.

Test Engine 5	**Engine: Waukesha L7042GSI**			**Rated Power@1200 rpm: 1480 bhp**						
2ND TEST SEQUENCE	**Unit**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
CO_2	(g/bhp-h)	523	509	501	490	487	484	481	475	475
CH_4	(g/bhp-h)	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
N_2O	(g/bhp-h)	0.016	0.016	0.016	0.015	0.015	0.015	0.015	0.015	0.015
CO_2e	(g/bhp-h)	531.1	517.2	508.4	496.6	493.7	490.1	487.6	481.1	480.6
Methane (% of total CO_2e)	%	0.6%	0.6%	0.4%	0.4%	0.3%	0.3%	0.3%	0.2%	0.2%
Fuel HHV	MJ/m3	39.6								
Fuel LHV	MJ/m3	35.2								
Emissions										
CO_2	(kg/h)	714	696	685	669	666	661	658	649	649
CH_4	(kg/h)	0.22	0.19	0.15	0.14	0.10	0.10	0.10	0.08	0.08
N_2O	(kg/h)	0.022	0.022	0.021	0.021	0.021	0.021	0.021	0.020	0.020
CO_2e	(kg/h)	725.5	706.4	694.5	678.4	674.4	669.4	666.1	657.2	656.5
NO	(kg/h)	1.0	1.6	2.7	4.2	5.5	8.0	9.3	12.5	15.9
NO_2	(kg/h)	1.2	1.2	1.2	1.2	1.3	1.4	1.4	1.6	1.8
NO_x	(kg/h)	2.2	2.7	3.9	5.5	6.8	9.3	10.8	14.1	17.7
CO	(kg/h)	2.0	1.8	1.7	1.6	1.5	1.4	1.4	1.3	1.2

Table 3-11: Summary of Test Engine 5 Sequence 3 recorded operating data, measured operating and emission data and calculated results.

Test Engine 5	**Engine: Waukesha L7042GSI**			**Nominal Rated Power@1200 rpm: 1480 bhp**				
3RD TEST SEQUENCE	**Unit**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Inlet Temp	C	21.6	19.6	17.9	16.6	15.7	15.2	14.7
Exhaust Temp	C	637.6	631.5	628.7	629.7	632	634.5	636.9
Manifold Pressure	PSI	6.67	5.4	4.35	3.79	3.18	2.78	2.32
Speed	RPM	1200	1201	1199	1198	1200	1200	1200
Stack Gas (measured)								
Lambda	-	1.56	1.49	1.45	1.40	1.36	1.32	1.28
O_2	%	8.1	7.5	7.0	6.5	6.0	5.5	5.0
CO	ppm	258	290	305	304	295.0	288	280
Total Combustible	ppm	170	150	140	50	40.0	150	150
Unburnt Fuel	ppm	170	150	140	50	40	150	150
NO	ppm	76	185	394	637	1098	1496	2137
NO_2	ppm	74	97	113	123	135	145	163
Fuel MW	-	18.1	18.1	18.1	18.1	18.1	18.1	18.1
Fuel	e3 sm3/d	7.00	6.75	6.57	6.49	6.45	6.42	6.34
Air	e3 sm3/d	108.9	100.8	94.9	90.9	87.8	84.7	81.4
Stack Gas	e3 sm3/d	116.2	107.9	101.8	97.7	94.5	91.4	88.0
Excess Air (%)	%	56.1	49.8	44.9	40.5	36.4	32.3	28.7
Exhaust MW	-	28.1	28.1	28.1	28.0	28.0	28.0	28.0
Dew Point Temp	°C	48.1	48.9	49.5	50.1	50.6	51.2	51.7

Table 3-11: Summary of Test Engine 5 Sequence 3 recorded operating data, measured operating and emission data and calculated results.

Test Engine 5	**Engine: Waukesha L7042GSI**			**Nominal Rated Power@1200 rpm: 1480 bhp**				
3RD TEST SEQUENCE	**Unit**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Emission Factors								
CO	ng/J	112	121	122	118	111	105	99
CO_2	ng/J	51113	51120	51128	51198	51217	51158	51170
CO_2e	ng/J	52449	52309	52254	51904	51881	52263	52254
Methane	ng/J	40	33	30	10	8	29	28
Ethane	ng/J	3.5	2.9	2.6	0.9	0.7	2.6	2.5
Total VOC	ng/J	3	2	2	1	1	2	2
Total Hydrocarbons	ng/J	46	39	35	12	9	34	33
N_2O	ng/J	1.6	1.6	1.6	1.6	1.6	1.6	1.6
NO	ng/J	35	82	170	265	443	583	809
NO_2	ng/J	53	66	75	78	83	87	95
Total Oxides of Nitrogen	ng/J	88	149	244	344	526	670	904
Non-CO_2 CO_2e	%	2.55%	2.27%	2.15%	1.36%	1.28%	2.11%	2.07%
Stack Gas (calculated)								
CO_2	mole frac.	0.074775	0.078199	0.081028	0.083871	0.086648	0.089430	0.092149
N_2	mole frac.	0.843647	0.000290	0.848020	0.850015	0.851784	0.853491	0.855121
O_2	mole frac.	0.081000	0.000185	0.070000	0.065000	0.060000	0.055000	0.050000
CO	mole frac.	0.000258	0.000097	0.000305	0.000304	0.000295	0.000288	0.000280
NO	mole frac.	0.000076	0.000140	0.000394	0.000637	0.001098	0.001496	0.002137
NO_2	mole frac.	0.000074	0.000007	0.000113	0.000123	0.000135	0.000145	0.000163
Methane	mole frac.	0.000159	0.000002	0.000131	0.000047	0.000037	0.000140	0.000140
Ethane	mole frac.	0.000007	0.000000	0.000006	0.000002	0.000002	0.000007	0.000007
Propane	mole frac.	0.000002	0.000000	0.000002	0.000001	0.000000	0.000002	0.000002
Butane	mole frac.	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Isobutane	mole frac.	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Output Values								
BHP	hp	1049	1049	1049	1049	1049	1049	1049
AFR	-	15.55	14.93	14.45	14.00	13.61	13.19	12.83
AFR_{STOIC}	-	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Lambda	-	1.56	1.49	1.45	1.40	1.36	1.32	1.28
BSFC (LHV)	btu/bhp-h	9276	8945	8707	8601	8548	8508	8402
NO_x	(g/bhp-h)	1.0	1.6	2.5	3.5	5.3	6.8	9.0
CO_2	(g/bhp-h)	563	543	528	523	520	517	510
CH_4	(g/bhp-h)	0.4	0.4	0.3	0.1	0.1	0.3	0.3
N_2O	(g/bhp-h)	0.018	0.017	0.017	0.016	0.016	0.016	0.016
CO_2e	(g/bhp-h)	577.5	555.4	540.0	529.9	526.4	527.8	521.1
Methane (% of total CO_2e)	%	1.6%	1.3%	1.2%	0.4%	0.3%	1.2%	1.1%
Fuel HHV	MJ/m3	39.6						
Fuel LHV	MJ/m3	35.2						
Emissions								
CO_2	(kg/h)	590	569	554	548	545	542	535

Table 3-11: Summary of Test Engine 5 Sequence 3 recorded operating data, measured operating and emission data and calculated results.

Test Engine 5	Engine: Waukesha L7042GSI			Nominal Rated Power@1200 rpm: 1480 bhp				
3RD TEST SEQUENCE	**Unit**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
CH_4	(kg/h)	0.46	0.37	0.33	0.11	0.09	0.31	0.29
N_2O	(kg/h)	0.018	0.018	0.017	0.017	0.017	0.017	0.017
CO_2e	(kg/h)	605.8	582.6	566.5	555.8	552.1	553.6	546.6
NO	(kg/h)	0.4	0.9	1.8	2.8	4.7	6.2	8.5
NO_2	(kg/h)	0.6	0.7	0.8	0.8	0.9	0.9	1.0
NO_x	(kg/h)	1.0	1.7	2.6	3.7	5.6	7.1	9.5
CO	(kg/h)	1.3	1.3	1.3	1.3	1.2	1.1	1.0

Table 3-12: Summary of Test Engine 5 Sequence 4 recorded operating data, measured operating and emission data and calculated results.

Test Engine 5	Engine: Waukesha L7042GSI			Rated Power@1200 rpm: 1480 bhp				
4TH TEST SEQUENCE	**Unit**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
Inlet Temp	C	42.3	38.1	38.1	36.1	34.4	33.3	31.4
Exhaust Temp	C	651.9	642.2	638	637.7	638.1	640.5	643.3
Manifold Pressure	PSI	13.97	11.66	9.3	9.02	7.82	7.03	6.32
Speed	RPM	1098	1102	1101	1100	1102	1100	1100
Stack Gas (measured)								
Lambda	-	1.55	1.51	1.45	1.41	1.37	1.32	1.29
O_2	%	8.0	7.6	7.0	6.6	6.1	5.5	5.1
CO	ppm	244	266	281	271	6.1	242	235
Total Combustible	ppm	245	230	220	210	5.5	190	190
Unburnt Fuel	ppm	245	230	220	210	200	190	190
NO	ppm	69	173	443	804	1285	2044	2652
NO_2	ppm	86	106	127	140	154	176	189
Fuel Mol. Wt.	-	18.13	18.13	18.13	18.13	18.13	18.13	18.13
Fuel	e3 sm3/d	8.15	7.80	7.54	7.38	7.25	7.12	7.07
Air	e3 sm3/d	126.1	117.4	109.0	104.2	99.3	94.2	91.5
Stack Gas	e3 sm3/d	134.7	125.6	116.9	111.9	106.9	101.6	98.9
Excess Air (%)	%	54.9	50.6	44.8	41.2	37.1	32.5	29.6
Exhaust MW	-	28.1	28.1	28.0	28.0	28.0	28.0	27.9
Dew Point Temp	°C	48.4	48.9	49.7	50.1	50.7	51.3	51.7
Emission Factors								
CO	ng/J	105	111	113	106	98	88	84
CO_2	ng/J	51069	51076	51087	51109	51132	51159	51169
CO_2e	ng/J	52762	52664	52570	52529	52489	52432	52421
Methane	ng/J	57	52	47	44	41	37	36
Ethane	ng/J	4.9	4.5	4.1	3.8	3.5	3.2	3.2
Total VOC	ng/J	4.0	4.0	3.0	3.0	3.0	3.0	3.0
Total Hydrocarbons	ng/J	66	60	55	51	47	43	42
N_2O	ng/J	1.6	1.6	1.6	1.6	1.6	1.6	1.6

Table 3-12: Summary of Test Engine 5 Sequence 4 recorded operating data, measured operating and emission data and calculated results.

Test Engine 5	**Engine: Waukesha L7042GSI**			**Rated Power@1200 rpm: 1480 bhp**				
4TH TEST SEQUENCE	**Unit**	**26**	**27**	**28**	**29**	**30**	**31**	**32**
NO	ng/J	32	78	190	337	521	798	1012
NO_2	ng/J	61	73	84	90	96	105	111
Total Oxides of Nitrogen	ng/J	93	151	274	426	617	904	1122
Non-CO_2 CO_2e	%	3.21%	3.02%	2.82%	2.70%	2.59%	2.43%	2.39%
Stack Gas (calculated)								
CO_2	mole frac.	0.07536	0.07763	0.08102	0.08324	0.08601	0.08929	0.09144
N_2	mole frac.	0.84400	0.84560	0.84791	0.84933	0.85109	0.85306	0.85430
O_2	mole frac.	0.08000	0.07600	0.07000	0.06600	0.06100	0.05500	0.05100
CO	mole frac.	0.00024	0.00027	0.00028	0.00027	0.00026	0.00024	0.00024
NO	mole frac.	0.00007	0.00017	0.00044	0.00080	0.00129	0.00204	0.00265
NO_2	mole frac.	0.00009	0.00011	0.00013	0.00014	0.00015	0.00018	0.00019
Methane	mole frac.	0.00023	0.00022	0.00021	0.00020	0.00019	0.00018	0.00018
Ethane	mole frac.	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001
Propane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Butane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Isobutane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Output Values								
BHP	hp	1308	1308	1308	1308	1308	1308	1308
AFR	-	15.47	15.05	14.46	14.11	13.69	13.22	12.95
AFR_{STOIC}	-	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Lambda	-	1.55	1.51	1.45	1.41	1.37	1.32	1.29
BSFC (LHV)	btu/bhp-h	8662	8290	8013	7843	7705	7567	7514
NO_x	(g/bhp-h)	1.0	1.5	2.6	4.0	5.6	8.1	10.0
CO_2	(g/bhp-h)	525	503	486	476	468	459	456
CH_4	(g/bhp-h)	0.6	0.5	0.4	0.4	0.4	0.3	0.3
N_2O	(g/bhp-h)	0.016	0.016	0.015	0.015	0.015	0.014	0.014
CO_2e	(g/bhp-h)	542.4	518.2	500.0	489.0	480.0	470.9	467.5
Methane (% of total CO_2e)	%	2.3%	2.1%	1.9%	1.8%	1.6%	1.5%	1.4%
Fuel HHV	MJ/m3	39.6						
Fuel LHV	MJ/m3	35.2						
Emissions								
CO_2	(kg/h)	687	657	636	622	612	601	597
CH_4	(kg/h)	0.77	0.67	0.58	0.54	0.49	0.43	0.42
N_2O	(kg/h)	0.022	0.021	0.020	0.019	0.019	0.019	0.019
CO_2e	(kg/h)	709.5	677.8	654.0	639.6	627.9	616.0	611.5
NO	(kg/h)	0.4	1.0	2.4	4.1	6.2	9.4	11.8
NO_2	(kg/h)	0.8	0.9	1.0	1.1	1.1	1.2	1.3
NO_x	(kg/h)	1.3	1.9	3.4	5.2	7.4	10.6	13.1
CO	(kg/h)	1.4	1.4	1.4	1.3	1.2	1.0	1.0

Table 3-13: Summary of Test Engine 5 Sequence 5 recorded operating data, measured operating and emission data and calculated results.

Test Engine 5	**Engine: Waukesha L7042GSI**			**Rated Power@1200 rpm: 1480 bhp**				
5TH TEST SEQUENCE	**Unit**	**33**	**34**	**35**	**36**	**37**	**38**	**39**
Inlet Temp	C	35.1	32	29.7	28.4	27.2	25.8	24.9
Exhaust Temp	C	614.1	607.4	606.5	608.4	610.4	613.2	616.2
Manifold Pressure	PSI	10.56	8.75	7.57	6.93	6.24	5.64	5.08
Speed	RPM	1004	999	999	999	999	999	1000
Stack Gas (measured)								
Lambda	-	1.56	1.50	1.44	1.40	1.36	1.32	1.29
O2	%	8.1	7.5	6.9	6.5	6.0	5.5	5.0
CO	ppm	239	275	271	258	240	227	216
Total Combustible	ppm	220	210	200	190	5.5	180	170
Unburnt Fuel	ppm	220	210	200	190	180	180	170
NO	ppm	96	293	574	1009	1572	2254	2973
NO2	ppm	68	100	113	124	135	154	161
Fuel MW	-	18.1	18.1	18.1	18.1	18.1	18.1	18.1
Fuel	e3 sm3/d	6.74	6.40	6.28	6.25	6.19	6.16	6.13
Air	e3 sm3/d	105.0	95.7	90.3	87.7	84.3	81.5	79.0
Stack Gas	e3 sm3/d	112.1	102.4	96.9	94.2	90.8	88.0	85.5
Excess Air (%)	%	56.0	49.7	43.9	40.5	36.4	32.6	29.0
Exhaust MW	-	28.1	28.1	28.0	28.0	28.0	28.0	27.9
Dew Point Temp	°C	48.2	49.0	49.7	50.2	50.7	51.2	51.7
Emission Factors								
CO	ng/J	104	114	108	100	90	83	77
CO_2	ng/J	51089	51087	51110	51132	51158	51173	51193
CO_2e	ng/J	52656	52570	52509	52468	52410	52404	52361
Methane	ng/J	51	47	43	40	36	35	32
Ethane	ng/J	4.5	4.1	3.7	3.4	3.2	3.1	2.8
Total VOC	ng/J	4	3	3	3	3	3	2
Total Hydrocarbons	ng/J	60	54	50	46	42	41	37
N_2O	ng/J	1.6	1.6	1.6	1.6	1.6	1.6	1.6
NO	ng/J	45	131	245	420	634	881	1128
NO_2	ng/J	49	68	74	79	83	92	94
Total Oxides of Nitrogen	ng/J	93	199	319	499	717	973	1222
Non-CO_2 CO_2e	%	2.98%	2.82%	2.66%	2.55%	2.39%	2.35%	2.23%
Stack Gas (calculated)								
CO_2	mole frac.	0.07478	0.07817	0.08158	0.08378	0.08654	0.08925	0.09195
N_2	mole frac.	0.84360	0.84595	0.84826	0.84964	0.85134	0.85294	0.85453
O_2	mole frac.	0.08100	0.07500	0.06900	0.06500	0.06000	0.05500	0.05000
CO	mole frac.	0.00024	0.00028	0.00027	0.00026	0.00024	0.00023	0.00022
NO	mole frac.	0.00010	0.00029	0.00057	0.00101	0.00157	0.00225	0.00297
NO_2	mole frac.	0.00007	0.00010	0.00011	0.00012	0.00014	0.00015	0.00016
Methane	mole frac.	0.00021	0.00020	0.00019	0.00018	0.00017	0.00017	0.00016
Ethane	mole frac.	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001

Table 3-13: Summary of Test Engine 5 Sequence 5 recorded operating data, measured operating and emission data and calculated results.

Test Engine 5	**Engine: Waukesha L7042GSI**			**Rated Power@1200 rpm: 1480 bhp**				
5TH TEST SEQUENCE	**Unit**	**33**	**34**	**35**	**36**	**37**	**38**	**39**
Propane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Butane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Isobutane	mole frac.	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Output Values								
BHP	hp	1145	1145	1145	1145	1145	1145	1145
AFR	-	15.58	14.95	14.4	14.03	13.61	13.24	12.89
AFR_{STOIC}	-	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Lambda	-	1.56	1.50	1.44	1.40	1.36	1.32	1.29
BSFC (LHV)	btu/bhp-h	8183	7770	7624	7588	7515	7479	7442
NO_x	(g/bhp-h)	0.9	1.8	2.9	4.5	6.4	8.6	10.8
CO_2	(g/bhp-h)	496	471	463	461	456	454	452
CH_4	(g/bhp-h)	0.5	0.4	0.4	0.4	0.3	0.3	0.3
N_2O	(g/bhp-h)	0.016	0.015	0.014	0.014	0.014	0.014	0.014
CO_2e	(g/bhp-h)	511.4	484.8	475.2	472.6	467.5	465.2	462.5
Methane (% of total CO_2e)	%	2.0%	1.9%	1.7%	1.6%	1.4%	1.4%	1.3%
Fuel HHV	MJ/m3	39.6						
Fuel LHV	MJ/m3	35.2						
Emissions								
CO_2	(kg/h)	568	539	530	527	523	520	518
CH_4	(kg/h)	0.57	0.50	0.45	0.41	0.37	0.36	0.32
N_2O	(kg/h)	0.018	0.017	0.017	0.017	0.016	0.016	0.016
CO_2e	(kg/h)	585.6	555.1	544.1	541.1	535.3	532.6	529.6
NO	(kg/h)	0.5	1.4	2.5	4.3	6.5	9.0	11.4
NO_2	(kg/h)	0.5	0.7	0.8	0.8	0.8	0.9	1.0
NO_x	(kg/h)	1.0	2.1	3.3	5.1	7.3	9.9	12.4
CO	(kg/h)	1.2	1.2	1.1	1.0	0.9	0.8	0.8

3.4 Combined Test Results

3.4.1 Lambda Effect on THC, BSFC and CO_2e Emission Factor

Not all engines exhibited the same concentration of THC in the flue gases. Engines 1, 2 and 3 exhibited THC emissions in the 1300 to 1800 ppm range while Engine 4 was estimated to be 500 ppm (because the THC component failed during the test) and Engine 5 varied from 20 to 250 ppm. This can be seen in the Methane (% of total CO_2e) line in each table. For engines 1, 2 and 3, methane contributed 10 to 15 % of the total CO_2e. For Engine 4, methane contributed 4-5% (estimated) and for Engine 5 only 1-2%. In general, THC emissions are related to engine settings other than Lambda and not controlled or affected by the REMVue system.

The observed increase in THC with increasing Lambda was significant for engines 1, 2 and 3 and very modest for Engine 5. For engines 1, 2 and 3, approximately 35 to 65% of the increase in CO_2e emissions with increasing Lambda was due to additional THC in the flue gases. This increase is reflected in the emission factor increase. The remainder is reflected in the BSFC increase with increasing Lambda. For Engine 5, the increase in CO_2e with increasing Lambda is minimal (about 3-10% of total).

In addition, the sensitivity of emission factors to THC values are depicted in Figure 3-32. ECOM THC readings in the range of 20-100ppm and AI THC readings in the range of 208 to 323 ppm are applied to the same Engine 5 Sequence 2 test. The higher THC data shifts Lambda to the left (richer) for all tests.

Applying the lower ECOM data instead of the AI data resulted in an average Lambda shift of 0.28% to the right (leaner) when the lower THC values are applied. (168 to 238 ppm reductions in THC shifted Lambda by 0.0027 to 0.0058 points, respectively for Lambdas of 1.28 and 1.57. The effect on the NO_x emission factor is negligible. The effect on CO_2e is an increase of about 2% comparable to the increase in THC (168 to 223 ppm equivalent to 28 to 53 ng/J of CH_4) times the GWP of CH_4 (590 to 1000 ng/J CO_2e).

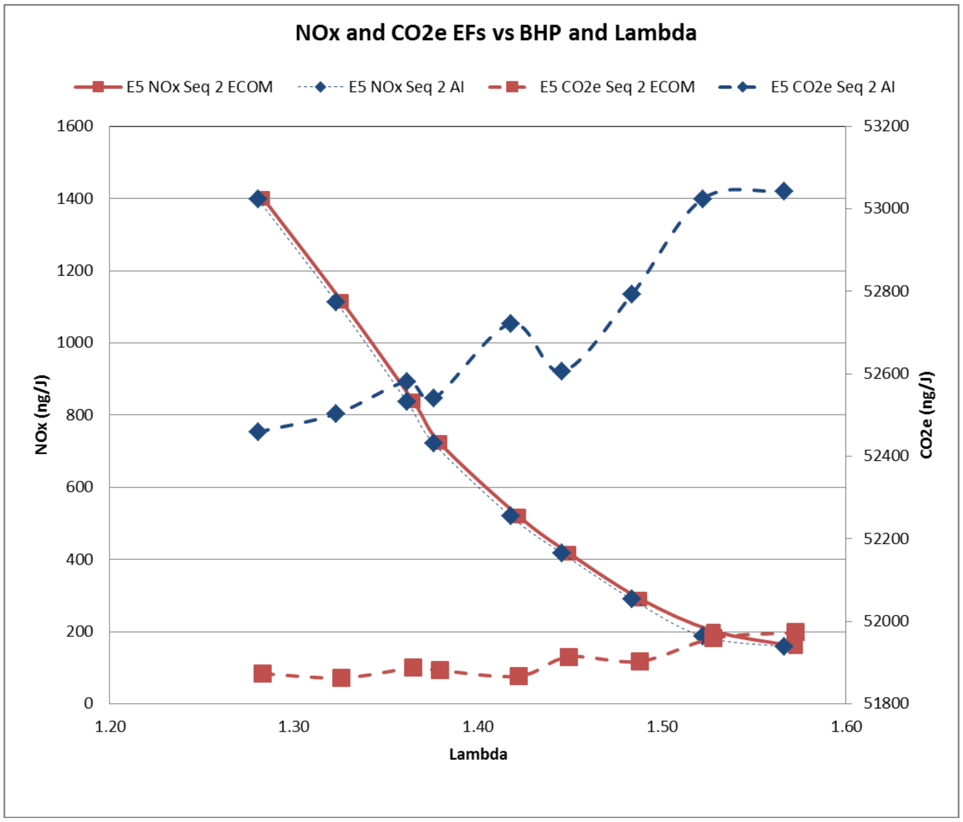


Figure 3-32: NO_x and CO_2e emission factors based on ECOM and AI flue gas data for THC.

3.4.2 NO_x and CO_2e Variations With Lambda

Although these engines were all Waukesha L7042GSI unit, potential differences related to year of manufacture, level of maintenance, and materials of construction suggest that they all were not initially nominally rated at a maximum of 1200 rpm and 1480 bhp. For example, engines 1 to 4 were initially rated at 1000 rpm and 1100 bhp. In any case, all results were examined as if the engines were essentially the same or similar and as a group representative of Waukesha L7042GSI engines in upstream oil & gas service.

For this analysis, only NO_x emissions in g/bhp-h and the NO_x reduction versus CO_2e increases (penalty) were considered.

Figure 3-33 presents the combined NO_x emissions versus Lambda for all engine tests. Emissions criteria are indicated as AB Reg- 4.48 g/bhp-h, EPA Recon Reg- 3.0 g/bhp-h and BC Reg- 2.0 g/bhp-h (equivalent to 6.0, 4.0 and 2.7 g/kWh, respectively). The results suggest compliance possibilities over the following ranges of Lambda:

- AB Reg 4.48 g/ghp-h: Lambda of 1.32 to 1.44
- EPA Recon Reg 3.00 g/bhp-h: Lambda of 1.38 to 1.48
- BC Reg 2.00 g/bhp-h: Lambda of 1.41 to 1.53

It is noted that Engine 3 could not achieve reductions past about 4 g/bhp-h in its current condition and most likely due to the inability of the turbos to push enough air to reach higher values of Lambda.

Referring to Table 3-14 and Figure 3-34, and assuming an engine baseline equal to the richest AFR (lowest Lambda value) tested, the data suggest that following CO_2e penalties:

- AB Reg 4.48 g/ghp-h: CO_2e penalty of 1%to 4%
- EPA Recon Reg 3.00 g/bhp-h: CO_2e penalty of 2% to 7%
- BC Reg 2.00 g/bhp-h: CO_2e penalty of 4% to 10%

It is noted that these penalties are not relative to the engine operating prior to REMVue installation and AFR control.

Table 3-14: NO_x emission reduction and CO_2e penalty based on lowest lambda value tested for all engine tests achieving stated criteria.

				AB Reg (4.48 g/bhp-h or 6.0 g/kWh)			EPA Recon Reg (3.0 g/bhp-h or 4.0 g/kWh)			BC Reg (2.0 g/bhp-h or 2.7 g/kWh)		
Engine	Test	bhp	RPM	L	NO_x (% change)[1]	CO_2e (% change)	L	NO_x (% change)	CO_2e (% change)	L	NO_x (% change)	CO_2e (% change)
1	1	824	987	1.39	-57%	3%	1.43	-71%	3%	1.46	-80%	4%
1	2	787	940	1.40	-59%	4%	1.45	-73%	7%	1.49	-82%	9%
1	3	749	898	1.40	-60%	4%	1.45	-74%	7%	1.50	-82%	10%
2	1	825	940	1.34	-34%	2%	1.38	-56%	3%	1.41	-70%	4%
2	2	785	860	1.32	-33%	2%	1.38	-55%	3%	1.43	-70%	5%
2	3	750	800	1.34	-42%	2%	1.38	-61%	3%	1.42	-74%	4%
3	1	1069	897	1.43	-72%	3%	NT	NT	NT	NT	NT	NT
3	2	1022	853	NA	NA	NA	NA	NA	NA	NA	NA	NA
4	1	1106	994	1.44	-60%	2%	1.48	-73%	3%	1.52	-82%	4%
5	1	1340	1205	1.42	-63%	3%	1.46	-75%	4%	1.48	-83%	6%
5	2	1366	1208	1.43	-66%	3%	1.48	-77%	6%	1.53	-85%	8%
5	3	1049	1208	1.38	-50%	1%	1.42	-67%	2%	1.47	-78%	5%
5	4	1308	1105	1.40	-55%	4%	1.44	-70%	6%	1.48	-80%	9%
5	5	1145	1005	1.40	-59%	2%	1.44	-72%	3%	1.49	-81%	4%
Minimum[2]		749	800	1.32	-72%	1%	1.38	-77%	2%	1.41	-85%	4%
Maximum[2]		1366	1208	1.44	-33%	4%	1.48	-55%	7%	1.53	-70%	10%
Average[2]		1008	1004	1.39	-55%	3%	1.43	-69%	4%	1.47	-79%	6%

[1] % Change is based on NO_x or CO_2e results at the lowest Lambda value tested.

[2] Engine 3, run 2, is not included in the minimum, maximum and average

NT – No test data for this condition due to engine equipment limitations.

NA – test data for condition was not acceptable.

Comparisons of the BFSC versus NO_x profiles of all engine tests are presented in Figure 3-35. The estimated OEM conditions for Standard Ecomony and 3-Way Catalytic Converter plus the industry average Pre and post REMVue conversion are included in the graph as reference points. In general, the BSFC versus NO_x profiles are relatively flat at NO_x levels above 4 g/bhp-h. At about 4 g/bhp-h, some engines start to exhibit a marked increase in BSFC. For others, the inflection point does not appear until NO_x levels of 3 g/bhp-h or even 2 g/bhp-h are achieved. Engine 3 is noted as an exception to the above observations.

CO_2e emissions relative to the CO_2e emissions at a NO_x emission rate of 8 g/bhp-h (expressed as a percent) are presented in Figure 3-36 at NOx emission rates below 8 g/bhp-h. The indicated emissions increases or penalties are different than those indicated in Figure 3-35 because they are relative to a baseline of NO_x = 8 g/bhp-h and not the NO_x or CO_2e emission rates at the lowest lambda tested.

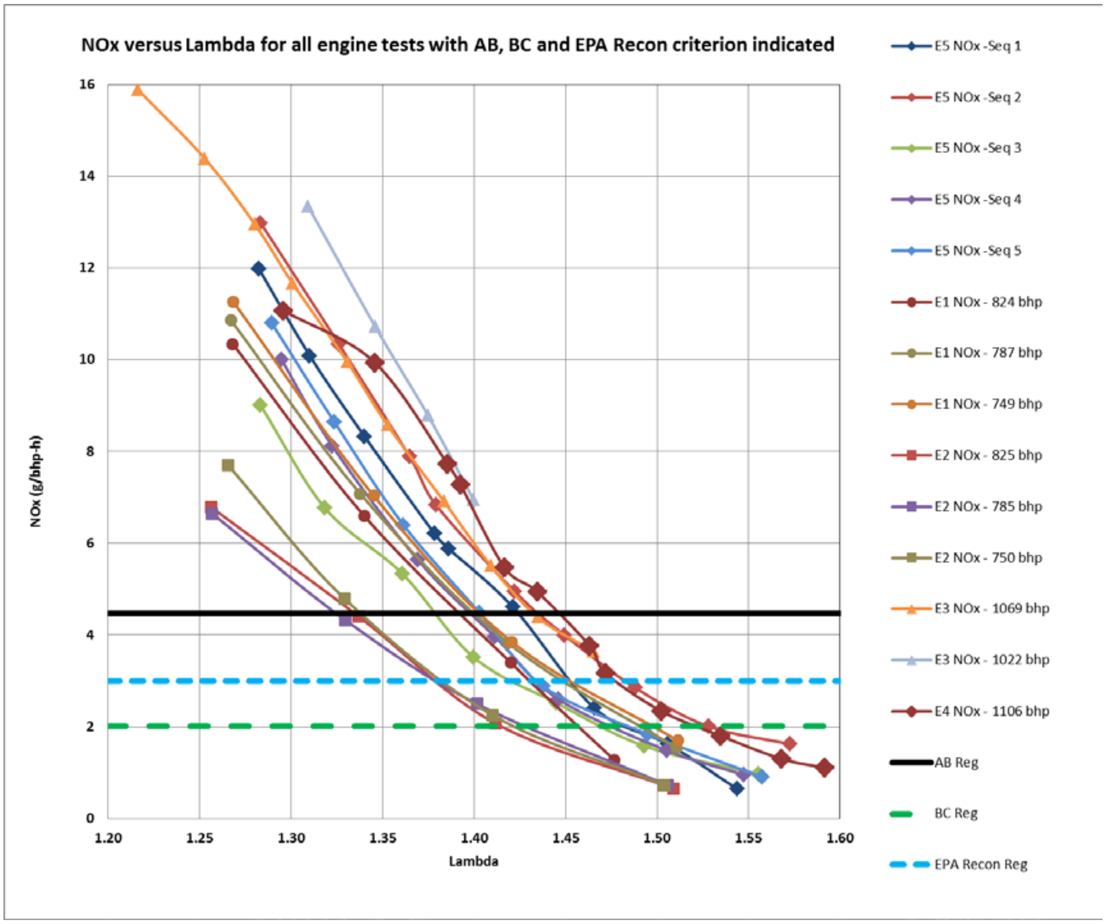


Figure 3-33: NO_x versus Lambda for all tests compared to NO_x emissions criteria of 2.0, 3.0 and 4.48 g/bhp-h and treating all engines tested as being a representative group of all existing Waukesha L7042GSI engines in upstream oil & gas industry service.

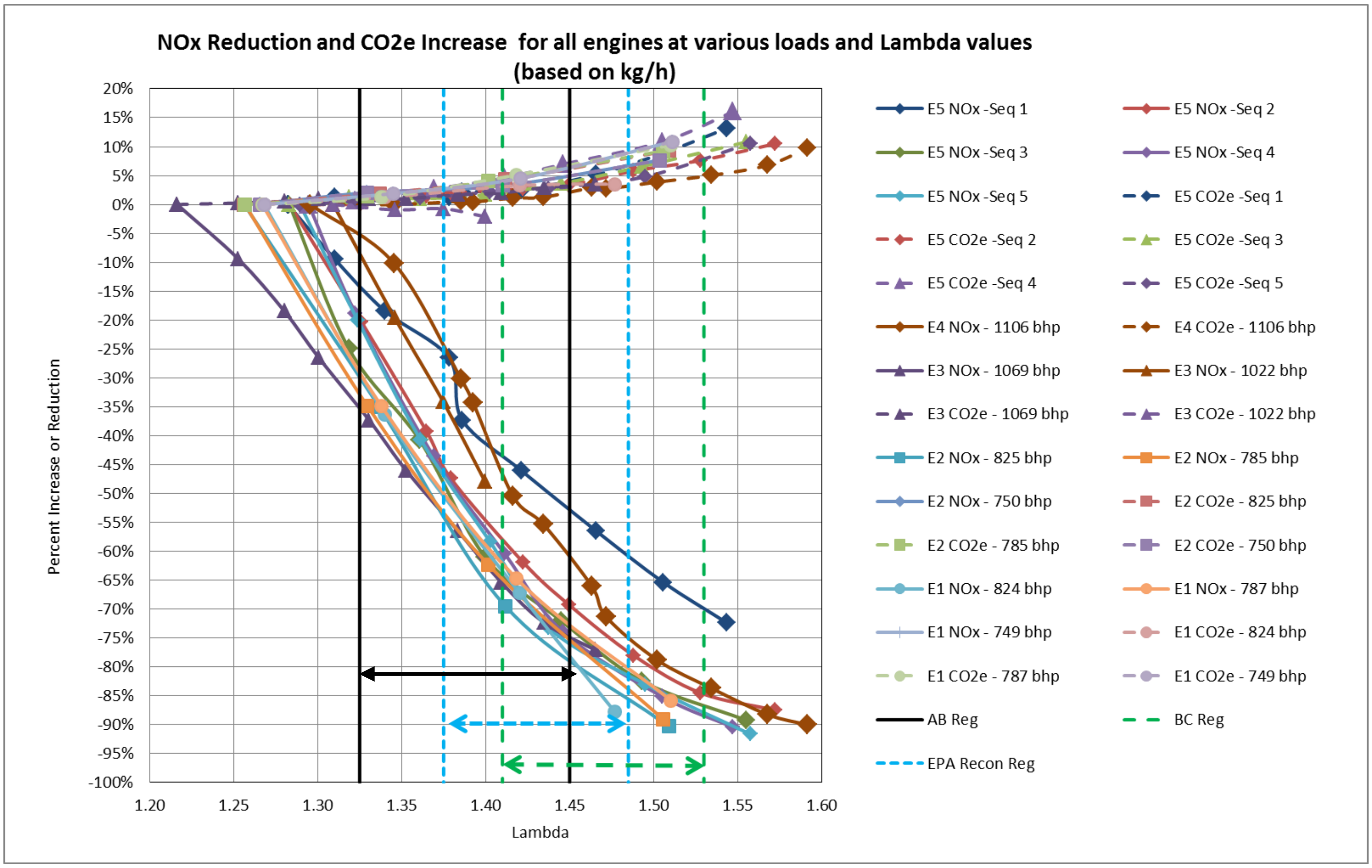


Figure 3-34: NO_x reduction versus CO_2e increase (penalty) versus Lambda for all tests and compared to NO_x emissions criteria of 2.0, 3.0 and 4.48 g/bhp-h and treating all engines tested as being a representative group of all existing Waukesha L7042GSI engines in upstream oil & gas industry service.

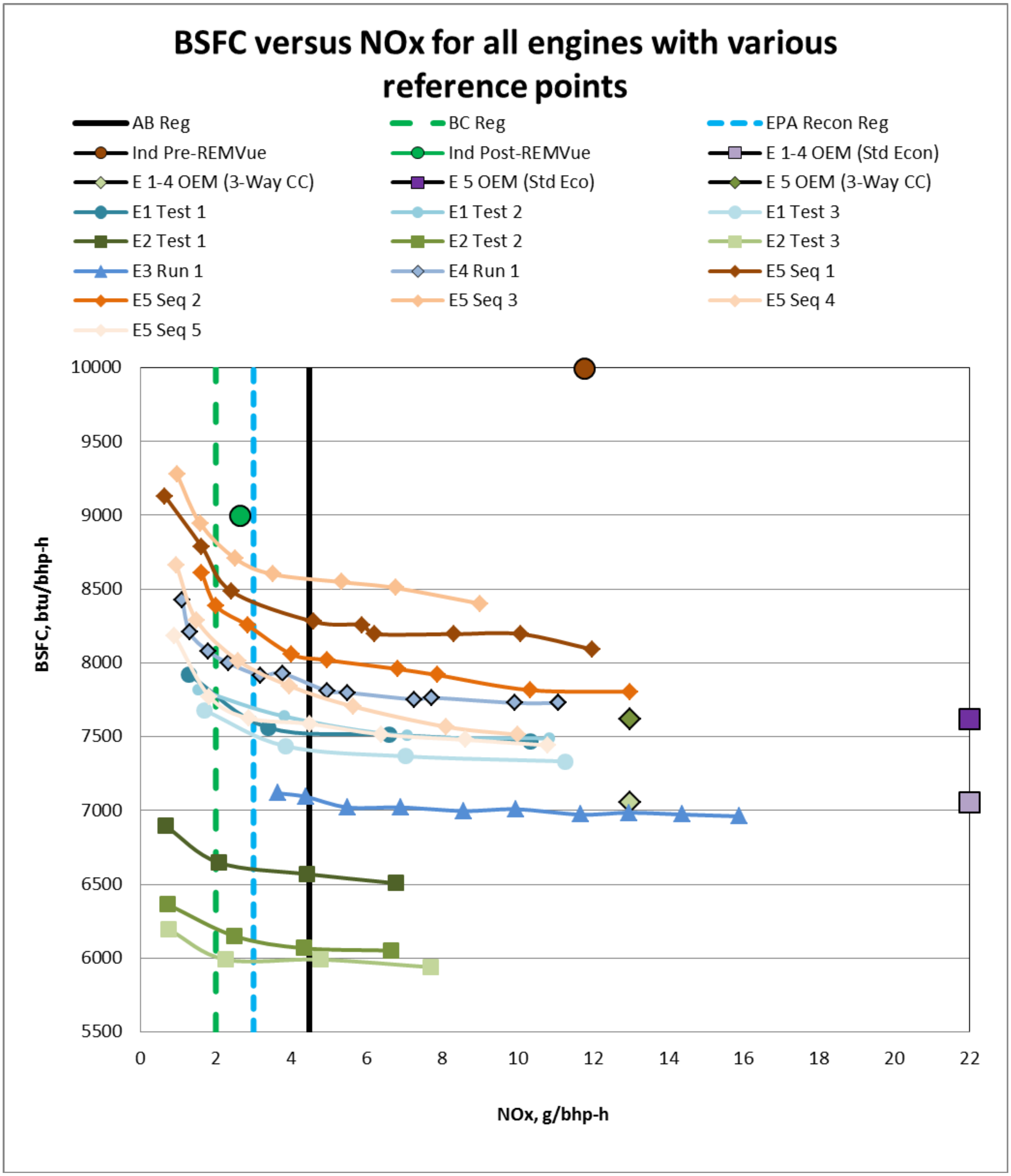


Figure 3-35: BSFC versus NO$_x$ for all engine tests at various Lambda with reference points for emissions criteria of 2.0, 3.0 and 4.48 g/bhp-h, industry average and Waukesha OEM conditions included.

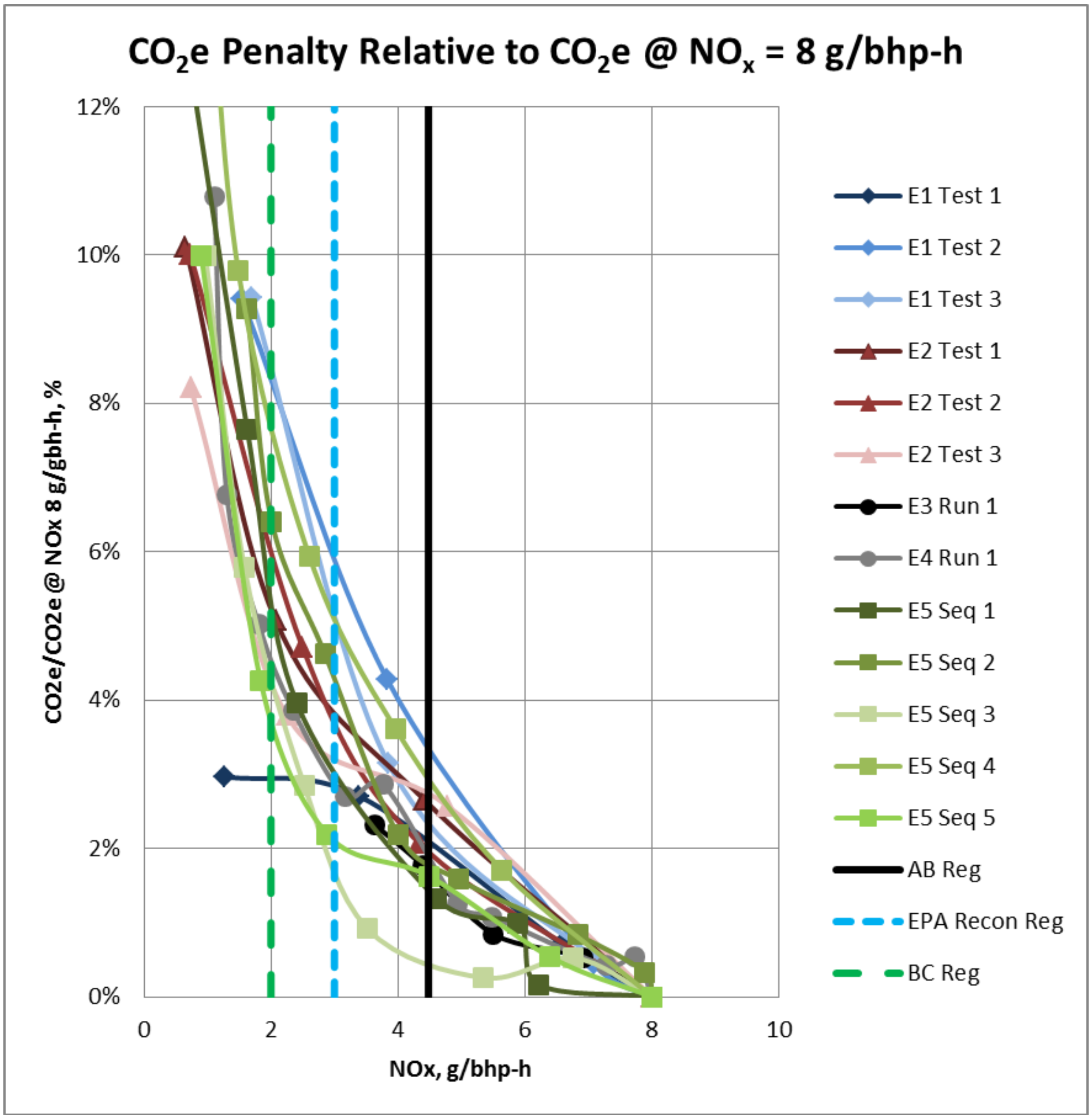


Figure 3-36: CO$_2$e penalty in percent based on CO$_2$e/CO$_2$e @ NO$_x$ = 8 g/bhp-h versus NO$_x$ for all engine tests at various Lambda with reference points for emissions criteria of 2.0, 3.0 and 4.48 g/bhp-h.

4 CONCLUSIONS AND RECOMMENDATIONS

Five Waukesha L7042GSI engines modified with the installation of REMVue AFR control systems were tested to characterize fuel consumption and emissions during a series of tests at difference Lambda values. Engine locations ranged from southern Alberta to northeast British Colombia. Power output levels varied from site to site based on site specific operating conditions and demand. Overall load values tested ranged from 750 bhp to 1366 bhp. The rated power output of new L7042GSI engines is 1480 bhp at 1200 rpm, however, four of the five engines were older versions with rated power levels of 1100 bhp at 1000 rpm.

All engines were tested at condition that attempted to achieve NO_x emission levels of 2.0 g/bhp-h (2.7 g/kWh) and all were tested in the lean burn region of operation compatible with the application of REMVue AFR control technology. Lambda values were in the range of 1.22 to 1.59. One engine appeared to be turbo limited and could not achieve NO_x levels lower than about 4.0 g/bhp-h (5.4 g/kWh).

Based on the tests completed the following general conclusions are made:

- Engine operation over the Lambda ranges tested resulted in no shut downs for the reported test conditions. However, most test conditions were maintained for a few minutes and no conclusions should be drawn with respect to long term operation at any condition.
- Engine emission performance, and specifically the relationship between NO_x and CO_2e, has been demonstrated and, in general, ARF control technology in the lean burn region has the potential to reduce NO_x emissions to levels at or below 2.0 g/bhp-h (2.7 g/kWh). However, application of this technology does not guarantee that a specific engine can achieve such a criterion.
- Performance of any engine is engine specific based on physical setup, maintenance and other site specific conditions and exact performance levels cannot be determined a priori.
- In general, all engines performed better than the average Industry Post-REMVue reference point and both above and below the OEM (Standard Economy) Waukesha BSFC reference point. These reference points are defined in Section 3.1 where it is noted that the Post-REMVue point is based on data contained in the Literature Review and the Waukesha points are from published company data sheets.
- All NO_x levels achieved were less than the OEM (Standard Economy) and OEM (3-Way Catalytic Converter) reference points.

Additional conclusions based on the five engines tested are:

- Except for Engine 3, all engines were able to achieve NO_x emission levels of 2.0 g/bhp-h (2.7 g/kWh) or less. Maximum NO_x reductions from a baseline condition defined as the lowest Lambda tested were up to 90^+%. One test sequence on one engine achieved only 70^+%.
- CO_2e increased as NO_x emissions decreased. For the most part, this was due to an increase in fuel consumption required to heat additional combustion air. Maximum CO_2e increases, corresponding to the 90^+% NO_x reduction from the defined baseline were up to about 15^+%. For some engines, NO_x emission levels of less than 1.0 g/bhp-h were achieved.
- THC emissions increase as Lambda increase resulting in an increased CO_2e emissions burden. Average increases in THC, as the engine moved from lowest to highest Lambda, were about 50%. THC emissions for each engine were different and ranged from a low of 2% to a high as 15% of total CO_2e. The reason for low or high THC emissions was not investigated as it was outside the scope of the project.

- Based on a compilation of all test results, a NO_x emissions criterion of 4.48 g/bhp-h (6.0 g/kWh) was achieved by the tested engines at Lambda values between 1.32 and 1.44. The CO_2e increase or penalty ranged from 1 of 4%. The increased operating cost for fuel only would be somewhat less.
- Based on a compilation of all test results, a NO_x emissions criterion of 3.0 g/bhp-h (4.0 g/kWh) were achieved by the tested engines at Lambda values between 1.38 and 1.48. The CO_2e increase or penalty ranged from 2 of 7%. The increased operating cost for fuel only would be somewhat less.
- Based on a compilation of all test results, a NO_x emissions criterion of 2.0 g/bhp-h (2.7 g/kWh) were achieved by the tested engines at Lambda values between 1.41 and 1.53. The CO_2e increase or penalty ranged from 4 to 10%. The increased operating cost for fuel only would be somewhat less.
- For engines that exhibit THC emissions greater than about 1000 ppm, the data suggest that increasing Lambda to reduce NO_x may lead to additional CO_2e emissions of up to 2% above those associated with an increase in BSFC. The extra CO_2e is associated with incremental increases in residual THC and CH_4 in the flue gases.
- Analyser bias was examined for O_2, THC and NO_x and is expressed relative to the ECOM data. O_2 bias is quite small and not considered to be significant. Likewise, bias in THC suggests that CO_2e may be marginally understated by as much as 20 g/bhp-h. NO_x bias appears to be a percent of actual NO_x values and NO_x emissions may be overstated by 0.2 g/bhp-h at low emission values of 1.0-2.0 g/bhp-h and overstated by as much as 1.8 g/bhp-h at high emission levels of 12-14 g/bhp-h. The effect of potential analyser bias is modest and does not negate conclusions regarding engine performance.
- Estimated uncertainties for AFR_{STOIC} (7.1%), AFR (9.3%), Lambda (16.0%), BSFC (7.7%), NO_x (kg/h 11.8%, g/bhp-h 12.8% and ng/J 13.1%) and CO_2e (kg/h 7.4%, g/bhp-h 8.9% and ng/J 9.4%) should be taken into consideration when the results of this study are applied. Based on other studies these uncertainties may not be conservative.

Conclusions with respect to flue gas testing are:

- Field instruments required for determining O_2 in the flue gas are acceptable with respect to setting the AFR and Lambda.
- Field instruments for determining THC and the methane component require additional evaluation and possibly more rigorous field calibration procedures.
- Potential differences in right and left side engine performance should be addressed in future engine emissions studies in order to improve consistency in collected data and calculated results.
- Analyser bias and absolute accuracy should be examined prior to any future studies especially at emission levels at or near potential regulatory requirements.

Conclusions with respect to fuel gas and energy output measurement are:

- Fuel gas meters calibration should be included with any future studies to eliminate potential bias and uncertainty.
- Engine power output should be determined at each test point to reduce variability in test results.

5 REFERENCES CITED

AENV 2002, Inventory of Nitrogen Oxide Emissions and Control Technologies in Alberta's Upstream Oil and Gas Industry, Sachin Bhardwaj, for Alberta Environment, Science and Standards Division, March 2002

CCEMC 2011, CCEMC Validation Guidance Document, Climate Change and Emissions Management Corporation, 2011.

Environment Canada 2011, National Inventory Report 1990-2008 Part 2 Greenhouse Gas Sources and sinks, Annex 8 A8.1.2.3.

US EPA 2008, Federal Register Friday, January 18, 2008 Part III Environmental Protection Agency 40 CFR Parts 60, 63, 85 et al. Page 3574, 1. SI NSPS

NovaLynx 2008, Elevation Correction Tables for Barometric Pressure Sensors, NovaLynx Corporation, Copyright © 1988-2008 by NovaLynx Corporation.

SGA 2000, Emission Factors and Uncertainties for CH_4 & N_2O from Fuel Combustion, SGA Energy Limited Report to Environment Canada, August 2000.

SGER 2009, Quantification Protocol for Engine Fuel Management and Vent Gas Capture Projects, Specified Gas Emitters Regulation, Alberta Environment Climate Change Policy Unit, 2009.

Cudney 2005, Comparative Evaluation of Test Methods for Reciprocating Engines; EPA Reference Methods vs. Portable Analyzer, R Cudney, Trinity Consultants, October 27, 2005.

Waukesha 2010, Environmental 9 Gas Engine Exhaust Emission Levels, Ref. S 8483-6, En: 152605, Date: 6/10.

6 Appendix A - Field Data

6.1 Combustion Calculation Software

Clearstone Engineering Limited software is used for performing combustion calculations based on the information typically gathered as a part of a gas burning combustion source testing program. The gas can be any mixture of pure compounds that contains combustible substances. The software handles four scenarios with minimum data availability as outlined in Table 1.

Table 1 Information requirements for combustion analyses software

Parameter	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Power Rating	X		X	
Load	X		X	
Fuel Analyses	X	X	X	X
Fuel Flow[1]		X		XXX
Air Flow Rate[1]				XXX
Flue Gas Analyses				X
Air-Fuel Ratio	Y	Y		
Flue Gas Flow[1]				XXX
Flue Gas temperature	X	X	X	X
Flue Gas Analyses (Minimum of O_2)			X	X
X - Required				
XXX – one of these three is required				
Y – If not provided a default value is used.				
1 – volume flow rate, pressure and temperature required or mass flow rate for fuel				

In scenarios 1 and 2, ideal combustion calculations are performed assuming complete combustion using dry air. In Scenarios 3 and 4, calculations take into considerations the measured levels of CO and hydrocarbons in the flue gases. The software can handle all hydrocarbons listed in the fuel gas analyses.

The following information is required regarding the equipment:

a) The manufacturer’s thermal efficiency data for the equipment.
b) The manufacturer’s air to fuel ratio data for the equipment.

In case the above information is not available, the following default values are applied:

a) Equipment loading - 100 percent.
b) Thermal efficiency:

i)	Heaters and Boilers	82 percent
ii)	Reciprocating engines four stroke	30 percent
iii)	Reciprocating engine two stroke	32 percent
iv)	Gas Turbine	30 percent

c) Air to fuel ratio is determined based on the maximum of the following normal ranges:

i)	Boilers and Heaters (Natural Draft)	Excess Air	10 – 15 percent.
ii)	Boilers and Heaters (Forced Draft)	Excess Air	5 – 10 percent.
iii)	Reciprocating Engine (Two Stroke)	Air/fuel Ratio	40 – 52
iv)	Reciprocating Engine (Four Stoke, Rich Burn)	O_2 in Exhaust	0.5 – 2 percent
v)	Reciprocating Engine (Four Stoke, Low NO_x)	O_2 in Exhaust	6.0 – 7.8 percent
vi)	Gas Turbine	O_2 in Exhaust	15.0 – 18.0 percent

In scenarios 3 and 4, the flue gas temperature and flue gas composition measurement data are provided. Scenario 3 is a situation where only the equipment nameplate details are available and no flow rate measurements for fuel, air or flue gas is available. Scenario 4 is the typical of the stack testing campaign.

The software takes into consideration the presence of water in fuel, gas and air, and the gross and net heating values of fuel are determined by rigorous calculation of heat of combustion reaction based on fuel gas composition and thermochemical data for the pure components in the fuel. The material balance considers the presence of inert compounds and combustion product in the fuel.

If the sulphur dioxide concentration in the flue gas is provided, emissions are computed based on the measured sulphur dioxide concentration in flue gas. If sulphur dioxide is not measured and sulphur compounds are present in the fuel, emissions are computed based on a material balance and complete combustion of the sulphur compounds.

The enthalpy of the air, fuel and flue gas streams are determined using the Peng-Robinson Equation of State.

Combustion calculations are performed in the following sequence:

a) Determine the gross and net heating value of the fuel gas.
b) Determine the flow rate of air, flue gas along with the composition of the flue gas by performing the rigorous material balance calculations. Calculations are based on 100 moles/h of fuel flow along with the known stack gas analysis data. Total combustion is assumed whenever ideal combustion calculations are performed.
c) Determine the actual flow rate of air, fuel and stack gas based on the known flow rate of one of these streams. When the calculations are based on equipment rating, the flow rate for fuel is determined based on the equipment rating, loading and thermal efficiency.
d) Determine the gross and net energy input to the combustion equipment based on the flow rate, temperature and pressure of air and fuel.
e) Determine the energy content of the flue gas based on the flow rate and known stack gas temperature and pressure.

f) Determine the dew point of the flue gas based on the computed composition of the flue gas.
g) Determine the recoverable heat from the flue gas as the enthalpy difference between the flue gas at the flue temperature and at 10 degrees Celsius above the calculated dew point temperature. Potential flue gas cooling is limited to 15 degrees Celsius.
h) Determine the ideal air flow based on the ideal air to fuel ratio for the particular equipment. The ideal air to fuel ratio is determined based on the appropriate default values as noted above.
i) When the air flow is higher than the ideal air flow rate, determine the excess air heat loss as the heat energy required to heat the extra air from inlet temperature to the flue gas outlet temperature.
j) When combustible gases are present in the flue gas determine the heat of combustion of the flue gas to determine the energy loss due to incomplete combustion.
k) Determine the cost of the lost energy based on the cost price of the fuel gas.
l) Determine the carbon combustion efficiency and the apparent thermal efficiency of the combustion equipment.

The material balance for the combustion process is performed using the following methodology:

- Based on the composition and flow rate of the fuel (100 moles/hr) and the composition of the air the following useful quantities are determined:
    i) Total moles of combustion product in fuel N_{pf} (carbon dioxide, nitrogen, water and sulphur dioxide).
    ii) Total moles of usable oxygen in the fuel N_{uof} (oxygen and total number of oxygen molecules in the combustible compounds).
    iii) Total moles of non-combustible substances excluding the compounds mentioned in step (i) and (ii) N_{inf}.
    iv) Total moles of oxygen molecule in the fuel N_{O2f}.
    v) Total moles of combustible hydrocarbon in fuel N_{hcf}.
    vi) Total moles of water in the fuel N_{wf}.
    vii) Total number of atoms of carbon n_C.
    viii) Total number of atoms of hydrogen n_H.
    ix) Total number of atoms of sulphur n_S.
    x) Mole fraction of water in air Y_{wa}.
    xi) Mole Fraction of oxygen in air Y_{oa}.
    xii) Mole fraction of nitrogen in air Y_{na}.
- The measured mole fraction of the flue gas compounds are expressed as:
  Carbon monoxide X_{COs}, Nitric Oxide X_{NOs}, Nitrogen dioxide X_{NO2s}, Sulphur dioxide X_{SO2s}, Oxygen X_{O2s}, and Total Hydrocarbons X_{THCs}.
- Assume the molar air flow rate F_a.
- Determine the total stack gas flow rate F_s using the following relationship where the stack gas analysis data is on wet basis:

$F_s = (n_H/4 + N_{pf} + N_{uof} + N_{inf} + F_a) / D$

Where:

$D = 1 - X_{THCs} + X_{THCs} / N_{hcf} * (n_H/4 + (N_{uof} - N_{O2f})) - X_{COs} / 2 + X_{NO2s} / 2$

- Determine the oxygen balance function Ho as follows:

  $Ho = (N_{O2f} + Y_{oa} * F_a + F_s * X_{COs} / 2 + (F_s * X_{THCs} / N_{hcf} -1) * (n_C + n_H/4 + n_S - N_{uof} + N_{O2f}) - F_s * (X_{NO2s} * 2 + X_{NOs}) / 2 - F_s * X_{O2s}) / (F_s * X_{O2s})$

- In case the stack gas composition is on dry basis the following calculations are performed:

  $F_{ds} = ((Y_{oa} + Y_{na}) * F_a + N_{pf} - N_{wf} - n_H/4 + N_{uof} + N_{inf}) / D_d$

  Where:

  $D_d = 1 - X_{THCs} + X_{THCs} / N_{hcf} * (-n_H/4 + (N_{uof} - N_{o2f})) - X_{COs} / 2 + X_{NO2s} / 2$

  $F_s = F_{ds} * (1 - X_{THCs} * n_H / 2 / N_{hcf}) + n_H / 2 + N_{wf} + Y_{wa} * F_a$

  And

  $T = F_{ds} / F_s$

  $X_{COsw} = X_{COs} * T$

  $X_{NOsw} = X_{NOs} * T$

  $X_{NO2sw} = X_{NO2s} * T$

  $X_{O2sw} = X_{O2s} * T$

  $X_{THCsw} = X_{THCs} * T$

  $Ho = (N_{O2f} + Y_{oa} * F_a + F_s * X_{COsw} / 2 + (F_s * X_{THCsw} / N_{hcf} -1) * (n_C + n_H/4 + n_S - N_{uof} + N_{O2f}) - F_s * (X_{NO2sw} * 2 + X_{NOsw}) / 2 - F_s * X_{O2sw}) / (F_s * X_{O2sw})$

- Correct the value of F_a using Newton-Raphson method to reduce the value of the function Ho to less than 1.0e-10.
- Determine the flow prorating factor T1 based on the specified flow rate of air, fuel or stack gas i.e.

  When fuel flow rate F_{fs} is known then $T1 = F_{fs} / 100.0$.

  When air flow rate F_{as} is known then $T1 = F_{as} / F_a$.

  When flue gas flow rate F_{ss} is known then $T1 = F_{ss} / F_s$.

- Determine the fuel, air and flue gas flow rate for the combustion device as follows:

  Fuel flow rate $F_{ff} = 100.0 * T1$

  Air flow rate $F_{af} = F_a * T1$

  Flue gas flow rate $F_{sf} = F_s * T1$

- Determine the total fuel energy input to the combustion device as follows:

  $E_{in} = F_{ff} * H_{hv}$

  Where H_{hv} is the gross heating value of the fuel in J/mol.

- Determine the emission factors in ng/J for various exhaust compound as follows:

  $EF_{CO2} = (Y_{CO2f} * 100.0 + n_C * (1 - F_s * X_{THCsw} / N_{hcf}) - F_s * X_{COsw}) * T1 / E_{in} * MW_{CO2} * 1.0e9.$

  $EF_{SO2} = (Y_{SO2f} * 100.0 + n_S * (1 - F_s * X_{THCsw} / N_{hcf})) * T1 / E_{in} * MW_{SO2} * 1.0e9.$

  $EF_{CO} = F_s * X_{COsw} * T1 / E_{in} * MW_{CO} * 1.0e9.$

  $EF_{NO} = F_s * X_{NOsw} * T1 / E_{in} * MW_{NO} * 1.0e9.$

$EF_{NO2} = F_s * X_{NO2sw} * T1 / E_{in} * MW_{NO2} * 1.0e9.$

$EF_{NOx} = EF_{NO2} + EF_{NO}$

$EF_{CH4} = (Y_{CH4f} * F_s * X_{THCsw} * 100.0 / N_{hcf})) * T1 / E_{in} * MW_{CH4} * 1.0e9.$

$EF_{C2H6} = (Y_{C2H6f} * F_s * X_{THCsw} * 100.0 / N_{hcf})) * T1 / E_{in} * MW_{C2H6} * 1.0e9.$

$EF_{THC} = F_s * X_{THCsw} * T1 / E_{in} * MW_{HCf} * 1.0e9.$

$EF_{VOC} = EF_{THC} - EF_{C2H6} - EF_{CH4}.$

6.2 Fuel Gas Analyses

Table 6-1 below summarizes the fuel gas compositions used in the calculations for each of the engines studied

Table 6-1: Summary of the applied fuel gas compositions for each engine studied.

Component	Mole Fraction				
	Engine 1	Engine 2	Engine 3	Engine 4	Engine 5
H_2	0.000	0.000	0.000	0.000	0.000
He	0.001	0.001	0.001	0.001	0.000
N_2	0.024	0.028	0.028	0.027	0.002
CO_2	0.001	0.002	0.002	0.001	0.026
H_2S	0.000	0.000	0.000	0.000	0.000
C_1	0.972	0.967	0.967	0.967	0.910
C_2	0.002	0.002	0.002	0.002	0.042
C_3	0.000	0.000	0.000	0.000	0.012
iC_4	0.000	0.000	0.000	0.000	0.002
C_4	0.000	0.000	0.000	0.000	0.003
iC_5	0.000	0.000	0.000	0.000	0.001
C_5	0.000	0.000	0.000	0.000	0.001
C_6	0.000	0.000	0.000	0.000	0.001
C_7	0.000	0.000	0.000	0.000	0.001
Total	1.000	1.000	1.000	1.000	1.000
THC	0.974	0.969	0.969	0.970	0.973
C_1/THC	0.997	0.997	0.997	0.997	0.936
HHV (MJ/m^3)	37.00	36.80	36.80	36.90	39.60
LHV (MJ/m^3)	32.80	32.60	32.60	32.60	35.20
Fuel MW (kg/kmol)	16.38	16.43	16.43	16.42	17.87

6.3 Engine Specific REMVue Installation Histories

All engines tested had maintenance and or upgrade work completed when the REMvue conversions were installed. Work completed for each engine was indicated to be:

- Engine 1:
    - Overhaul included cleaning and combing of the JW and Aux Cooler and full rebuild.
    - Upgrades included Intercooler Turbulator Spring retrofit (GSI to GL Conversion) and changing turbos to T18 from T30.
    - REMVue with AFR End-device installation and ignition upgraded to MPI-16.
- Engine 2
    - Overhaul not done.
    - Upgrades included throttle plate using existing T30 turbos.
    - REMVue with AFR End-device installation and ignition upgraded to MPI-16.
- Engine 3
    - Overhaul included full overhaul minus head replacement.
    - Upgrades included changing turbos to T18 from T30 and pilot Spartan Aux trim cooler.
    - This engine appeared to have turbo problems and could not achieve Lambda values greater than those tested.
    - REMVue with AFR End-device installation and ignition upgraded to MPI-16.
- Engine 4
    - Overhaul included replacement of all heads.
    - Upgrades were none.
    - REMVue with AFR End-device installation and ignition upgraded to MPI-16.
- Engine 5
    - Overhaul not done.
    - Upgrades included, Intercooler Turbulator Spring Retrofit (GSI to GL Conversion). Turbo was a T18 and not upgraded.
    - REMVue AFRC installation with panel subplate upgrade (Enerflex Exacta to REMVue 500AS), AFR End-device Installation, and ignition upgrade to Altronic to MPI-16.
    - External AUX-W Trim Cooler installed about 1 year after REMVue AFRC installation (Summer 2011).

6.4 Engine Data

Table 6-2 to Table 6-25 represent raw data collected in the field from each of the engines studied. Data required which is not shown here was obtained from another data source such as the REMVue output data files, combustion analyser output files, or meteorological instrument log files. Data shown here also may not represent the values used in the combustion analysis calculations as averaged values from the aforementioned sources were used when possible.

Table 6-2: Engine 1 data collection sheet

Site Data			
Engine Name/Tag No	Engine 1	Testing Date	18-Oct-11
Engine Data			

Manufacturer	Waukesha	Date Manufactured	
Model	L7042GSI	Serial #	
Rated Power (kW or HP)	1100 HP	Number of Cylinders	12
Bore (in or mm)		Stroke (in or mm)	
Displacement (cu in or L)		Turbo Charger (Y/N)	Y, dual (twin) turbo
AFR Make/Model	REMVue 500AS Plus	Catalytic Convertor (Y/N)	N
Fuel Gas Meter Make/Model		Fuel Gas Meter Calibration Date	
Cooler manufacturer:	Air-X-Changer	Cooler model #	144-EH
Cooler job #:	768078D		
Compressor Data			
Manufacturer	Worthington	Date Manufactured	
Model	0F6-SU4	Serial #	Cylinder nameplates - see below
Compression Stages	2	Number of Cylinders	4
Interstage Cooler (Y/N)	Y	Lube Oil Pump (Y/N)	Y
Stage 1:			
Compressor cylinder #1 S/N:	L-99068	Compressor cylinder #3 S/N:	L-98465
Cylinder #1 Bore:	10	Cylinder #3 Bore:	10
Cylinder #1 stroke:	6	Cylinder #3 stroke:	6
Cylinder #1 Max press. (psi):	1000	Cylinder #3 Max press. (psi):	1000
Cylinder #1 piston/rod weight (lb):	87	Cylinder #3 piston/rod weight (lb):	86
Stage 2:			
Compressor cylinder #3 S/N:	L-98467	Compressor cylinder #4 S/N:	L-98468
Cylinder #2 Bore:	6	Cylinder #4 Bore:	10
Cylinder #2 stroke:	6	Cylinder #4 stroke:	6
Cylinder #2 Max press. (psi):	1800	Cylinder #4 Max press. (psi):	1800
Cylinder #2 piston/rod weight (lb):	73	Cylinder #4 piston/rod weight (lb):	73
Fuel and Process Gas			
Gas Analysis Date		Process Gas Analysis Date	
Flue Gas Data			
Sample Point	Between manifold & turbo	Temperature Measurement Point	Same (TC readout in REMVue)
Measurement Device Data			
Power Measurement:	Dynalco Reciptrap 9260	Flue gas analyzer:	ECOM-KL
		Flue gas serial no:	2405 OLVNXH
Other Comments / Observations:			
Suction gas temperatures read from gauge			
Gas analyzer time half an hour ahead of REMVue unit time (1:52 sensor = 1:22 REMVue Data)			
Engine missing nameplate			
Data from weather station collected. REMVue data logs collected. Fuel gas data collected.			
Ignition angle 24 degrees BTDC at all settings (confirmed after main data collection)			
No fuel gas temperature sensor present. Measured pipe temperature with laser (Raytek), roughly 22°C			

Table 6-3: Engine 1 Test data at 985 RPM and 824 HP for various air-fuel ratios

Test Data	Air-Fuel Ratio Setting											
	1(1,2)			2			3			4		
Oxygen Set point	7.5			7.0			6.0			5.0		
Site Conditions												
Ambient Temperature (°C)	11.0			12.3			13.1			13.5		
Relative Humidity (%)	45.4			43.1			41.8			39.6		
Barometric Pressure (kPa)	103.89			103.86			103.83			103.86		
Engine												
Intake Manifold Pressure (psi) (L/R)	3.3/3.4			1.9/2.0			0.9/1.0			0.3/0.3		
Intake Manifold Air Temperature (°C) (L/R)	38.1/38.3			37.6/37.8			37.7/38.1			37.5/37.7		
Speed (rpm)	985			985			989			987		
Torque (%)	68%			68%			68%			68%		
Fuel index (%)	71%			67%			66%			66%		
Ignition Angle (° BTDC)	24			24			24			24		
Exhaust Temperature (°C)	600.7			597.8			602.2			609.0		
Mass Fuel Flow (kg/h)	145.5			139			137.1			137.3		
Fuel Temperature (°C)	22			22			22			22		
Fuel Pressure (psi)	47.2			47.7			47.9			47.9		
Compressor												
Flow (kg/h)	Unavailable											
1st Stage Suction Pressure (psi)	55.2			55.5			55.5			55.6		
1st Stage Suction Temperature (°C)	28			28			29			30		
1st Discharge Pressure (psi)	21.6			216			216			216		
1st Discharge Temperature (°C) (#1/#3)	139.5/138.3			140.5/139.4			141.4/140.3			142.3/141.2		
2nd Stage Suction Pressure (psi)	212			212			213			213		
2nd Stage Suction Temperature (°C)	29			29			30			30		
2nd Discharge Pressure (psi)	803			802			803			803		
2nd Discharge Temperature (°C) (#2/#4)	156.5/153.4			156.2/153			156.8/153.6			157.1/153.4		
Compressor Load (HP)	824			824			824			824		
Flue Gas	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**
Time of Measurement (analyzer)	11:34	11:38	11:43	11:59	12:01	12:03	12:12	12:15	12:17	12:33	12:36	12:37
Temperature at sampling point (°C)	600	600	602	598	597.5	598	601.9	602.5	602.3	608.8	609.2	608.9
Room Temperature (°F)	ND	ND	ND	89	89	89	90	90	90	93	92	92
O_2 Concentration (%)	7.5	7.5	7.5	7.0	7.0	7.0	6.0	6.0	5.9	5.0	5.0	5.0
CO_2 Concentration (%)	7.5	7.5	7.5	7.8	7.8	7.8	8.4	8.4	8.4	8.9	8.9	8.9

Table 6-3: Engine 1 Test data at 985 RPM and 824 HP for various air-fuel ratios

Test Data	Air-Fuel Ratio Setting											
	1(1,2)			2			3			4		
NO Concentration (ppm)	197.1	198.3	214.7	708	718	709	1558	1595	1624	2759	2745	2736
NO_2 Concentration (ppm)	66.8	66.7	67.8	115	117	117	168	173	174	246	233	238
NO_x Concentration (ppm)	263.9	265.1	282.5	823	835	826	1726	1768	1798	3005	2978	2974
CO Concentration (ppm)	261	262	262	279	284	287	286	289	287	262	263	261
THC Concentration (ppm Testo, % ECOM)	910	1020	680	0.147	0.149	0.151	0.139	0.139	0.139	0.136	0.139	0.139
Efficiency (Testo/ECOM)	89.1	89.1	89.2	89.5	89.5	89.5	89.5	89.5	89.5	89.6	89.5	89.5
(Excess air % Testo, Lambda ECOM)	48.90%	49.20%	49.00%	1.5	1.5	1.5	1.4	1.4	1.39	1.31	1.31	1.31
Sensor temp (°F)	ND	ND	ND	82	83	83	84	84	84	86	86	86

1. Test # 1 flue gas analysis was completed with the Testo analyzer, The remaining were performed with the ECOM Analyzer

2. ND denotes "no data available"

Table 6-4: Engine 1 test data at 940 RPM and 787 HP for various air-fuel ratios

Test Data	Air-Fuel Ratio Setting			
	5	6	7	8
Oxygen Set Point	8.0	7.0	6.0	5.0
Site Conditions				
Ambient Temperature (°C)	15.5	15.8	16.4	16.4
Relative Humidity (%)	36.0	35.6	34.5	33.4
Barometric Pressure (kPa)	103.76	103.73	103.73	103.69
Engine				
Intake Manifold Pressure (psi) (L/R)	3.0/3.2	1.7/1.7	0.8/0.9	0.2/0.2
Intake Manifold Air Temperature (°C) (L/R)	40.1/40.3	38.7/38.9	39.1/39.3	38.8/39.1
Speed (rpm)	940	940	940	940
Torque (%)	68%	68%	68%	68%
Fuel index (%)	69%	67%	66%	66%
Ignition Angle (° BTDC)	24	24	24	24
Exhaust Temperature (°C)	587.2	584.7	589.3	596.5
Mass Fuel Flow (kg/h)	136.7	134.1	131.7	131.4
Fuel Temperature (°C)	22	22	22	22
Fuel Pressure (psi)	48	48.2	48.3	48.3
Compressor				

Table 6-4: Engine 1 test data at 940 RPM and 787 HP for various air-fuel ratios

Test Data	Air-Fuel Ratio Setting											
	5			6			7			8		
Flow (kg/h)												
1st Stage Suction Pressure (psi)	57.5			57.4			57.6			57.7		
1st Stage Suction Temperature (^{o}C)	31			31			32.5			33		
1st Discharge Pressure (psi)	221			220			221			221		
1st Discharge Temperature (^{o}C) (#1/#3)	142.6/141.4			142.8/142.1			143.2/142.6			143.8/143.1		
2nd Stage Suction Pressure (psi)	218			217			217			218		
2nd Stage Suction Temperature (^{o}C)	31			31			32			31		
2nd Discharge Pressure (psi)	803			803			803			804		
2nd Discharge Temperature (^{o}C) (#2/#4)	155.9/153.2			156.3/153			156.2/152.4			155.9/152.8		
Compressor Load (HP)	787			787			787			787		
Flue Gas	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**
Time of Measurement (analyzer)	1:18	1:21	1:23	1:34	1:37	1:38	1:49	1:51	1:52	2:04	2:06	2:07
Temperature at sampling point (^{o}C)	588.3	586.7	586.7	583.8	584.9	585.3	588.6	590.1	589.3	596.4	596.5	596.5
Room Temperature (°F)	94	94	94	95	95	95	95	95	95	96	96	96
O_2 Concentration (%)	8.0	8.0	8.0	7.0	7.0	6.9	6.0	6.0	5.9	5.0	5.0	5.0
CO_2 Concentration (%)	7.2	7.2	7.2	7.8	7.8	7.9	8.4	8.4	8.4	8.9	8.9	8.9
NO Concentration (ppm)	236	239	248	810	812	809	1731	1724	1742	2869	2925	2877
NO_2 Concentration (ppm)	84	82	82	121	124	125	169	175	179	237	242	243
NO_x Concentration (ppm)	320	321	330	931	936	934	1900	1899	1921	3106	3167	3120
CO Concentration (ppm)	245	247	246	281	278	275	270	272	272	236	237	238
THC Concentration (%)	0.196	0.189	0.188	0.171	0.169	0.169	0.152	0.152	0.152	0.144	0.145	0.146
Efficiency (%)	89.4	89.4	89.4	89.5	89.5	89.5	89.5	89.5	89.5	89.6	89.6	89.5
Lambda	1.62	1.62	1.62	1.5	1.5	1.49	1.4	1.4	1.39	1.31	1.31	1.31
Sensor temp (°F)	89	89	89	90	90	90	91	91	91	91	91	91

Table 6-5: Engine 1 test data at 900 RPM and 749 HP at various air-fuel ratio settings

Test Data	Air-Fuel Ratio Setting			
	9	10	11	12
Oxygen Set Point	8.0	7.0	6.0	5.0
Site Conditions				

Table 6-5: Engine 1 test data at 900 RPM and 749 HP at various air-fuel ratio settings

Test Data	Air-Fuel Ratio Setting											
	9			10			11			12		
Ambient Temperature (^oC)	19.1			18.6			18.5			17.8		
Relative Humidity (%)	28.6			30.8			29.1			30.1		
Barometric Pressure (kPa)	103.69			103.66			103.66			103.62		
Engine												
Intake Manifold Pressure (psi) (L/R)	2.9/2.9			1.6/1.6			0.7/0.8			0.1/0.1		
Intake Manifold Air Temperature (^oC) (L/R)	42.3/42.4			41.8/41.9			40.0/40.2			38.8/39.0		
Speed (rpm)	900			900			900			900		
Torque (%)	68%			68%			68%			68%		
Fuel index (%)	67%			64%			63%			63%		
Ignition Angle (^{o} BTDC)	24			24			24			24		
Exhaust Temperature (^oC)	576.6			575.7			578.8			586.7		
Mass Fuel Flow (kg/h)	128.3			124.3			122.9			122.4		
Fuel Temperature (^oC)	22			22			22			22		
Fuel Pressure (psi)	48.4			48.7			48.8			48.8		
Compressor												
Flow (kg/h)												
1st Stage Suction Pressure (psi)	59.2			59.2			59.2			59.3		
1st Stage Suction Temperature (^oC)	34			33.5			33.5			33.5		
1st Discharge Pressure (psi)	224			224			224			224		
1st Discharge Temperature (^oC) (#1/#3)	143.9/143.1			144.0/143.1			143.8/142.6			143.6/142.1		
2nd Stage Suction Pressure (psi)	220			221			221			221		
2nd Stage Suction Temperature (°C)	31			31.5			31.5			31.5		
2nd Discharge Pressure (psi)	804			804			805			805		
2nd Discharge Temperature (°C) (#2/#4)	154.5/150.8			155.0/151.3			154.8/151.1			154.6/150.7		
Compressor Load (HP)	749			749			749			749		
Flue Gas	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**
Time of Measurement (analyzer)	2:42	2:44	2:45	2:58	2:59	3:00	3:08	3:10	3:10	3:21	3:23	3:25
Temperature at sampling point (^oC)	576.7	576.6	576.4	575.6	575.6	575.9	578.7	578.6	579	585.8	586.7	587.6
Room Temperature (°F)	97	97	97	96	96	96	95	95	95	95	95	95
O_2 Concentration (%)	8.0	8.0	8.0	7.0	7.0	7.0	6.0	6.1	6.1	5.0	5.0	5.0
CO_2 Concentration (%)	7.2	7.2	7.2	7.8	7.8	7.8	8.4	8.3	8.3	8.9	8.9	8.9
NO Concentration (ppm)	262	285	288	820	843	856	1735	1751	1764	3017	3027	3081
NO_2 Concentration (ppm)	86	87	87	122	124	126	168	169	172	262	263	267
NO_x Concentration (ppm)	348	372	375	942	967	982	1903	1920	1936	3279	3290	3348

Table 6-5: Engine 1 test data at 900 RPM and 749 HP at various air-fuel ratio settings

Test Data	Air-Fuel Ratio Setting											
	9			10			11			12		
CO Concentration (ppm)	247	244	244	274	274	272	265	263	263	219	217	222
THC Concentration (%)	0.186	0.186	0.186	0.162	0.162	0.162	0.15	0.147	0.147	0.135	0.136	0.136
Efficiency (%)	89.4	89.4	89.4	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5
Lambda	1.62	1.62	1.62	1.5	1.5	1.5	1.4	1.41	1.41	1.31	1.31	1.31
Sensor temp (°F)	93	93	93	93	93	93	93	93	93	92	92	92

Table 6-6: Engine 2 data collection sheet

Site Data			
Engine Name/Tag No	Engine 2	Testing Date	19-Oct-11
Engine Data			
Manufacturer	Waukesha	Date Manufactured	
Model	L-7042GSI	Serial #	387449
Rated Power (kW or HP)		Number of Cylinders	12
Bore (in or mm)		Stroke (in or mm)	
Displacement (cu in or L)		Turbo Charger (Y/N)	Y, twin
AFR Make/Model	REMVue 500AS Plus	Catalytic Convertor (Y/N)	
Fuel Gas Meter Make	Micromotion	Fuel Gas Meter Calibration Date	
Fuel Gas Meter Model	R050S113NCAAEZZZZ	Fuel Gas Meter Serial	14235444
Fuel Gas Meter Deus cal:	4330048914.25		
Cooler manufacturer:		Cooler model #	
Cooler job #:			
Compressor Data			
Manufacturer	Ingersoll Rand	Date Manufactured	
Model		Serial #	See below (cylinders)
Compression Stages	2	Number of Cylinders	4
Interstage Cooler (Y/N)	Y	Lube Oil Pump (Y/N)	Y
Cylinder type:	RDH		
Stage 1:			
Compressor cylinder #2 S/N:	SR-205	Compressor cylinder #4 S/N:	SR-204
Cylinder #2 Bore:	9.5	Cylinder #4 Bore:	9.5
Cylinder #2 stroke:	5	Cylinder #4 stroke:	5
Cylinder #2 rated press. (psig):	600	Cylinder #4 rated press. (psig):	600
Cylinder #2 Max press. (psi):	650	Cylinder #4 Max press. (psi):	650
Cylinder #2 disch. valve:	60CS1B	Cylinder #4 disch. valve:	60CS1B
Cylinder #2 inlet valve:	60CS2B	Cylinder #4 inlet valve:	60CS2B
Stage 2:			
Compressor cylinder #1 S/N:	6X6627	Compressor cylinder #3 S/N:	6X6628
Cylinder #1 Bore:	6.009	Cylinder #3 Bore:	6.007
Cylinder #1 stroke:	5	Cylinder #3 stroke:	5
Cylinder #1 rated press. (psig):	1500	Cylinder #3 rated press. (psig):	1500
Cylinder #1 Max press. (psi):	1650	Cylinder #3 Max press. (psi):	1650
Cylinder #1 disch. valve:	36CS1E	Cylinder #3 disch. valve:	36CS1E
Cylinder #1 inlet valve:	36CS2E	Cylinder #3 inlet valve:	36CS2E
Fuel and Process Gas			
Gas Analysis Date		Process Gas Analysis Date	
Flue Gas Data			
Sample Point	Pre-turbo, right side	Temperature Measurement Point	Same (TC readout in REMVue)
Measurement Device Data			
Power Measurement:	No measurement	Flue gas analyzer:	ECOM-KL
		Flue gas serial no:	2405 OLVNXH
Other Comments / Observations:			
Suction gas temperature read from gauge			

Table 6-6: Engine 2 data collection sheet
Site uses supplementary fuel collected from analyzers and vents for compressor fuel
Coolers driven by electric motor (50hp)
Data from weather station collected. REMVue data logs collected. Fuel gas data collected.
Fuel gas temperature ~20C, estimated from inlet pipe temperature
Ignition angle 24 degrees BTDC at all settings
Combustion analyzer time is 7 mins slower than REMVue

Table 6-7: Engine 2 test data at 940 RPM and 824 HP at various air-fuel ratio settings

Test Data	Air-Fuel Ratio Setting											
	1			2			3			4		
Oxygen Set point	8.0			7.0			6.0			5.0		
Site Conditions												
Ambient Temperature (^oC)	14.3			14.4			15.1			15.8		
Relative Humidity (%)	38.2			38.1			36.1			34.9		
Barometric Pressure (kPa)	102.88			102.88			102.84			102.84		
Engine												
Intake Manifold Pressure (psi) (L/R)	2.4/2.4			1.0/1.0			0.1/0.1			-0.4/-0.4		
Intake Manifold Air Temperature (^oC) (L/R)	35.1/36.2			34.5/35.1			33.4/33.9			33.4/33.6		
Speed (rpm)	940			940			940			940		
Torque (%)												
Fuel index (%)	62%			59%			58%			58%		
Ignition Angle (^{o} BTDC)	24			24			24			24		
Exhaust Temperature (^oC)	577.9			574.4			575.4			582.0		
Mass Fuel Flow (kg/h)	128.7			124			121.7			122.5		
Fuel Temperature (^oC)	20			20			20			20		
Fuel Pressure (psi)	53.7			54.1			54.2			54.2		
Compressor												
Flow (kg/h)												
1st Stage Suction Pressure (psi)	79.4			79			79.2			78.9		
1st Stage Suction Temperature (^oC)	19			19			19			19		
1st Discharge Pressure (psi)	254			254			254			256		
1st Discharge Temperature (^oC) (#2/#4)	116.7/114.3			116.9/114.4			117.1/114.5			117.3/114.6		
2nd Stage Suction Pressure (psi)	252			252			254			254		
2nd Stage Suction Temperature (°C)	42.5			42.5			42.5			43		
2nd Discharge Pressure (psi)	846			847			848			849		
2nd Discharge Temperature (°C) (#1/#3)	150.7/152.8			151.2/153.3			151.1/153.3			151.4/153.5		
Compressor Load (HP)	824			824			824			824		
Flue Gas	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**
Time of Measurement (analyzer)	10:51	10:54	10:55	11:10	11:13	11:14	11:18	ND	11:21	11:25	11:26	11:28
Temperature at sampling point (^oC)	577.7	577.9	ND	574	574.8	ND	574.5	ND	576.2	582.1	582.1	581.9
Room Temperature (°F)	89	88	88	89	89	89	89	ND	89	90	90	89
O_2 Concentration (%)	8.0	8.0	8.0	7.1	7.0	7.0	6.1	ND	6.0	5.1	5.0	5.0
CO_2 Concentration (%)	7.2	7.2	7.2	7.7	7.8	7.8	8.3	ND	8.4	8.9	8.9	8.9
NO Concentration (ppm)	130	114	126	540	518	526	1301	ND	1284	2188	2190	2211

Table 6-7: Engine 2 test data at 940 RPM and 824 HP at various air-fuel ratio settings

Test Data	Air-Fuel Ratio Setting											
	1			2			3			4		
NO_2 Concentration (ppm)	34	33	34	58	61	61	75	ND	82	100	104	108
NO_x Concentration (ppm)	164	147	160	598	579	587	1376	ND	1366	2288	2294	2319
CO Concentration (ppm)	212	213	213	247	247	248	258	ND	253	260	260	259
THC Concentration (%)	0.152	0.154	0.154	0.15	0.151	0.152	0.147	ND	0.14	0.139	0.139	0.137
Efficiency (%)	89.4	89.4	89.4	89.5	89.5	89.5	89.5	ND	89.5	89.6	89.6	89.5
Lambda	1.62	1.62	1.62	1.51	1.5	1.5	1.41	ND	1.4	1.32	1.31	1.31
Sensor temp (°F)	83	84	84	85	85	85	85	ND	85	86	86	86

Table 6-8: Engine 2 test data at 860 RPM and 787 HP at various air-fuel ratio settings

Test Data	Air-Fuel Ratio Setting			
	5	6	7	8
Oxygen Set point	8.0	7.0	6.0	5.0
Site Conditions				
Ambient Temperature (°C)	16.2	16.0	16.6	17.8
Relative Humidity (%)	33.6	33.8	32.3	30.5
Barometric Pressure (kPa)	102.84	102.81	102.78	102.78
Engine				
Intake Manifold Pressure (psi) (L/R)	1.8/1.8	0.4/0.4	-0.3/-0.3	-0.7/-0.8
Intake Manifold Air Temperature (°C) (L/R)	34.8/35.7	33.9/34.3	33.4/33.7	33.9/34.0
Speed (rpm)	860	860	860	860
Torque (%)				
Fuel index (%)	57	56	54	54
Ignition Angle (°BTDC)	24	24	24	24
Exhaust Temperature (°C)	560.0	553.5	554.1	560.0
Mass Fuel Flow (kg/h)	112.5	108.6	108.1	107.3
Fuel Temperature (°C)	20	20	20	20
Fuel Pressure (psi)	54.7	55.1	54.9	55
Compressor				
Flow (kg/h)				
1st Stage Suction Pressure (psi)	80.1	80.1	80.1	80
1st Stage Suction Temperature (°C)	19.5	20	20	20
1st Discharge Pressure (psi)	254	254	254	253
1st Discharge Temperature (°C) (#2/#4)	116.5/113.5	116.6/113.8	116.6/113.9	117.1/114.3

Table 6-8: Engine 2 test data at 860 RPM and 787 HP at various air-fuel ratio settings

Test Data	Air-Fuel Ratio Setting												
	5			6				7			8		
2nd Stage Suction Pressure (psi)	253			252				254			252		
2nd Stage Suction Temperature (°C)	41.5			41.5				41.5			42		
2nd Discharge Pressure (psi)	850			848				846			845		
2nd Discharge Temperature (°C) (#1/#3)	148.8/151.2			148.6/151.0				148.5/151			148.7/151.1		
Compressor Load (HP)	787			787				787			787		
Flue Gas	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**
Time of Measurement (analyzer)	11:52	11:53	11:55	12:10	12:12	12:13	12:13	12:22	12:23	12:23	1:00	1:01	1:02
Temperature at sampling point (°C)	559.7	559.8	560.5	552.9	553.7		553.8	554.1	553.6	554.5	559.3	560.6	560.2
Room Temperature (°F)	89	89	89	88	88	88	88	89	89	88	89	89	89
O_2 Concentration (%)	8.0	8.0	8.0	6.9	7.0	6.9	6.9	6.0	6.0	6.0	5.1	5.0	5
CO_2 Concentration (%)	7.2	7.2	7.2	7.9	7.8	7.9	7.9	8.4	8.4	8.4	8.9	8.9	8.9
NO Concentration (ppm)	149	148	142	683	729	688	736	1358	1320	1414	2225	2294	2347
NO_2 Concentration (ppm)	44	43	41	67	68	69	69	95	98	98	122	121	119
NO_x Concentration (ppm)	193	191	183	750	797	757	805	1453	1418	1512	2347	2415	2466
CO Concentration (ppm)	208	208	208	237	235	235	235	246	245	244	232	231	231
THC Concentration (%)	0.164	0.167	0.168	0.16	0.16	0.158	0.158	0.151	0.151	0.15	0.143	0.143	0.143
Efficiency (%)	89.4	89.4	89.4	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.6	89.6	89.6
Lambda	1.62	1.62	1.62	1.49	1.5	1.49	1.49	1.4	1.4	1.4	1.32	1.31	1.31
Sensor temp (°F)	87	87	87	86	86	86	96	86	86	86	86	86	86

Table 6-9: Engine 2 test data at 800 RPM and 749 HP at various air-fuel ratio settings

Test Data	Air-Fuel Ratio Setting			
	9	10	11	12
Oxygen Set Point	8.0	7.0	6.0	5.0
Site Conditions				
Ambient Temperature (°C)	18.0	18.3	18.2	19.4
Relative Humidity (%)	29.7	29.5	29.9	28.5
Barometric Pressure (kPa)	102.74	102.71	102.71	102.68
Engine				
Intake Manifold Pressure (psi) (L/R)	1.9/1.9	0.7/0.7	-0.1/-0.1	-0.5/-0.6
Intake Manifold Air Temperature (°C) (L/R)	35.1/36.1	34.3/34.9	33.7/33.9	33.5/33.7
Speed (rpm)	800	800	800	800
Torque (%)				

Table 6-9: Engine 2 test data at 800 RPM and 749 HP at various air-fuel ratio settings

Test Data	**Air-Fuel Ratio Setting**											
	9			**10**			**11**			**12**		
Fuel index (%)	56			54			54			54		
Ignition Angle (°BTDC)	24			24			24			24		
Exhaust Temperature (°C)	546.6			540.8			539.0			546.0		
Mass Fuel Flow (kg/h)	104.6			101.6			101.2			101.1		
Fuel Temperature (°C)	20			20			20			20		
Fuel Pressure (psi)	55			55.6			55.8			55.1		
Compressor												
Flow (kg/h)												
1st Stage Suction Pressure (psi)	85.2			85.3			85.4			85.4		
1st Stage Suction Temperature (°C)	21			21			20.5			21		
1st Discharge Pressure (psi)	262			262			263			0.9		
1st Discharge Temperature (°C) (#2/#4)	114.8/112			114.9/112.2			114.9/112.2			115.0/112.2		
2nd Stage Suction Pressure (psi)	260			261			261			261		
2nd Stage Suction Temperature (°C)	41			41			41			41		
2nd Discharge Pressure (psi)	848			849			859			850		
2nd Discharge Temperature (°C) (#1/#3)	145.2/147.3			145.1/147.2			145.2/147.5			145.3/147.6		
Compressor Load (HP)	749			749			749			749		
Flue Gas	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**
Time of Measurement (analyzer)	1:33	1:34	1:35	1:44	1:45	1:46	1:53	1:54	1:55	2:03	2:05	2:05
Temperature at sampling point (°C)	546.1	546	547.6	540.6	540.5	541.4	538.9	539.1	539.1	545.2	546.4	546.5
Room Temperature (°F)	88	88	88	88	88	88	89	89	89	90	90	90
O_2 Concentration (%)	8.0	8.0	8.0	7.0	7.0	7.0	6.0	6.0	6.0	5.1	5.1	5.0
CO_2 Concentration (%)	7.2	7.2	7.2	7.8	7.8	7.8	8.4	8.4	8.4	8.9	8.9	8.9
NO Concentration (ppm)	143	157	156	631	643	661	1563	1528	1532	2631	2695	2669
NO_2 Concentration (ppm)	46	45	45	66	67	68	96	103	104	150	153	158
NO_x Concentration (ppm)	189	202	201	697	710	729	1659	1631	1636	2781	2848	2827
CO Concentration (ppm)	202	203	203	238	238	238	239	239	238	229	230	228
THC Concentration (%)	0.173	0.173	0.173	0.173	0.176	0.176	0.169	0.17	0.169	0.161	0.16	0.16
Efficiency (%)	89.4	89.4	89.4	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5
Lambda	1.62	1.62	1.62	1.5	1.5	1.5	1.4	1.4	1.4	1.32	1.32	1.31
Sensor temp (°F)	85	85	85	85	85	85	85	85	85	86	86	86

Table 6-10: Engine 3 data collection sheet

Site Data			
Engine Name/Tag No	Engine 3	Testing Date	20-Oct-11
Engine Data			
Manufacturer	Waukesha	Date Manufactured	
Model	7042GSI	Serial #	missing nameplate
Rated Power (kW or HP)		Number of Cylinders	12
Bore (in or mm)		Stroke (in or mm)	
Displacement (cu in or L)		Turbo Charger (Y/N)	Y, twin
AFR Make/Model	REMVue 500AS Plus	Catalytic Convertor (Y/N)	No
Fuel Gas Meter Make/Model	micromotion	Fuel Gas Meter Calibration Date	
Compressor Data			
Manufacturer	Worthington	Date Manufactured	
Model	0F6-SU4	Serial #	See below
Compression Stages	2	Number of Cylinders	4
Interstage Cooler (Y/N)	Y	Lube Oil Pump (Y/N)	Y
Stage 1:			
Compressor cylinder #1 S/N:	L-99215	Compressor cylinder #3 S/N:	L-99214
Cylinder #1 Bore:	10.012	Cylinder #3 Bore:	10.000
Cylinder #1 stroke:	6.000 S	Cylinder #3 stroke:	6.000 S
Cylinder #1 Max press. (psi):	1000	Cylinder #3 Max press. (psi):	1000 psig
Cylinder #1 piston/rod weight (lb):		Cylinder #3 piston/rod weight (lb):	
Stage 2:			
Compressor cylinder #3 S/N:	A-10527	Compressor cylinder #4 S/N:	A-10526
Cylinder #2 Bore:	6	Cylinder #4 Bore:	6
Cylinder #2 stroke:	6	Cylinder #4 stroke:	6
Cylinder #2 Max press. (psi):	1800	Cylinder #4 Max press. (psi):	1800
Cylinder #2 piston/rod weight (lb):	70	Cylinder #4 piston/rod weight (lb):	70
Other compressor loads	Y		
Fuel and Process Gas			
Gas Analysis Date		Process Gas Analysis Date	
Flue Gas Data			
Sample Point	Between manifold & turbo	Temperature Measurement Point	Same (TC readout in REMVue)
Measurement Device Data			
Power Measurement:	Dynalco Reciptrap 9260	Flue gas analyzer:	ECOM-KL
		Flue gas serial no:	2405 OLVNXH
Other Comments / Observations:			
Suction gas temperature read from Reciptrap report (assumed constant over test duration)			
Engine missing nameplate			
Fuel gas temperature estimated from inlet pipe temperature (measured by Raytek laser).			
Data from weather station collected. Data logs collected. Fuel gas data collected.			
First tests on each sheet (i.e. 3-1 and 3-11) are the leanest conditions possible at those engine speeds. The turbos are not adequate at this site and are running heavy to meet air demand, the higher O_2 set points signify the maximum attainable.			
Fuel flow readings are fluctuating.			
Data for test 2 (850 rpm) noticeably less stable			

Table 6-10: Engine 3 data collection sheet
Remvue 5 mins ahead of analyzer (i.e. data files will read 5 mins ahead: Remvue 9:48 = analyzer 9:43)
Coolers driven by engine

Table 6-11: Engine 3 test data at 900 RPM and 1069 HP at various air-fuel ratios – Set 1

Test Data	Air-Fuel Ratio Setting											
	1				2				3			
Oxygen Set Point	7.3				7.0				6.7			
Site Conditions												
Ambient Temperature (^{o}C)	7.4				9.3				9.7			
Relative Humidity (%)	79.9				73.2				67.9			
Barometric Pressure (kPa)	102.78				102.78				102.78			
Engine												
Intake Manifold Pressure (psi) (L/R)	8.2/8.1				7.8/7.7				7.5/7.5			
Intake Manifold Air Temperature (^{o}C) (L/R)	61.0/59.0				61.3/59.3				60.9/58.9			
Speed (rpm)	898				894				895			
Torque (%)	97%				97%				97%			
Fuel index (%)	88%				86%				87%			
Ignition Angle (^{o} BTDC)	24				24				24			
Exhaust Temperature (^{o}C)	598.9				600.1				601.5			
Mass Fuel Flow (kg/h)	172				170.4				168.9			
Fuel Temperature (^{o}C) (est.)	17				17				17			
Fuel Pressure (psi)	60.2				62				62			
Compressor												
Flow (kg/h)												
1st Stage Suction Pressure (psi)	96.8				96.8				96.6			
1st Stage Suction Temperature (^{o}C)	20				20				20			
1st Discharge Pressure (psi)	321				321				321			
1st Discharge Temperature (^{o}C) (#1/#3)	120.3/120.4				120.6/120.6				120.8/120.8			
2nd Stage Suction Pressure (psi)	316				316				315			
2nd Stage Suction Temperature (^{o}C)	40				40				40			
2nd Discharge Pressure (psi)	879				878				877			
2nd Discharge Temperature (^{o}C) (#2/#4)	144.6/142.7				144.7/142.9				144.7/142.9			
Compressor Load (HP)	1069				1069				1069			
Flue Gas	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 1**	**Run 2**	**Run 3**	**Run 4**
Time of Measurement (analyzer)	9:21	9:23	9:24	9:25	9:31	9:33	9:34	9:35	9:40	9:41	9:41	9:43
Temperature at sampling point (^{o}C)	599	598.9	599.1	598.5	600.4	600.0	600.0	600.1	601.9	601.3	601.5	601.1
Room Temperature (^{o}F)	91	92	92	92	92	93	93	93	94	94	94	94
O_2 Concentration (%)	7.3	7.3	7.3	7.3	7.0	7.0	7.0	7.0	6.7	6.7	6.7	6.8
CO_2 Concentration (%)	7.6	7.6	7.6	7.6	7.8	7.8	7.8	7.8	8.0	8.0	8.0	7.9

Table 6-11: Engine 3 test data at 900 RPM and 1069 HP at various air-fuel ratios – Set 1

Test Data	Air-Fuel Ratio Setting											
	1				2				3			
NO Concentration (ppm)	803	853	829	826	1020	1075	1033	1052	1398	1420	1405	1369
NO_2 Concentration (ppm)	105	105	109	109	114	113	115	116	115	118	120	122
NO_x Concentration (ppm)	908	958	938	935	1134	1188	1148	1168	1513	1538	1525	1491
CO Concentration (ppm)	342	341	342	342	341	342	340	341	341	340	342	337
THC Concentration (%)	0.130	0.132	0.133	0.134	0.132	0.131	0.132	0.132	0.136	0.136	0.136	0.136
Efficiency	89.4	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5
Lambda	1.53	1.53	1.53	1.53	1.50	1.50	1.50	1.50	1.47	1.47	1.47	1.48
Sensor temp (°F)	82	82	82	83	84	84	84	84	85	85	85	85

Table 6-12: Engine 3 test data at 900 RPM and 1069 HP at various air-fuel ratios – Set 2

Test Data	Air-Fuel Ratio Setting		
	4	5	6
Oxygen Set Point	6.4	6.0	5.7
Site Conditions			
Ambient Temperature (°C)	10.4	10.3	8.9
Relative Humidity (%)	66.2	65.0	68.4
Barometric Pressure (kPa)	102.78	102.78	102.74
Engine			
Intake Manifold Pressure (psi) (L/R)	6.9/6.8	6.5/6.4	6.2/6.1
Intake Manifold Air Temperature (°C) (L/R)	60.2/58.4	59.2/57.8	58.2/57.0
Speed (rpm)	894	898	900
Torque (%)	97%	97%	97%
Fuel index (%)	86%	85%	86%
Ignition Angle (° BTDC)	24	24	24
Exhaust Temperature (°C)	604.3	606.7	608.9
Mass Fuel Flow (kg/h)	168.5	167.7	167.5
Fuel Temperature (°C) (est.)	17	17	17
Fuel Pressure (psi)	60.4	62	60.9
Compressor			
Flow (kg/h)			
1st Stage Suction Pressure (psi)	96.7	96.8	96.8
1st Stage Suction Temperature (°C)	20	20	20
1st Discharge Pressure (psi)	321	320	320

Table 6-12: Engine 3 test data at 900 RPM and 1069 HP at various air-fuel ratios – Set 2

Test Data	Air-Fuel Ratio Setting										
	4				5			6			
1st Discharge Temperature (^oC) (#1/#3)	120.8/120.7				120.5/120.6			120.5/120.5			
2nd Stage Suction Pressure (psi)	315				315			315			
2nd Stage Suction Temperature (^oC)	40				40			40			
2nd Discharge Pressure (psi)	878				878			879			
2nd Discharge Temperature (^oC) (#2/#4)	144.6/142.7				144.2/142.4			144.3/142.1			
Compressor Load (HP)	1069				1069			1069			
Flue Gas	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 4**
Time of Measurement (analyzer)	9:48	9:50	9:51	9:52	9:55	9:57	9:58	10:02	10:04	10:05	10:06
Temperature at sampling point (^oC)	604.7	604.5	604	603.8	606.6	606.9	606.7	608.9	609	608.9	608.8
Room Temperature (^oF)	95	95	95	95	97	97	97	98	98	98	98
O_2 Concentration (%)	6.3	6.4	6.4	6.4	6.0	6.0	6.0	5.7	5.7	5.7	5.7
CO_2 Concentration (%)	8.2	8.1	8.1	8.1	8.4	8.4	8.4	8.5	8.5	8.5	8.5
NO Concentration (ppm)	1880	1878	1745	1781	2354	2334	2359	2802	2799	2794	2761
NO_2 Concentration (ppm)	125	133	136	138	150	151	155	167	171	173	173
NO_x Concentration (ppm)	2005	2011	1881	1919	2504	2485	2514	2969	2970	2967	2934
CO Concentration (ppm)	330	330	330	330	323	319	322	309	310	309	309
THC Concentration (%)	0.135	0.135	0.134	0.133	0.134	0.133	0.133	0.132	0.134	0.135	0.136
Efficiency	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5
Lambda	1.43	1.44	1.44	1.44	1.40	1.40	1.40	1.37	1.37	1.37	1.37
Sensor temp (^oF)	86	86	86	87	87	87	88	88	89	89	89

Table 6-13: Engine 3 test data at 900 RPM and 1069 HP at various air-fuel ratios – Set 3

Test Data			
	7	8	9
Oxygen Set Point	5.3	5.0	4.6
Site Conditions			
Ambient Temperature (^oC)	8.6	8.4	8.1
Relative Humidity (%)	70.7	70.1	71.1
Barometric Pressure (kPa)	102.78	102.81	102.81
Engine			
Intake Manifold Pressure (psi) (L/R)	5.7/5.6	5.5/5.4	5.2/5.1
Intake Manifold Air Temperature (^oC) (L/R)	57.7/56.7	57.4/56.4	56.6/55.9
Speed (rpm)	898	897	899

Table 6-13: Engine 3 test data at 900 RPM and 1069 HP at various air-fuel ratios – Set 3

Test Data	**7**				**8**				**9**			
Torque (%)	97%				97%				97%			
Fuel index (%)	85%				85%				86%			
Ignition Angle (° BTDC)	24				24				24			
Exhaust Temperature (°C)	612.7				615.4				619.7			
Mass Fuel Flow (kg/h)	168.4				168.1				166.6			
Fuel Temperature (°C) (est.)	17				17				17			
Fuel Pressure (psi)	62.4				60.9				62.7			
Compressor												
Flow (kg/h)												
1st Stage Suction Pressure (psi)	96.9				96.7				96.8			
1st Stage Suction Temperature (°C)	20				20				20			
1st Discharge Pressure (psi)	320				320				320			
1st Discharge Temperature (°C) (#1/#3)	120.2/120.3				120.2/120.3				120.2/120.1			
2nd Stage Suction Pressure (psi)	315				315				315			
2nd Stage Suction Temperature (°C)	40				40				40			
2nd Discharge Pressure (psi)	880				880				881			
2nd Discharge Temperature (°C) (#2/#4)	144.1/142.1				143.9/142.0				143.6/141.7			
Compressor Load (HP)	1069				1069				1069			
Flue Gas	Run 1	Run 2	Run 3	Run 4	Run 1	Run 2	Run 3	Run 4	Run 1	Run 2	Run 3	Run 4
Time of Measurement (analyzer)	10:12	10:13	10:14	10:15	10:24	10:25	10:26	10:27	10:32	10:33	10:34	10:35
Temperature at sampling point (°C)	612.6	612.3	613	612.8	615.7	615.5	614.6	615.7	619.4	620	619.7	619.8
Room Temperature (°F)	99	99	99	99	100	100	100	100	100	100	100	100
O_2 Concentration (%)	5.3	5.3	5.3	5.3	5.0	5.0	5.0	5.0	4.6	4.6	4.6	4.6
CO_2 Concentration (%)	8.7	8.7	8.7	8.7	8.9	8.9	8.9	8.9	9.1	9.1	9.1	9.1
NO Concentration (ppm)	3360	3351	3390	3426	3802	3845	3768	3815	4398	4356	4313	4342
NO_2 Concentration (ppm)	193	193	195	197	220	219	222	221	234	242	243	243
NO_x Concentration (ppm)	3553	3544	3585	3623	4022	4064	3990	4036	4632	4598	4556	4585
CO Concentration (ppm)	297	397	294	294	284	293	281	280	276	274	273	276
THC Concentration (%)	0.146	0.143	0.142	0.14	0.139	0.136	0.136	0.135	0.137	0.136	0.137	0.139
Efficiency	89.5	89.5	89.5	89.5	89.6	89.6	89.6	89.6	89.6	89.6	89.6	89.6
Lambda	1.34	1.34	1.34	1.34	1.31	1.31	1.31	1.31	1.28	1.28	1.28	1.28
Sensor temp (°F)	90	90	90	90	91	91	92	92	92	92	92	92

Table 6-14: Engine 3 test data at 900 RPM and 1069 HP at various air-fuel ratios – Set 4				
Test Data	**Air-Fuel Ratio Setting**			
	10			
Oxygen Set Point	4.0			
Site Conditions				
Ambient Temperature (^oC)	8.5			
Relative Humidity (%)	72.2			
Barometric Pressure (kPa)	102.78			
Engine				
Intake Manifold Pressure (psi) (L/R)	4.7/4.6			
Intake Manifold Air Temperature (^oC) (L/R)	56.1/55.4			
Speed (rpm)	899			
Torque (%)	97%			
Fuel index (%)	85%			
Ignition Angle (^{o} BTDC)	24			
Exhaust Temperature (^oC)	626.7			
Mass Fuel Flow (kg/h)	168.2			
Fuel Temperature (^oC) (est.)	17			
Fuel Pressure (psi)	62.4			
Compressor				
Flow (kg/h)				
1st Stage Suction Pressure (psi)	96.8			
1st Stage Suction Temperature (^oC)	20			
1st Discharge Pressure (psi)	320			
1st Discharge Temperature (^oC) (#1/#3)	120.3/120.2			
2nd Stage Suction Pressure (psi)	315			
2nd Stage Suction Temperature (^oC)	40			
2nd Discharge Pressure (psi)	881			
2nd Discharge Temperature (^oC) (#2/#4)	143.9/141.8			
Compressor Load (HP)	1069			
Flue Gas	**Run 1**	**Run 2**	**Run 3**	**Run 4**
Time of Measurement (analyzer)	10:42	10:43	10:43	10:44
Temperature at sampling point (^oC)	626.5	626.4	627.2	626.6
Room Temperature (^oF)	101	101	101	100
O_2 Concentration (%)	4.0	3.9	4.0	4.0
CO_2 Concentration (%)	9.5	9.5	9.5	9.5
NO Concentration (ppm)	5031	5026	5020	5041

Table 6-14: Engine 3 test data at 900 RPM and 1069 HP at various air-fuel ratios – Set 4

Test Data	Air-Fuel Ratio Setting			
	10			
NO_2 Concentration (ppm)	235	246	247	250
NO_x Concentration (ppm)	5276	5272	5267	5291
CO Concentration (ppm)	265	263	263	262
THC Concentration (%)	0.139	0.14	0.14	0.139
Efficiency	89.6	89.6	89.6	89.6
Lambda	1.24	1.23	1.24	1.24
Sensor temp (^{o}F)	93	93	93	93

Table 6-15: Engine 3 test data at 850 RPM and 1022 HP at various air-fuel ratios - Set 1

Test Data	Air-Fuel Ratio Setting		
	11	12	13
Oxygen Set Point	6.6	6.3	5.9
Site Conditions			
Ambient Temperature (^{o}C)	9.7	10.9	11.0
Relative Humidity (%)	74.0	65.9	65.0
Barometric Pressure (kPa)	102.78	102.84	102.84
Engine			
Intake Manifold Pressure (psi) (L/R)	7.0/7.0	7.0/6.9	6.7/6.6
Intake Manifold Air Temperature (^{o}C) (L/R)	58.6/57.0	59.6/58.2	59.6/58.2
Speed (rpm)	853	852	850
Torque (%)	97	97	97
Fuel index (%)	85	87	87
Ignition Angle (^{o} BTDC)	24	24	24
Exhaust Temperature (^{o}C)	589.6	593.8	597.7
Mass Fuel Flow (kg/h)	159.5	161.7	162.2
Fuel Temperature (^{o}C) (est.)	20	20	20
Fuel Pressure (psi)	63	63.1	61.9
Compressor			
Flow (kg/h)			
1st Stage Suction Pressure (psi)	101.9	106	107.3
1st Stage Suction Temperature (^{o}C)	22.5	22.5	22.5
1st Discharge Pressure (psi)	332	343	345
1st Discharge Temperature (^{o}C) (#1/#3)	118.7/118.3	118.4/118.4	118.4/118.4

Table 6-15: Engine 3 test data at 850 RPM and 1022 HP at various air-fuel ratios - Set 1

Test Data	**Air-Fuel Ratio Setting**										
	11			**12**				**13**			
2nd Stage Suction Pressure (psi)	327			338				340			
2nd Stage Suction Temperature (^{o}C)	44			44				44			
2nd Discharge Pressure (psi)	880			881				880			
2nd Discharge Temperature (^{o}C) (#2/#4)	141.1/139.0			141.5/139.6				141.1/139.3			
Compressor Load (HP)	1022			1022				1022			
Flue Gas	**Run 1**	**Run 2**	**Run 3**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 1**	**Run 2**	**Run 3**	**Run 4**
Time of Measurement (analyzer)	11:10	11:11	11:12	11:22	11:23	11:24	11:25	11:30	11:32	11:33	11:34
Temperature at sampling point (^{o}C)	589.5	589.5	589.9	593.1	593.5	594.1	594.4	597.3	597.9	597.4	598
Room Temperature (^{o}F)	102	102	102	103	103	103	103	104	104	104	104
O_2 Concentration (%)	6.6	6.6	6.6	6.3	6.3	6.2	6.2	6.0	5.9	5.9	5.8
CO_2 Concentration (%)	8.0	8.0	8.0	8.2	8.2	8.2	8.2	8.4	8.4	8.4	8.5
NO Concentration (ppm)	1785	1776	1810	2236	2298	2328	2357	2835	2825	2888	2943
NO_2 Concentration (ppm)	162	163	164	181	184	187	192	218	223	228	230
NO_x Concentration (ppm)	1947	1939	1974	2417	2482	2515	2549	3053	3048	3116	3173
CO Concentration (ppm)	310	312	311	304	302	300	300	291	291	287	287
THC Concentration (%)	0.157	0.158	0.159	0.16	0.159	0.159	0.159	0.154	0.152	0.152	0.153
Efficiency	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5	89.5
Lambda	1.46	1.46	1.46	1.43	1.43	1.42	1.42	1.4	1.39	1.39	1.38
Sensor temp (^{o}F)	95	95	95	96	96	96	96	96	96	96	97

Table 6-16: Engine 3 test data at 850 RPM and 1022 HP at various air-fuel ratio settings - Set 2

Test Data	**Air-Fuel Ratio Setting**
	14
Oxygen Set Point	5.4
Site Conditions	
Ambient Temperature (^{o}C)	11.5
Relative Humidity (%)	61.1
Barometric Pressure (kPa)	102.84
Engine	
Intake Manifold Pressure (psi) (L/R)	6.3/6.3
Intake Manifold Air Temperature (^{o}C) (L/R)	59.6/58.4
Speed (rpm)	851
Torque (%)	97

Table 6-16: Engine 3 test data at 850 RPM and 1022 HP at various air-fuel ratio settings - Set 2

Test Data	**Air-Fuel Ratio Setting**			
	14			
Fuel index (%)	88			
Ignition Angle (° BTDC)	24			
Exhaust Temperature (°C)	603.4			
Mass Fuel Flow (kg/h)	163.7			
Fuel Temperature (°C) (est.)	20			
Fuel Pressure (psi)	62.5			
Compressor				
Flow (kg/h)				
1st Stage Suction Pressure (psi)	108.4			
1st Stage Suction Temperature (°C)	22.5			
1st Discharge Pressure (psi)	349			
1st Discharge Temperature (°C) (#1/#3)	118.6/118.4			
2nd Stage Suction Pressure (psi)	344			
2nd Stage Suction Temperature (°C)	44			
2nd Discharge Pressure (psi)	880			
2nd Discharge Temperature (°C) (#2/#4)	141.2/139.2			
Compressor Load (HP)	1022			
Flue Gas	**Run 1**	**Run 2**	**Run 3**	**Run 4**
Time of Measurement (analyzer)	11:43	11:45	11:46	11:47
Temperature at sampling point (°C)	603.1	603.6	603.4	603.3
Room Temperature (°F)	106	106	106	106
O_2 Concentration (%)	5.4	5.4	5.4	5.4
CO_2 Concentration (%)	8.7	8.7	8.7	8.7
NO Concentration (ppm)	3670	3694	3644	3651
NO_2 Concentration (ppm)	264	269	269	268
NO_x Concentration (ppm)	3934	3963	3913	3919
CO Concentration (ppm)	276	273	275	276
THC Concentration (%)	0.153	0.152	0.152	0.153
Efficiency	89.6	89.5	89.5	89.5
Lambda	1.35	1.35	1.35	1.35
Sensor temp (°F)	97	98	98	98

Table 6-17: Engine 4 data collection sheet

Site Data			
Engine Name/Tag No	Engine 4	Testing Date	21-Oct-11
Engine Data			
Manufacturer	Waukesha	Date Manufactured	
Model	L70420GSI	Serial #	306254
Rated Power (kW or HP)		Number of Cylinders	12
Bore (in or mm)		Stroke (in or mm)	
Displacement (cu in or L)		Turbo Charger (Y/N)	Dual
AFR Make/Model	REMVue 500AS Plus	Catalytic Convertor (Y/N)	
Fuel Gas Meter Make/Model		Fuel Gas Meter Calibration Date	
Cooler manufacturer:		Cooler model #	
Cooler job #:		Electric Driven Cooling Fan (Y/N)	Y
Compressor Data			
Manufacturer	Ingersoll Rand	Date Manufactured	
Model		Serial #	
Compression Stages	2	Number of Cylinders	4
Interstage Cooler (Y/N)	Y	Lube Oil Pump (Y/N)	N
Cylinder type:	RDS		
Stage 1:			
Compressor cylinder #1 S/N:	Y6R-1129	Compressor cylinder #3 S/N:	Y6R 1749C
Cylinder #1 Bore:	11 1/2"	Cylinder #3 Bore:	11 1/2"
Cylinder #1 stroke:	5 1/2"	Cylinder #3 stroke:	5 1/2"
Cylinder #1 Max press. (psi):	605 psig	Cylinder #3 Max press. (psi):	605 psig
Cylinder #1 piston/rod weight (lb):		Cylinder #3 piston/rod weight (lb):	
Stage 2:			
Compressor cylinder #2 S/N:	Y6R-1515C	Compressor cylinder #4 S/N:	Y6R-1514C
Cylinder #2 Bore:	6"	Cylinder #4 Bore:	6"
Cylinder #2 stroke:	5 1/2"	Cylinder #4 stroke:	5 1/2"
Cylinder #2 Max press. (psi):	1650 psig	Cylinder #4 Max press. (psi):	1650 psig
Cylinder #2 piston/rod weight (lb):		Cylinder #4 piston/rod weight (lb):	
Fuel and Process Gas			
Gas Analysis Date		Process Gas Analysis Date	
Flue Gas Data			
Sample Point	Between manifold & turbo	Temperature Measurement Point	Same (TC readout in REMVue)
Measurement Device Data			
Power Measurement:	Dynalco Reciptrap 9260	Flue gas analyzer:	ECOM-KL
		Flue gas serial no:	2405 OLVNXH
Other Comments / Observations:			
Suction gas temperatures read from gauges			
Engine running poorly on Spartan's previous visit. Suspected that engine heads need to be replaced, NO readings are not stable as a result			
Firing voltages fluctuating, as are emissions readouts. Collecting logged and averaged samples instead of printouts.			
Data from weather station collected, data logs from REMVue collected, fuel gas data collected.			
Fuel temperature estimated from pipe temperature (measured by Raytek)			
Hydrocarbon sensor on th ECOM malfunctioning, reading 0.000%			

Table 6-18: Engine 4 test data at 1000 RPM and 1106 HP at various air-fuel ratio settings – Set 1

Test Data	**Air-Fuel Ratio Setting**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Oxygen Set point	8.6	8.3	8.0	7.7	7.5	7.3	7.0
Site Conditions							
Ambient Temperature (°C)	-0.6	-0.1	0.4	0.7	1	3.3	4.1
Relative Humidity (%)	100	98.3	100	100	100	86.7	84.2
Barometric Pressure (kPa)	103.76	103.76	103.79	103.76	103.79	103.76	103.73
Engine							
Intake Manifold Pressure (kPa) (L/R)	83.7/84.0	77.7/76.9	69.8/69.7	65.5/64.7	62.1/61.4	60.5/59.8	56.0/56.0
Intake Manifold Air Temperature (°C) (L/R)	58.8/55.1	56.5/53.2	54.4/51.6	53.0/50.5	52.2/50.0	51.8/49.8	50.9/49.1
Speed (rpm)	995	995	992	999	993	994	992
Fuel index (%)	93	91	89	88	87	88	85
Ignition Angle (° BTDC)	24	24	24	24	24	24	24
Exhaust Temperature (°C)	510.0	511.4	514.3	517.1	520.5	522.9	527.0
Mass Fuel Flow (kg/h)	210.6	204.5	203	200.2	198.4	199.8	195.3
Fuel Temperature (°C)	13	13	13	13	13	13	13
Fuel Pressure (kPa)	355.8	358.5	360.5	361.0	361.8	362.5	366.5
Compressor							
Flow (kg/h)							
1st Stage Suction Pressure (kPa)	792	790	785	783	789	790	789
1st Stage Suction Temperature (°C)	33	33	34	35	35	34	34
1st Discharge Pressure (kPa)	2536	2530	2521	2516	2531	2536	2533
1st Discharge Temperature (°C) (#1/#3)	120.0/121.1	119.9/121.3	119.8/120.8	119.8/121.7	119.5/121.7	119.9/121.7	120.0/121.9
2nd Stage Suction Pressure (kPa)	2461	2456	2444	2441	2456	2462	2459
2nd Stage Suction Temperature (°C)	36	36	36	36	37	37	37
2nd Discharge Pressure (kPa)	6045	6045	6046	6042	6050	6048	6051
2nd Discharge Temperature (°C) (#2/#4)	119.5/120.2	119.5/120.3	120.0/120.8	120.2/121.0	120.3/121.1	120.7/121.7	121.3/122.2
Compressor Load (HP)	1106	1106	1106	1106	1106	1106	1106
Flue Gas							

Table 6-18: Engine 4 test data at 1000 RPM and 1106 HP at various air-fuel ratio settings – Set 1

Test Data	Air-Fuel Ratio Setting						
	1	2	3	4	5	6	7
Time of Measurement (analyzer)	9:51-9:53	10:03 - 10:05	10:10 - 10:12	10:15 - 10:17	10:23-10:26	10:30-10:32	10:38-10:40
Temperature at sampling point (^oC)	510.0	511.4	514.3	517.1	520.5	522.9	527.0
Room Temperature (^oF)	90	92	94	96	98	97	93
O_2 Concentration (%)	8.5	8.3	8.0	7.7	7.4	7.3	7.0
CO_2 Concentration (%)	7.0	7.1	7.2	7.4	7.6	7.6	7.8
NO Concentration (ppm)	168	213	319	449	657	806	1117
NO_2 Concentration (ppm)	41	46	57	64	69	68	78
NO_x Concentration (ppm)	208	259	376	513	726	874	1195
CO Concentration (ppm)	202	209	219	221	221	217	211
THC Concentration (%)	0	0	0	0	0	0	0

Table 6-19: Engine 4 test data at 1000 RPM an 1106 HP at various air-fuel ratio settings - Set 2

Test Data	Air-Fuel Ratio Setting					
	8	9	10	11	12	13
Oxygen Set point	6.7	6.5	6.3	6.0	5.7	5.5
Site Conditions						
Ambient Temperature (^oC)	4.4	5.7	6.5	7.2	8.3	8.4
Relative Humidity (%)	84.7	81	79.1	77.9	74.7	69
Barometric Pressure (kPa)	103.73	103.73	103.73	103.73	103.73	103.73
Engine						
Intake Manifold Pressure (kPa) (L/R)	54.3/54.1	51.2/50.4	50.6/49.9	47.1/46.7	46.6/46.2	44.4/44.5
Intake Manifold Air Temperature (^oC) (L/R)	50.8/49.0	50.3/48.7	51.1/49.3	50.6/49.2	50.3/49.0	50.0/48.7
Speed (rpm)	995	997	996	990	992	997
Fuel index (%)	85	85	85	85	85	86
Ignition Angle (^{o} BTDC)	24	24	24	24	24	24
Exhaust Temperature (^oC)	529.3	533.3	534.1	539.5	542.5	550.0
Mass Fuel Flow (kg/h)	195.1	194.1	194.6	193.6	194.2	196.3
Fuel Temperature (^oC)	13	13	13	13	12	12
Fuel Pressure (kPa)	364.0	365.0	365.5	367.0	368.0	366.3

Table 6-19: Engine 4 test data at 1000 RPM an 1106 HP at various air-fuel ratio settings - Set 2						
Test Data	**Air-Fuel Ratio Setting**					
	8	**9**	**10**	**11**	**12**	**13**
Compressor						
Flow (kg/h)						
1st Stage Suction Pressure (kPa)	788	787	792	791	791	811
1st Stage Suction Temperature (^{o}C)	34	33	34	34	34	35
1st Discharge Pressure (kPa)	2534	2530	2537	2533	2535	2584
1st Discharge Temperature (^{o}C) (#1/#3)	119.9/122.0	119.9/122.1	120.2/122.1	120.4/122.3	120.8/122.4	120.8/122.7
2nd Stage Suction Pressure (kPa)	2460	2457	2464	2461	2464	2512
2nd Stage Suction Temperature (°C)	37	37	36	36	36	37
2nd Discharge Pressure (kPa)	6049	6044	6042	6042	6040	6061
2nd Discharge Temperature (°C) (#2/#4)	121.7/122.3	120.9/121.5	120.3/120.8	120.2/120.6	120.2/120.7	119.6/120.0
Compressor Load (HP)	1106	1106	1106	1106	1106	1106
Flue Gas						
Time of Measurement (analyzer)	10:44-10:47	10:52-10:55	11:03-11:05	11:09 - 11:11	11:16-11:18	11:26-11:28
Temperature at sampling point (^{o}C)	529.3	533.3	534.1	539.5	542.5	550.0
Room Temperature (^{o}F)	91	91	94	95	95	93
O_2 Concentration (%)	6.8	6.5	6.4	5.9	5.8	5.2
CO_2 Concentration (%)	7.9	8.1	8.1	8.4	8.5	8.8
NO Concentration (ppm)	1259	1736	1839	2511	2727	3661
NO_2 Concentration (ppm)	88	104	120	153	191	249
NO_x Concentration (ppm)	1347	1840	1959	2665	2918	3911
CO Concentration (ppm)	203	193	186	173	161	153
THC Concentration (%)	0	0	0	0	0	0

Table 6-20: Engine 5 data collection sheet

Site Data			
Engine Name/Tag No	Engine 5	Testing Date	November 3/4 2011
Engine Data			
Manufacturer	Waukesha	Date Manufactured	Apr-04
Model	L7042GSI	Serial #	C-1506371
Rated Power (kW or HP)	1480 bhp @ 1200 rpm	Number of Cylinders	12
Bore (in or mm)		Stroke (in or mm)	
Displacement (cu in or L)		Turbo Charger (Y/N)	Y
AFR Make/Model	REMVue 500A Plus	Catalytic Convertor (Y/N)	N
Fuel Gas Meter Make/Model	Micromotion model R050S113NCAAEZZZZ	Fuel Gas Meter Calibration Date	
Cooler manufacturer:	Air-X-changer	Cooler model #	156-EH
Cooler job #:	44625		
Compressor Data			
Manufacturer	Ariel	Date Manufactured	May-04
Model	JGK-4	Serial #	F-19768
Compression Stages	2	Number of Cylinders	4
Interstage Cooler (Y/N)	Y	Lube Oil Pump (Y/N)	Y - Graco husky 1040
Stage 1:	Rated RPM 1200	**Stage 1**	Rated RPM 1200
Compressor cylinder #1 S/N:	C-62520	Compressor cylinder #3 S/N:	C-62521
Cylinder #1 Bore:	8.375 in	Cylinder #3 Bore:	8.375 in
Cylinder #1 stroke:	5.50 in	Cylinder #3 stroke:	5.50 in
Cylinder #1 Max press. (psi):	1895 psig	Cylinder #3 Max press. (psi):	1985 psig
Cylinder #1 piston/rod weight (lb):		Cylinder #3 piston/rod weight (lb):	
Stage 2:	Rated RPM 1200	**Stage 2:**	Rated RPM 1200
Compressor cylinder #3 S/N:	C-62518	Compressor cylinder #4 S/N:	C-62519
Cylinder #2 Bore:	15.875	Cylinder #4 Bore:	15.875
Cylinder #2 stroke:	5.5	Cylinder #4 stroke:	5.5
Cylinder #2 Max press. (psi):	635 PSIG	Cylinder #4 Max press. (psi):	635 psig
Cylinder #2 piston/rod weight (lb):		Cylinder #4 piston/rod weight (lb):	
Fuel and Process Gas			
Gas Analysis Date		Process Gas Analysis Date	
Flue Gas Data			
Sample Point	betweem ex manifold and turbo	Temperature Measurement Point	exhaust manifold (remvue)
Measurement Device Data			
Power Measurement:	Dynalco Reciptrap 9260	Flue gas analyzer:	ECOM-KL
		Flue gas serial no:	2405 OLVNXH
Other Comments / Observations:			
Measurements were also performed with a Testo combustion analyzer after the turbo			
Combustion gas samples were taken from the L exhaust manifold at each test point and submitted for analysis			

Table 6-21: Engine 5 test sequence 1 at 1200 RPM and 1340 HP

Test Data	Air-Fuel Ratio Setting								
	1	2	3	4	5	6	7	8	9
Oxygen Set Point	8.0	7.6	7.2	6.7	6.3	6.2	5.7	5.3	4.9
Site Conditions									
Ambient Temperature (°C)	-8.2	-8.5	-8.4	-8.8	-8.6	-8.1	-7.8	-7.9	-8.4
Relative Humidity (%)	90.5	90.9	89.7	89.2	88.7	86.9	87.4	81.8	86.5
Barometric Pressure (kPa)	90.6	90.6	90.7	90.7	90.7	90.7	90.7	90.7	90.7
Engine									
Intake Manifold Pressure (kPa)	95.1	81.5	69.5	58.4	55.0	52.8	49.8	46.8	42.6
Intake Manifold Air Temp (°C)	42.7	38.6	36.2	32.2	30.7	29.5	28.8	27.9	26.3
Speed (rpm)	1199	1200	1199	1199	1200	1199	1199	1199	1200
Torque (%)	90%	90%	90%	90%	90%	90%	90%	90%	90%
Fuel index (%)	96%	92%	89%	86%	85%	85%	84%	85%	83%
Ignition Angle (° BTDC)	23	23	23	23	23	23	23	23	23
Stack Gas Temperature (°C)	674.7	664.8	658.3	657.6	658.8	658.4	662.0	665.0	666.7
Mass Fuel Flow (kg/h)	281.3	270.6	261.3	255.0	254.2	252.3	252.5	252.5	249.3
Fuel Temperature (°C)	20	20	20	20	20	20	20	20	20
Fuel Pressure (kPa)									
Compressor									
Flow (kg/h)									
1st Stage Suction Press (kPa)	428.7	434.2	428.7	431.8	430.5	428.3	433.0	435.7	432.0
1st Stage Suction Temp (°C)	8.4	8.0	8.0	8.1	8.2	8.4	8.4	8.3	8.3
1st Discharge Pressure (kPa)	1331.7	1340.8	1338.0	1347.5	1346.5	1344.3	1346.0	1359.3	1350.8
1st Discharge Tempe(°C) (1/3)	110.6	109.8/105	110.9/106.2	109.8/105.5	109.7/105.4	109.3/105.1	109.0/104.7	108.9/104.6	109.0/104.6
2nd Stage Suction Press (kPa)	1326.8	1337.8	1332.2	1340.3	1343.0	1338.8	1344.3	1352.2	1342.8
2nd Stage Suction Temp (°C)	27.2	26.0	26.5	26.4	26.7	26.1	26.3	26.3	26.0
2nd Discharge Pressure (kPa)	2830.3	2839.8	2838.5	2847.2	2850.2	2850.8	2858.7	2862.8	2855.0
2nd Discharge Temp (°C) (2/4)	115.2	115.1/106	115.9/106.3	115.1/105.7	114.9/105.6	115.3/106.0	115.0/105.7	114.9/105.5	114.6/105.3
Compressor Load (HP)	1340	1340	1340	1340	1340	1340	1340	1340	1340
Flue Gas									
Time of sample (analyzer)	10:34	11:05	11:28	11:47	12:10	12:28	12:43	13:00	13:18
Temp at sampling point (°C)									
Room Temperature (°F)	82.4	83.9	82.7	75.5	72.4	70.7	70.0	69.2	68.5
O_2 Concentration (%)	8.0	7.6	7.2	6.7	6.3	6.2	5.7	5.3	4.9
CO_2 Concentration (%)	7.2	7.5	7.7	8.0	8.2	8.2	8.5	8.7	9.0
NO Concentration (ppm)	80	178	363	894	1225	1324	1887	2376	2957

Table 6-21: Engine 5 test sequence 1 at 1200 RPM and 1340 HP

Test Data	**Air-Fuel Ratio Setting**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
NO_2 Concentration (ppm)	32	110	121	141	152	156	179	200	226
NO_x Concentration (ppm)	112	288	485	1035	1376	1480	2066	2576	3183
CO Concentration (ppm)	280	305	315	316	304	300	288	277	268
THC Concentration (ppm)	100	100	100	90	80	70	60	60	60

Table 6-22: Engine 5 test data sequence 2 at 1200 RPM and 1366 HP at various air-fuel ratios

Test Data	**Air-Fuel Ratio Setting**								
	10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Oxygen Set Point	8.2	7.8	7.4	7.0	6.7	6.2	6.0	5.5	4.9
Site Conditions									
Ambient Temperature (^{o}C)	-7.8	-8.0	-7.8	-7.5	-7.3	-8.1	-8.4	-8.2	-8.5
Relative Humidity (%)	85.8	84.4	83.3	82.5	80.8	81.5	82.5	81.8	82.2
Barometric Pressure (kPa)	90.8	90.8	90.8	90.8	90.8	90.8	90.8	90.8	90.9
Engine									
Intake Manifold Pressure (kPa)	93.5	83.3	75.1	66.6	62.1	56.3	53.7	48.2	44.7
Intake Manifold Air Temp (^{o}C)	62.9	59.3	54.9	51.5	49.4	46.7	45.5	43.6	42.5
Speed (rpm)	1199	1200	1199	1199	1199	1200	1198	1200	1199
Torque (%)	92%	92%	92%	92%	92%	92%	92%	92%	92%
Fuel index (%)	92%	89%	87%	85%	84%	84%	83%	81%	82%
Ignition Angle (^{o} BTDC)	23	23	23	23	23	23	23	23	23
Stack Gas Temperature (^{o}C)	665.4	660.4	658.3	656.9	658.0	658.7	659.9	662.2	668.5
Mass Fuel Flow (kg/h)	270.3	263.2	259.2	253.0	251.7	249.7	248.7	245.0	245.0
Fuel Temperature (^{o}C)	20	20	20	20	20	20	20	20	20
Fuel Pressure (kPa)									
Compressor									
Flow (kg/h)									
1st Stage Suction Press (kPa)	426.2	426.2	429.5	425.7	421.3	423.2	421.2	418.7	424.7
1st Stage Suction Temp (^{o}C)	8.1	8.1	8.1	8.0	8.1	8.2	8.3	8.1	8.2
1st Discharge Pressure (kPa)	1328.8	1332.0	1338.0	1330.3	1324.0	1330.2	1325.0	1318.5	1326.5
1st Discharge Tempe(^{o}C) (1/3)	110/105.4	110.0/105.6	109.0/104.6	109.4/105.1	109.6/105.0	109.4/105.0	109.2/105.0	109.4/105.2	108.5/104.5
2nd Stage Suction Press (kPa)	1326.8	1326.0	1333.3	1326.0	1317.0	1320.0	1316.8	1310.8	1321.7
2nd Stage Suction Temp (°C)	25.9	26.1	26.1	25.9	26.0	25.7	25.9	26.1	26.1

Table 6-22: Engine 5 test data sequence 2 at 1200 RPM and 1366 HP at various air-fuel ratios

Test Data	Air-Fuel Ratio Setting								
	10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
2nd Discharge Pressure (kPa)	2834.5	2825.2	2826.8	2821.3	2809.8	2809.0	2803.5	2791.8	2794.2
2nd Discharge Temp (°C) (2/4)	115.2/105.7	115.5/106.0	114.9/105.7	115.2/105.9	115.1/106.0	115.6/106.5	115.6/106.4	115.7/106.2	115.0/105.8
Compressor Load (HP)	1366	1366	1366	1366	1366	1366	1366	1366	1366
Flue Gas									
Time of sample (analyzer)	14:32	14:48	15:03	15:19	15:39	15:55	16:08	16:27	16:40
Temp at sampling point (°C)									
Room Temperature (°F)	71.0	71.9	70.9	69.2	68.9	68.4	68.1	68.1	68.0
O_2 Concentration (%)	8.2	7.8	7.4	7.0	6.7	6.2	6.0	5.5	4.9
CO_2 Concentration (%)	7.1	7.4	7.6	7.8	8.0	8.2	8.4	8.6	9.0
NO Concentration (ppm)	155	255	448	748	998	1507	1802	2523	3327
NO_2 Concentration (ppm)	119	122	136	144	152	169	179	210	245
NO_x Concentration (ppm)	273	377	584	892	1150	1676	1982	2734	3572
CO Concentration (ppm)	323	305	315	308	302	289	283	272	265
THC Concentration (ppm)	323	327	277	234	265	221	234	215	208

Table 6-23: Engine 5 test data sequence 3 at 1200 RPM and 1049 HP at various air-fuel ratios

Test Data	Air-Fuel Ratio Setting						
	19	**20**	**21**	**22**	**23**	**24**	**25**
Oxygen Set Point	8.1	7.5	7.0	6.5	6.0	5.5	5.0
Site Conditions							
Ambient Temperature (°C)	-14.4	-14.1	-14.1	-13.8	-13.5	-12.8	-12.6
Relative Humidity (%)	100	100	100	100	100	100	100
Barometric Pressure (kPa)	90.2	90.2	90.2	90.2	90.2	90.2	90.2
Engine							
Intake Manifold Pressure (kPa)	46.0	37.2	30.0	26.1	21.9	19.2	16.0
Intake Manifold Air Temperature (°C)	21.6	19.6	17.9	16.6	15.7	15.2	14.7
Speed (rpm)	1200	1201	1199	1198	1200	1200	1200
Torque (%)	70%	70%	70%	70%	70%	70%	70%
Fuel index (%)	72%	69%	66%	66%	65%	65%	64%
Ignition Angle (° BTDC)	23	23	23	23	23	23	23
Stack Gas Temperature (°C)	637.6	631.5	628.7	629.7	632.0	634.5	636.9
Mass Fuel Flow (kg/h)	223.5	215.7	210.0	207.2	206.2	205.0	202.5

Table 6-23: Engine 5 test data sequence 3 at 1200 RPM and 1049 HP at various air-fuel ratios

Test Data	**Air-Fuel Ratio Setting**						
	19	**20**	**21**	**22**	**23**	**24**	**25**
Fuel Temperature (^{o}C)	20	20	20	20	20	20	20
Fuel Pressure (kPa)							
Compressor							
Flow (kg/h)							
1st Stage Suction Pressure (kPa)	280.3	280.0	282.2	279.8	280.0	279.3	281.0
1st Stage Suction Temperature (^{o}C)	7.8	7.8	7.7	7.5	7.4	7.3	7.1
1st Discharge Pressure (kPa)	1000.7	995.3	998.3	999.7	997.2	999.7	1000.8
1st Discharge Temperature (^{o}C) (#1/#3)	134.6/120.7	134.7/120.6	134.7/120.5	135.1/120.6	135.6/121.0	136.0/126.8	136.1/126.7
2nd Stage Suction Pressure (kPa)	1001.7	1000.8	1002.5	1001.0	1001.5	1000.3	1001.7
2nd Stage Suction Temperature (°C)	13.1	13.1	13.0	13.0	13.1	13.3	12.6
2nd Discharge Pressure (kPa)	2744.2	2739.2	2736.2	2737.3	2742.7	2744.2	2745.0
2nd Discharge Temperature (°C) (#2/#4)	125.1/113.8	125.8/114.3	125.5/114.4	125.9/114.4	126.8/115.2	121.4/115.2	126.6/115.0
Compressor Load (HP)	1049	1049	1049	1049	1049	1049	1049
Flue Gas							
Time of Measurement (analyzer)	9:16	9:27	9:39	9:56	10:05	10:14	10:26
Temperature at sampling point (^{o}C)							
Room Temperature (^{o}F)	65.7	64.9	64.2	64.9	65.8	67.1	68.1
O$_2$ Concentration (%)	8.1	7.5	7.0	6.5	6.0	5.5	5.0
CO$_2$ Concentration (%)	7.2	7.5	7.8	8.1	8.4	8.6	8.9
NO Concentration (ppm)	76	185	394	637	1098	1496	2137
NO$_2$ Concentration (ppm)	74	97	113	123	135	145	163
NO$_x$ Concentration (ppm)	150	282	507	760	1233	1642	2300
CO Concentration (ppm)	258	290	305	304	295	288	280
THC Concentration (ppm)	170	150	140	50	40	150	150

Table 6-24: Engine 5 test data sequence 4 at 1100 RPM and 1308 HP at various air-fuel ratios

Test Data	**Air-Fuel Ratio Setting**						
	26	**27**	**28**	**29**	**30**	**31**	**32**
Oxygen Set Point	8.0	7.6	7.0	6.6	6.1	5.5	5.1
Site Conditions							
Ambient Temperature (^{o}C)	0.5	5.8	5.8	5.1	7.7	5.6	5.4

Table 6-24: Engine 5 test data sequence 4 at 1100 RPM and 1308 HP at various air-fuel ratios

Test Data	Air-Fuel Ratio Setting						
	26	**27**	**28**	**29**	**30**	**31**	**32**
Relative Humidity (%)	54.7	42.2	41.2	41.8	37.6	39.8	40.2
Barometric Pressure (kPa)	89.9	89.9	89.9	89.9	89.9	89.9	89.9
Engine							
Intake Manifold Pressure (kPa)	96.3	80.4	64.1	62.2	53.9	48.5	43.6
Intake Manifold Air Temperature (^{o}C)	42.3	38.1	38.1	36.1	34.4	33.3	31.4
Speed (rpm)	1098	1102	1101	1100	1102	1100	1100
Torque (%)	96%	96%	96%	96%	96%	96%	96%
Fuel index (%)	96%	90%	87%	84%	83%	81%	80%
Ignition Angle (^{o} BTDC)	23	23	23	23	23	23	23
Stack Gas Temperature (^{o}C)	651.9	642.2	638.0	637.7	638.1	640.5	643.3
Mass Fuel Flow (kg/h)	260.5	249.2	240.8	235.8	231.5	227.3	225.8
Fuel Temperature (^{o}C)	20	20	20	20	20	20	20
Fuel Pressure (kPa)							
Compressor							
Flow (kg/h)							
1st Stage Suction Pressure (kPa)	465.8	463.7	464.3	461.7	453.2	448.3	444.8
1st Stage Suction Temperature (^{o}C)	7.0	7.0	7.1	7.2	7.3	7.4	7.5
1st Discharge Pressure (kPa)	1356.8	1359.0	1362.8	1354.7	1335.8	1322.3	1311.3
1st Discharge Temperature (^{o}C) (#1/#3)	98.7/94.5	98.6/94.4	99.2/94.8	99.8/95.4	100.3/96.0	101.1/96.7	101.2/97.0
2nd Stage Suction Pressure (kPa)	1348.7	1346.5	1347.8	1343.8	1324.8	1310.7	1301.5
2nd Stage Suction Temperature (°C)	25.1	24.9	25.1	25.6	25.5	25.6	25.5
2nd Discharge Pressure (kPa)	2938.8	2951.3	2953.2	2950.0	2942.5	2929.3	2916.7
2nd Discharge Temperature (°C) (#2/#4)	102.4/96.6	102.0/96.2	103.0/97.1	103.0/97.0	102.9/98.1	102.9/98.1	102.8/98.1
Compressor Load (HP)	1308	1308	1308	1308	1308	1308	1308
Flue Gas							
Time of Measurement (analyzer)	14:43	14:56	15:06	15:13	15:22	15:29	15:39
Temperature at sampling point (^{o}C)							
Room Temperature (^{o}F)	78.8	79.2	79.5	79.7	79.9	80.3	80.7
O_2 Concentration (%)	8.0	7.6	7.0	6.6	6.1	5.5	5.1
CO_2 Concentration (%)	7.2	7.5	7.8	8.0	8.3	8.6	8.9
NO Concentration (ppm)	69	173	443	804	1285	2044	2652
NO_2 Concentration (ppm)	86	106	127	140	154	176	189
NO_x Concentration (ppm)	155	279	571	945	1438	2220	2841
CO Concentration (ppm)	244	266	281	271	260	242	235

Table 6-24: Engine 5 test data sequence 4 at 1100 RPM and 1308 HP at various air-fuel ratios							
Test Data	**Air-Fuel Ratio Setting**						
	26	**27**	**28**	**29**	**30**	**31**	**32**
THC Concentration (ppm)	245	230	220	210	200	190	190

Table 6-25: Engine 5 test data sequence 5 at 1000 RPM and 1145 HP at various air-fuel ratios							
Test Data	**Air-Fuel Ratio Setting**						
	33	**34**	**35**	**36**	**37**	**38**	**39**
Oxygen Set Point	8.1	7.5	6.9	6.5	6.0	5.5	5.0
Site Conditions							
Ambient Temperature (°C)	0.0	0.3	-1.1	-1.6	-1.8	-2.2	-2.3
Relative Humidity (%)	51.7	53.7	59.0	60.7	61.8	63.3	64.6
Barometric Pressure (kPa)	89.9	89.9	89.9	89.9	89.8	89.8	89.8
Engine							
Intake Manifold Pressure (kPa)	72.8	60.3	52.2	47.8	43.0	38.9	35.0
Intake Manifold Air Temperature (°C)	35.1	32.0	29.7	28.4	27.2	25.8	24.9
Speed (rpm)	1004	999	999	999	999	999	1000
Torque (%)	92%	92%	92%	92%	92%	92%	92%
Fuel index (%)	83%	79%	77%	76%	76%	75%	75%
Ignition Angle (° BTDC)	23	23	23	23	23	23	23
Stack Gas Temperature (°C)	614.1	607.4	606.5	608.4	610.4	613.2	616.2
Mass Fuel Flow (kg/h)	215.3	204.5	200.7	199.7	197.7	196.8	196.0
Fuel Temperature (°C)	20	20	20	20	20	20	20
Fuel Pressure (kPa)							
Compressor							
Flow (kg/h)							
1st Stage Suction Pressure (kPa)	459.8	461.5	460.0	464.2	463.2	459.7	457.0
1st Stage Suction Temperature (°C)	7.9	8.0	8.1	8.1	8.1	8.1	8.2
1st Discharge Pressure (kPa)	1336.3	1334.8	1336.7	1348.7	1341.8	1340.8	1330.2
1st Discharge Temperature (°C) (#1/#3)	97.4/92.8	97.5/92.9	97.9/92.8	96.8/92.4	96.8/92.4	96.9/92.4	97.4/92.9
2nd Stage Suction Pressure (kPa)	1331.0	1330.0	1329.7	1338.2	1334.5	1329.7	1332.0
2nd Stage Suction Temperature (°C)	25.7	25.9	26.1	26.1	26.0	25.9	25.9
2nd Discharge Pressure (kPa)	2896.7	2894.7	2890.3	2894.7	2893.2	2890.7	2882.8
2nd Discharge Temperature (°C) (#2/#4)	101.8/97.3	101.9/97.3	102.4/97.6	101.9/97.0	102.1/97.1	102.4/97.1	102.7/97.5
Compressor Load (HP)	1145	1145	1145	1145	1145	1145	1145

Table 6-25: Engine 5 test data sequence 5 at 1000 RPM and 1145 HP at various air-fuel ratios

Test Data	Air-Fuel Ratio Setting						
	33	34	35	36	37	38	39
Flue Gas							
Time of Measurement (analyzer)	16:15	16:34	16:49	16:57	17:06	17:15	17:24
Temperature at sampling point (^{o}C)							
Room Temperature (^{o}F)	80.0	78.6	78.1	77.7	77.5	77.0	77.2
O_2 Concentration (%)	8.1	7.5	6.9	6.5	6.0	5.5	5.0
CO_2 Concentration (%)	7.2	7.6	7.9	8.1	8.4	8.6	8.9
NO Concentration (ppm)	96	293	574	1009	1572	2254	2973
NO_2 Concentration (ppm)	68	100	113	124	135	154	161
NO_x Concentration (ppm)	163	393	688	1132	1707	2409	3133
CO Concentration (ppm)	239	275	271	258	240	227	216
THC Concentration (ppm)	220	210	200	190	180	180	170

7 Appendix B - Literature Review

STATIONARY ENGINES AIR EMISSIONS RESEARCH LITERATURE REVIEW

PREPARED FOR:

PTAC (Petroleum Technology Alliance Canada)
Suite 400, Chevron Plaza, 500-5 Avenue S.W.
Calgary, AB
T2P 3L5

Contact: Susie Dwyer
Innovation and Technology Development Coordinator
Telephone: (403) 218-7708
E-mail: sdwyer@ptac.org

PREPARED BY:

Clearstone Engineering Ltd.
700, 900-6th Avenue S.W.
Calgary, AB
T2P 3K2

Contact: Dave Picard, P. Eng
Telephone: (403) 215-2730
E-mail: dave.picard@clearstone.ca
Website: www.clearstone.ca

April 23, 2012

DISCLAIMER

While reasonable effort has been made to ensure the accuracy, reliability and completeness of the information presented herein, this report is made available without any representation as to its use in any particular situation and on the strict understanding that each reader accepts full liability for the application of its contents, regardless of any fault or negligence of Clearstone Engineering Ltd.

EXECUTIVE SUMMARY

Clearstone Engineering Ltd. is conducting a study on behalf of PTAC to evaluate NOx control technologies suitable for installation on existing natural gas fuelled reciprocating internal combustion engines (RICE) used for gas compression in the upstream oil and gas industry. The objective of the study is to determine the effectiveness of the technologies in reducing NOx emissions over a range of operating conditions and investigate their impact on fuel consumption and greenhouse gas emissions.

The first phase of the study was to conduct a literature review of commercially available retrofit NOx reduction technologies, focusing on air-fuel ratio controllers and non-selective catalytic converters. Its purpose was to analyze existing engine test information and to identify any gaps that occur in the data to assist in the engine selection process. This report summarizes the findings of the literature review.

There is a substantial amount of information that has been published regarding the control of emissions from stationary engines, including data from shop and field testing. Much of the information relates to the recent development of regulations in the United States which specify NOx and Hazardous Air Pollutant (HAP) emission limits for new and existing stationary RICE. Clearstone Engineering was able to compile a wide variety of documentation that will support the objectives of the study. Sources of the documentation include:

- Government Agencies (e.g. AENV, US EPA, California, Texas, Colorado State Environmental Agencies)
- Research Organizations (e.g. Houston Advanced Research Center, Southwest Research Institute, Oakridge National Lab)
- Academic Institutions (e.g. Kansas State University, Colorado State University)
- Operating Companies (e.g. Conoco Phillips, PetroCanada, BP, Southern California Gas Company)
- Industry Associations (e.g. CAPP, API, GMRC, GTI)
- Engine manufacturers (e.g. Waukesha, Caterpillar)
- Manufacturers of emission control equipment

A review of the literature confirmed that there are a number of commercially available technologies that are being used to successfully control NOx emissions. The information includes NOx reduction efficiencies for different control technologies and costs to install the equipment. Reduction costs in dollars per ton of NOx are provided in many cases.

At present, Non-selective catalytic reduction (NSCR) is the control technology that is most widely used to reduce NOx emissions from rich-burn engines. Although the technology has been used for many years and there is agreement that it is effective in reducing NOx emissions, there is some question as to whether NOx emissions in the range of 2 g/hp-hr can be achieved over long periods of time under changing operating conditions. The use of air-fuel ratio control to convert a rich-burn engine to a lean-burn engine to reduce NOx emissions does not appear to be a common application.

Uncontrolled NOx emissions from lean-burn engines are significantly less than the uncontrolled emissions from a similarly sized rich-burn engine. Consequently, there is less potential for large emission reductions. Retrofit air-fuel ratio controllers and improved ignition systems are being used in some applications to reduce NOx emissions from lean burn engines.

There is less information available regarding the impact of the various NOx control technologies on fuel consumption and other engine emissions such as greenhouse gases. The relationship is described in much of the documentation, but the literature search proved that complete test data on common engines is limited.

Most of the control technology information and data reviewed is from development work and operating experience in the United States. Although much of the information will be relevant to Canada, there are likely differences in the operating environments where the control technologies are applied and will require consideration.

TABLE OF CONTENTS

1.0 INTRODUCTION 1
  1.1 GAS COMPRESSION IN THE UPSTREAM OIL AND GAS SECTOR 1
  1.2 STATIONARY ENGINE CHARACTERIZATION 2
    1.2.1 4-Stroke Engines 2
    1.2.2 2-Stroke Engines 2
    1.2.3 Rich-Burn vs. Lean-Burn 3
    1.2.4 Reciprocating Gas Engine Inventory 3
2.0 ENGINE EMISSIONS 7
3.0 RETROFIT NO_X REDUCTION TECHNOLOGIES 11
  3.1 AIR-FUEL RATIO (AFR) CONTROLLERS 11
    3.1.1 Technologies in Market 12
    3.1.2 Impact of the Technologies on NO_x and GHG Emissions 13
  3.2 CONTROLLING NOX EMISSIONS WITH CATALYSTS 18
    3.2.1 Non-Selective Catalytic Convertors (NSCR) 18
    3.2.2 Selective Catalytic Convertors 21
    3.2.3 Impacts of Catalyst Technology 22
4.0 RICE REGULATORY REQUIREMENTS 28
  4.1 CANADIAN REGULATIONS 28
  4.2 STATIONARY RICE EMISSION REGULATIONS IN THE UNITED STATES 29
5.0 RECOMMENDATIONS 31
6.0 REFERENCES 32

LIST OF TABLES

Table 1-1: Summary of reciprocating internal combustion engine data regulated by Alberta Environment 2002. 4
Table 1-2: Assortment of reciprocating internal combustion engine models regulated by Alberta Environment 2002. 4
Table 2-1: Typical exhaust gas components from gas fuelled reciprocating engines. 8
Table 3-1: Emission control options for gas fuelled reciprocating internal combustion engines. 11
Table 3-2: Pre- and post-REMVue retrofit NOx emission rates and BSFC obtained from industry test data. 14
Table 3-3: Catalyst technologies available for gas fuelled reciprocating internal combustion engines. 18
Table 3-4: NOx emission rates from reciprocating compressor gas engines before and after the installation of an air-fuel ratio controller and NSCR catalytic converter. 24
Table 3-5: Typical emission reductions using NSCR technology on gas fuelled reciprocating internal combustion engines. 25
Table 3-6: Percent of time various emissions levels were maintained on the 1467 hp engine. 25
Table 3-7: SCR NOx conversion efficiencies for gas fuelled reciprocating internal combustion engines provided by various vendors. 26
Table 4-1: Upstream Oil and Gas BLIER for Natural Gas Fuelled RICE. 29

LIST OF FIGURES

FIGURE 1-1: COMPARISON OF RECIPROCATING GAS ENGINE TYPES IN ALBERTA, BRITISH COLUMBIA, AND SASKATCHEWAN (SOURCE: CLEARSTONE ENGINEERING LTD. DATABASE). 5
FIGURE 1-2: COMPARISON OF GAS FUELLED ENGINES BY MANUFACTURER FROM THE CLEARSTONE ENGINEERING LTD. DATABASE POWERING RECIPROCATING COMPRESSORS LOCATED IN ALBERTA, BRITISH COLUMBIA, AND SASKATCHEWAN. 5
FIGURE 1-3: NUMBER OF COMMON GAS FUELLED WAUKESHA ENGINES FROM THE CLEARSTONE ENGINEERING LTD. DATABASE POWERING RECIPROCATING COMPRESSORS IN ALBERTA, BRITISH COLUMBIA, AND SASKATCHEWAN. 6
FIGURE 1-4: NUMBER OF COMMON GAS FUELLED CATERPILLAR ENGINES FROM THE CLEARSTONE ENGINEERING LTD. DATABASE POWERING RECIPROCATING COMPRESSORS IN ALBERTA, BRITISH COLUMBIA, SASKATCHEWAN. 7
FIGURE 1-5: NUMBER OF COMMON GAS FUELLED WHITE SUPERIOR ENGINES FROM THE CLEARSTONE ENGINEERING LTD. DATABASE POWERING RECIPROCATING COMPRESSORS IN ALBERTA, BRITISH COLUMBIA, AND SASKATCHEWAN. 7
FIGURE 2-1: TYPICAL EXHAUST GAS EMISSIONS OF GAS FUELLED RECIPROCATING INTERNAL COMBUSTION ENGINES (SOURCE: LAMBERT, 1995). 9
FIGURE 2-2: GHG EMISSIONS FROM GAS FUELLED RECIPROCATING ENGINES (COURTESY OF SPARTAN CONTROLS LTD.) 10
FIGURE 3-1: OPERATING ZONES OF REMVUE SYSTEMS INSTALLED ON GAS FUELLED RECIPROCATING INTERNAL COMBUSTION ENGINES (COURTESY OF SPARTAN CONTROLS LTD.). 14
FIGURE 3-2: EFFECTS OF BRAKE SPECIFIC NOX EMISSIONS ON BRAKE SPECIFIC FUEL CONSUMPTION FOR VARIOUS 2-STROKE AND 4-STROKE ENGINES (COURTESY OF HUTCHERSON ET. AL.). 16
FIGURE 3-3: EFFECTS OF AIR-FUEL RATIO ON BRAKE SPECIFIC FUEL CONSUMPTION FOR SPARK IGNITED ENGINES FUELLED BY NATURAL GAS AND GASOLINE (COURTESY OF EVANS AND BLASZCZYK). 17
FIGURE 3-4: EFFECTS OF AIR-FUEL RATIO ON BRAKE SPECIFIC NOX EMISSIONS FOR SPARK IGNITED ENGINES FUELLED BY NATURAL GAS AND GASOLINE (COURTESY OF EVANS AND BLASZYCZK). 17
FIGURE 3-5: EFFECTS OF NOX REDUCTION ON CO_2 EMISSIONS FOR A WAUKESHA L7042GSI ENGINE EQUIPPED WITH A REMVUE SYSTEM (COURTESY OF ACCURATA INC.). 18
FIGURE 3-6: EFFECT OF AIR-FUEL RATIO ON EMISSIONS FROM GAS FUELLED RECIPROCATING INTERNAL COMBUSTION ENGINES (COURTESY OF JOHNSON MATTHEY). 20
FIGURE 3-7: SCR SYSTEM COMBINED WITH AN OXIDATION CATALYST (COURTESY OF JOHNSON MATTHEY). 21
FIGURE 3-8: MIRATECH SCR CATALYST HOUSING (COURTESY OF MIRATECH CORPORATION). 22
FIGURE 3-9: CONVERSION EFFICIENCY OF JOHNSON MATTHEY NSCR TECHNOLOGY ON GAS FUELLED RECIPROCATING INTERNAL COMBUSTION ENGINES (COURTESY OF JOHNSON MATTHEY). 23
FIGURE 3-10: MIRATECH NSCR CATALYST CONVERSION EFFICIENCIES ON GAS FUELLED RECIPROCATING INTERNAL COMBUSTION ENGINES (COURTESY OF SOUTHERN CALIFORNIA GAS COMPANY). 24
FIGURE 3-11: SCR NOX CONVERSION EFFICIENCIES OF VARIOUS CATALYST MATERIALS FOR GAS FUELLED RECIPROCATING INTERNAL COMBUSTION ENGINES (COURTESY OF JOHNSON MATTHEY). 27

LIST OF ACRONYMS

AENV	Alberta Environment
AFR	Air to Fuel Ratio
AQMS	Air Quality Management System
BLIERS	Base Level Industrial Emission Requirements
CAAQS	Canadian Ambient Air Quality Standards
CAC	Criteria Air Contaminant
CAMS	Comprehensive Air Management System
CCME	Canadian Council of Ministers of Environment
CO	Carbon Monoxide
CO_2	Carbon Dioxide
g	gram
GHG	Greenhouse Gas
HAP	Hazardous Air Pollutant
kW	Kilowatt
NESHAP	National Emissions Standard for Hazardous Air Pollutants
NMHC	Non-Methane Hydrocarbons
NOx	Oxides of Nitrogen
HP	Horse Power
NSCR	Non-selective catalytic reduction
NSPS	New Source Performance Standards
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SO_2	Sulphur Dioxide
SO_x	Sulphur Oxides
THC	Total Hydrocarbons
RICE	Reciprocating Internal Combustion Engine
US EPA	Unites States Environmental Protection Agency
VOC	Volatile Organic Compound
WOT	Wide Open Throttle
2SLB	2-stroke lean-burn engine
4SLB	4-stroke lean-burn engine
4SRB	4-stroke rich-burn engine

1.0 INTRODUCTION

Stationary reciprocating engines release the majority of NOx emissions from the upstream oil and gas industry. There are proven technologies available to reduce NOx emissions from these sources; however, a better understanding of their effects on fuel consumption and greenhouse gas (GHG) emissions is required.

Clearstone Engineering Ltd. is conducting a study on behalf of PTAC to evaluate NOx control technologies suitable for installation on existing natural gas fuelled reciprocating internal combustion engines (RICE), and to investigate their impact on fuel consumption and GHG emissions. The results of the research study will be used to help establish new NOx emission limits for this type of equipment.

The first phase of the study was to conduct a literature review of commercially available retrofit NOx reduction technologies, focusing on air-fuel ratio controllers and non-selective catalytic convertors. Its purpose was to analyze existing engine test information and to identify any gaps that occur in the data to assist in selecting engines for testing. This report summarizes the findings of the literature review.

1.1 Gas Compression in the Upstream Oil and Gas Sector

Reciprocating internal combustion engines are a common source of mechanical power in the upstream oil and gas sector, particularly in locations where electric power is not available. Engines ranging in size from less than 50 kW to over 2,500 kW are used to power rotating equipment such as compressors, generators and pumps.

The majority of the installed reciprocating engines are used to drive compressors that collect gas from upstream production facilities and move it through gathering lines to gas processing facilities and pipeline distribution systems. Many of the engines are located in isolated areas, so the engines must be reliable and suitable for long periods of continuous unattended operation.

Compressor sizing and selection are determined by process requirements such as gas composition, flow rates, and suction and discharge pressures. There are three types of compressors powered by reciprocating internal combustion engines commonly used at upstream oil and gas facilities.

- Separable-reciprocating compressors;
- Integral compressors; and
- Rotary screw compressors

The separable-reciprocating compressor is the most common of the three. They typically have low rotational and piston speeds, leading to high reliability. Compression ratios are limited, so where large differential pressures are required, multi-stage units are used.

In an integral setup, the engine and compressor are integral components that cannot be separated. Integral compressors use two-stroke, slow-speed (approx. 450 rpm) engines. These compressors are of an older design, are less efficient than separable compressor units and are costly to replace. They can, however, tolerate higher concentrations of sulphur compounds in the fuel gas which can be useful in some applications. Nevertheless, there use is on the decline as available new units are limited and typically not purchased.

Rotary screw compressors also use positive displacement to compress gas between rotary lobes confined in a cylinder. Rotary screw compressors have the ability to operate over a wide range of load conditions and are often selected for low pressure applications. Rotary screw compressors are also well-suited for high compression ratio applications.

1.2 Stationary Engine Characterization

There are four basic operations that occur as reciprocating engines work: intake, compression, power, and exhaust. Engines are classified into two separate categories based on the number of crank shaft revolutions completed during each power cycle. Two-stroke engines complete each power cycle in a single crankshaft revolution whereas two crank shaft revolutions are required for 4-stroke engines.

1.2.1 4-Stroke Engines

Four stroke engines have a single operation associated with each movement of the piston. During the intake stroke, the intake valve opens and fuel is drawn into the combustion chamber by the downward motion of the piston. In carbureted and indirect fuel injected engines, fuel is mixed with air before being introduced into the combustion chamber. In direct gas injection engines, the fuel is injected into the combustion chamber while air is drawn in by the downward motion of the piston. At the end of the downward stroke, the valves close and the compression stroke begins with the pistons moving upward, compressing the air/fuel mixture. Spark plugs are used to ignite the air/fuel mixture.

During the power stroke, the high-pressure gases from combustion drive the pistons downward. When the piston reach the full downward position, the exhaust valves open and the combustion products are pushed from the engine by the upward motion of the pistons. Near the full upward travel of the pistons, the exhaust valves close, the intake valves open and the intake stroke is repeated.

1.2.2 2-Stroke Engines

Two stroke engines complete two operations with each rotation of the crank shaft. The air-fuel charge is injected through ports in the cylinder wall which are uncovered as the piston nears the bottom of the power stroke. The intake ports are then closed, and the piston moves to the top of the cylinder, compressing the charge. The charge is ignited by a spark plug and the expansion of the combustion products starts the power stroke with the downward movement of the piston. As the piston reaches the bottom of the power stroke, exhaust ports are opened and the exhaust gases are swept out by a fresh air-fuel charge transferred into the cylinder through the intake ports. The intake air is pressurized to improve the efficiency of the exhaust scavenging.

2-stroke engines are usually the driver used with integral compressors. The number of 2-stroke engines in gas compression service in the Canadian upstream oil and gas sector is relatively small compared to 4-stroke engines and is declining further as integral compressors units are retired or replaced.

1.2.3 Rich-Burn vs. Lean-Burn

Reciprocating gas engines are also characterized in terms of the air to fuel ratio (AFR). A rich-burn engine is classified as excess fuel in the combustion chamber and a lean-burn engine is classified as excess air in the combustion chamber. Lambda (λ), the ratio of actual AFR to stoichiometry, is used in some cases.

Lean-burn engines operate with excess air, as much as 50% to 100% more air than the stoichiometric requirement. The excess air absorbs heat during the combustion process which reduces the combustion temperature and pressure, resulting in good fuel efficiency, reduced downtime, and a decrease in engine power. As the AFR increases, combustion speed decreases. If the AFR is increased too far, combustion will eventually become unstable and lean misfire may result.

There are some different definitions of a rich-burn engine available in the literature. For example, some literature defines a rich-burn engine as an engine operating near stoichiometric conditions, with a lambda ratio of 1.1 or less, or with an oxygen rich exhaust of 4% or less. However, for the purpose of this study, a rich-burn engine is defined as an engine operating with an AFR less than the stoichiometric AFR, or one with less than 0.5% oxygen in the exhaust. Under rich-burn conditions, the combustion chamber is rich with fuel, resulting in increased combustion temperatures, increased engine power, and decreased engine efficiency. In some cases, an engine can be set to operate slightly leaner than the stoichiometric point to reduce wasted fuel and minimize fuel consumption.

Determining the ideal engine for a particular location will depend on site specific conditions as well as trade-offs between controlling emissions and operating costs.

1.2.4 Reciprocating Gas Engine Inventory

As part of the process to select engines for testing, it is important to have an understanding of the types of engines that make up the current inventory. Selecting common engines provides a representative sample of the engine fleet in the upstream oil and gas industry.

In 2002, Alberta Environment developed a database of engines in Alberta based on information submitted to them as part of the regular environmental reporting process. The results were included in the 2002 report "Inventory of Nitrogen Oxide Emissions and Control Technologies in Alberta's Upstream Oil and Gas Industry". The data from this report is summarized in Table 1-1 and Table 1-2.

Table 1-1: Summary of reciprocating internal combustion engine data regulated by Alberta Environment 2002.

Number of Facilities	Number of Engines	Rich-Burn	Lean-Burn	Engines with Emission Controls	Average Engine Power Rating (kW)
35	1832	76%	24%	23%	720

Source: Alberta Environment, 2002

Table 1-2: Assortment of reciprocating internal combustion engine models regulated by Alberta Environment 2002.

Engine Manufacturer	Waukesha	White Superior	Caterpillar	Cooper	Others
	42%	23%	15%	6%	14%

Source: Alberta Environment, 2002

Clearstone has a database that it uses for preparing annual emissions estimates for upstream oil and gas facilities in Alberta, British Columbia, and Saskatchewan. Included in the database is information regarding reciprocating gas engines that are currently in service. The available information includes engine make and model, power rating, average load, operating hours, and in some cases, an indication whether an emissions control device has been installed. The database includes approximately 1,300 engines.

The information in Clearstone's database was sorted further to estimate the split between 2-stroke lean-burn (2SLB), 4-stroke lean-burn (4SLB) and 4-stroke rich-burn (4SRB) engines (Figure 1-1). The most common engines by manufacturer was also identified (Figure 1-2). There is reasonable correlation between the information from AENV and Clearstone databases, particularly when considering the 10 year span in the data. However, some changes can be observed. The ratio between lean-burn and rich-burn engines has narrowed and the number of Caterpillar models is larger in the Clearstone database.

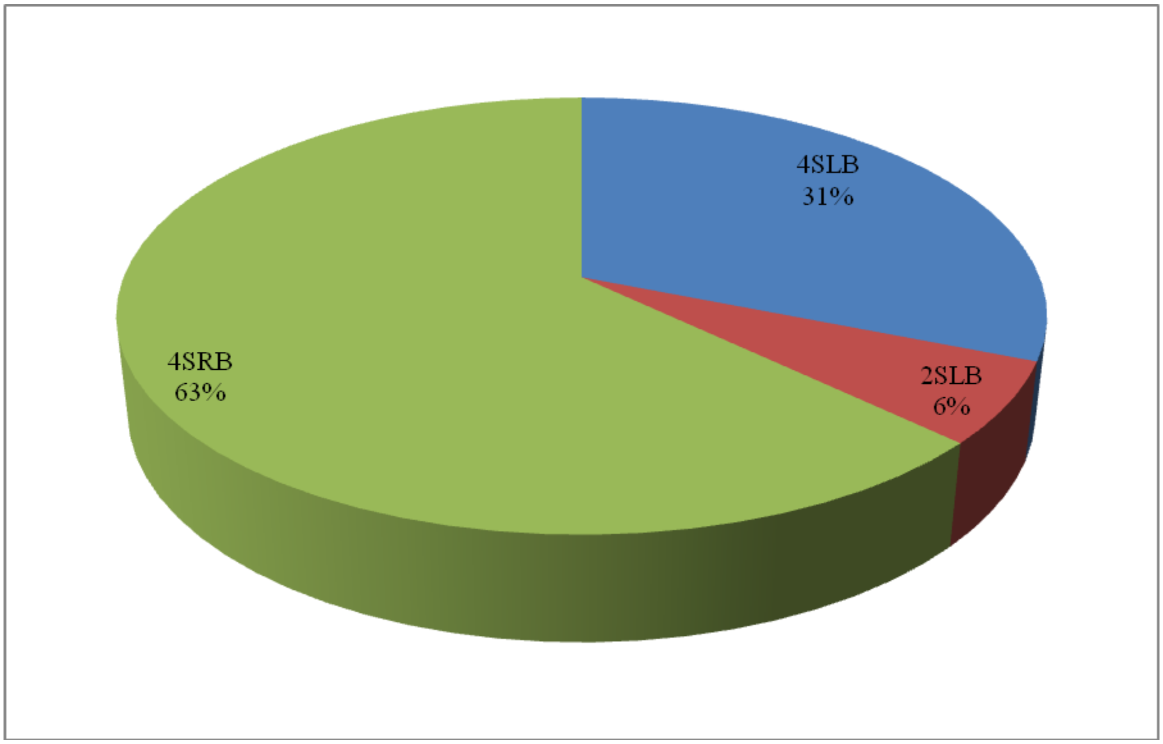


Figure 1-1: Comparison of reciprocating gas engine types in Alberta, British Columbia, and Saskatchewan (source: Clearstone Engineering Ltd. database).

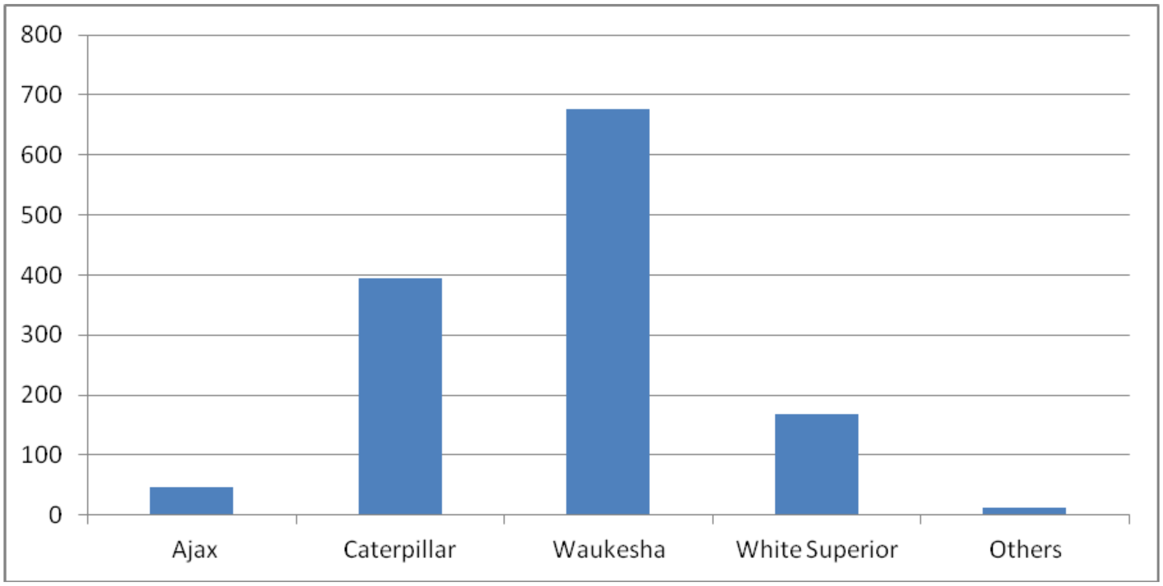


Figure 1-2: Comparison of gas fuelled engines by manufacturer from the Clearstone Engineering Ltd. database powering reciprocating compressors located in Alberta, British Columbia, and Saskatchewan.

Based on the engine population data from AENV and the Clearstone database, it is beneficial to analyze common engine models in Western Canada from Waukesha (Figure 1-3), Caterpillar (Figure 1-4), and White Superior (Figure 1-5).

Engines F3521GSI, L7042GL, and L7042GSI appear to be the most common Waukesha models. L7042GSI is a 12 cylinder rich-burn engine with a turbocharger and an intercooler, producing approximately 1100 kW. L7042GL is a lean-burn engine with similar options and power output as the GSI model. F3521GSI is a 6 cylinder rich-burn engine with a turbocharger and an intercooler, producing approximately 550 kW.

Some common Caterpillar engines in Western Canada appear to be the G3408TA and G3512TALE models. G3408TA is an 8 cylinder rich-burn engine with a turbocharger and aftercooler, rated for approximately 300 kW. The G3512TALE model is an 8 cylinder lean-burn engine with a turbocharger and aftercooler, rated for approximately 600 kW.

8G-825 is the most common White Superior model. This rich-burn engine is available in a 12 or 16 cylinder arrangement, rated for approximately 600 kW.

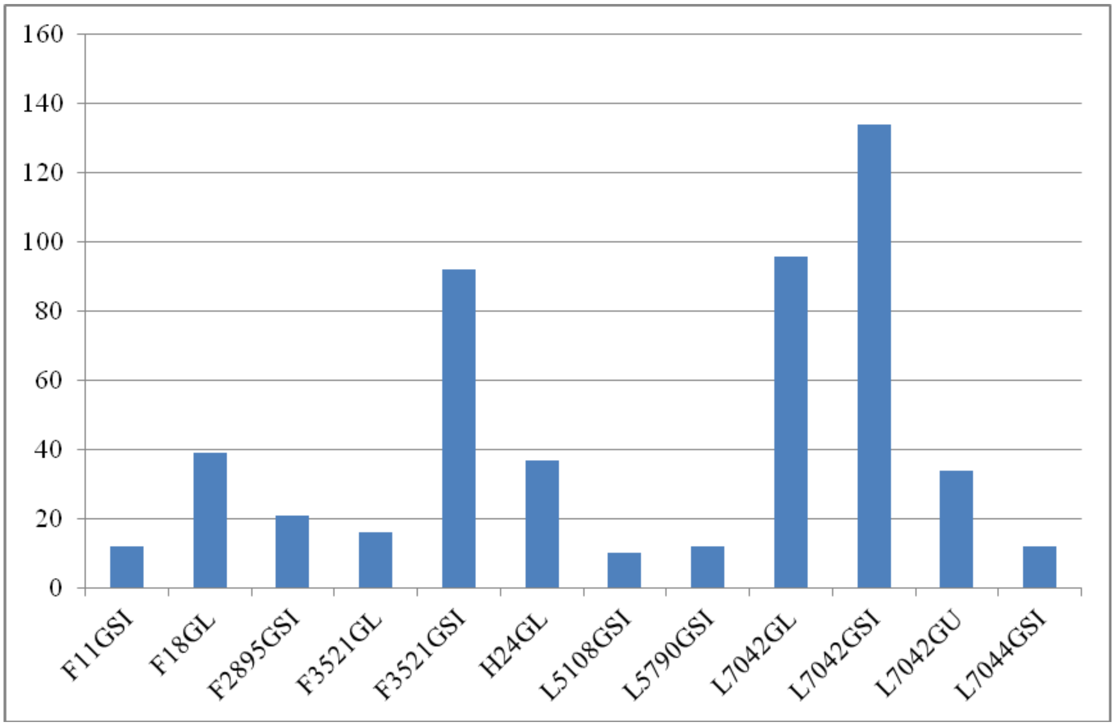


Figure 1-3: Number of common gas fuelled Waukesha engines from the Clearstone Engineering Ltd. database powering reciprocating compressors in Alberta, British Columbia, and Saskatchewan.

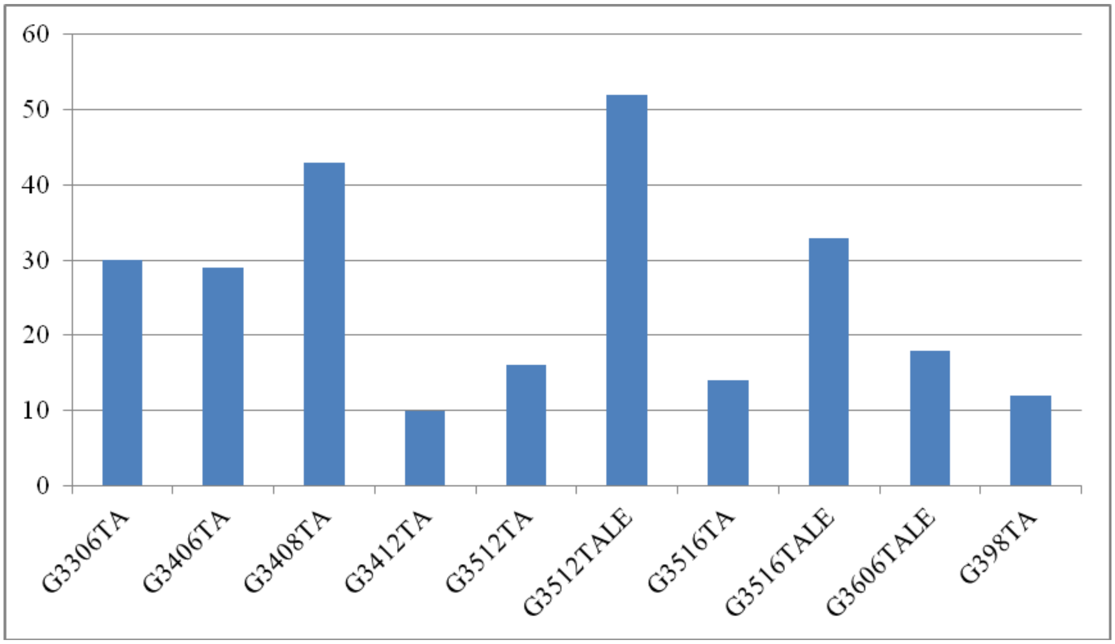


Figure 1-4: Number of common gas fuelled Caterpillar engines from the Clearstone Engineering Ltd. database powering reciprocating compressors in Alberta, British Columbia, Saskatchewan.

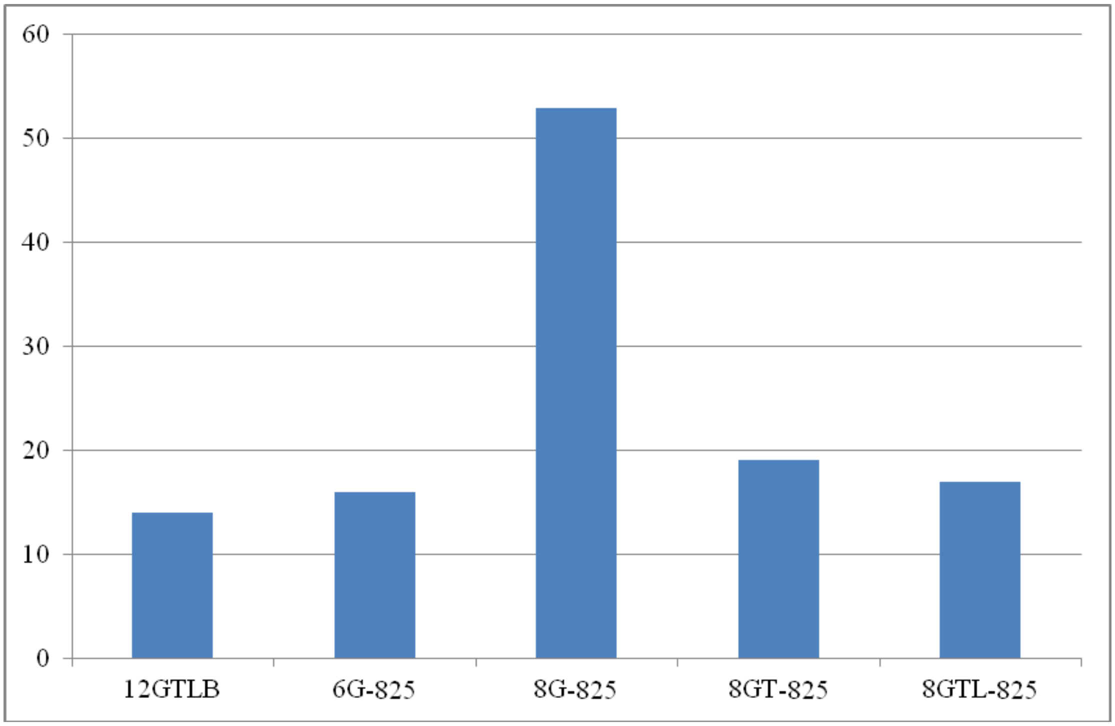


Figure 1-5: Number of common gas fuelled White Superior engines from the Clearstone Engineering Ltd. database powering reciprocating compressors in Alberta, British Columbia, and Saskatchewan.

2.0 ENGINE EMISSIONS

The primary emissions from natural gas reciprocating engines are oxides of nitrogen (NOx), carbon monoxide (CO), GHG, and hydrocarbons. Emissions may also include small quantities of particulate matter and sulphur oxides (SOx). The actual concentration of these criteria pollutants depends on the engine, operating conditions, and the type of fuel used. Table 2-1 lists the exhaust components from a typical natural gas fuelled internal combustion engine.

Table 2-1: Typical exhaust gas components from gas fuelled reciprocating engines.

Component	**Rich Burn Engine λ = 1**		**Lean Burn Engine λ = 1.5**	
	% weight	**% volume**	**% weight**	**% volume**
Nitrogen	72.0	70.7	73.3	73.1
Water	12.7	19.4	8.6	13.3
Carbon Dioxide	13.8	8.6	9.3	5.9
Oxygen	0.5	0.4	7.9	6.5
Oxides of Nitrogen	.35	.21	.05	.03
Carbon Monoxide	.45	.44	.03	.03
Unburned Hydrocarbons	.08	.07	.07	.15

Source: Caterpillar, 2007

Nitric oxide (NO) and nitrogen dioxide (NO_2) are typically grouped together as NOx emissions. Nitric oxide is created from the oxidation of atmospheric nitrogen. Once NO arrives in the atmosphere, it reacts with diatomic oxygen to form NO_2. The formation of NOx is related to combustion temperature in the engine cylinder. Significant amounts of NOx begin to form when combustion temperatures reach 2800^{o}F. NOx formation increases drastically after this point. More specifically, the maximum NOx formation occurs when the excess air ratio is approximately 1.1 (Figure 2-1). Lower excess air levels starve the reaction of oxygen, and higher excess air levels reduce the combustion temperature, slowing the reaction rate. The other pollutants, CO and VOC species, are primarily the result of incomplete combustion.

CO is the result of incomplete combustion of carbon and oxygen. CO is formed when insufficient oxygen or poor charge mixing interferes with the mechanism to produce CO2. As shown in Figure 2-1, CO formation is greatest when the fuel mixture is rich. CO will also form when a very lean mixture cannot sustain complete combustion.

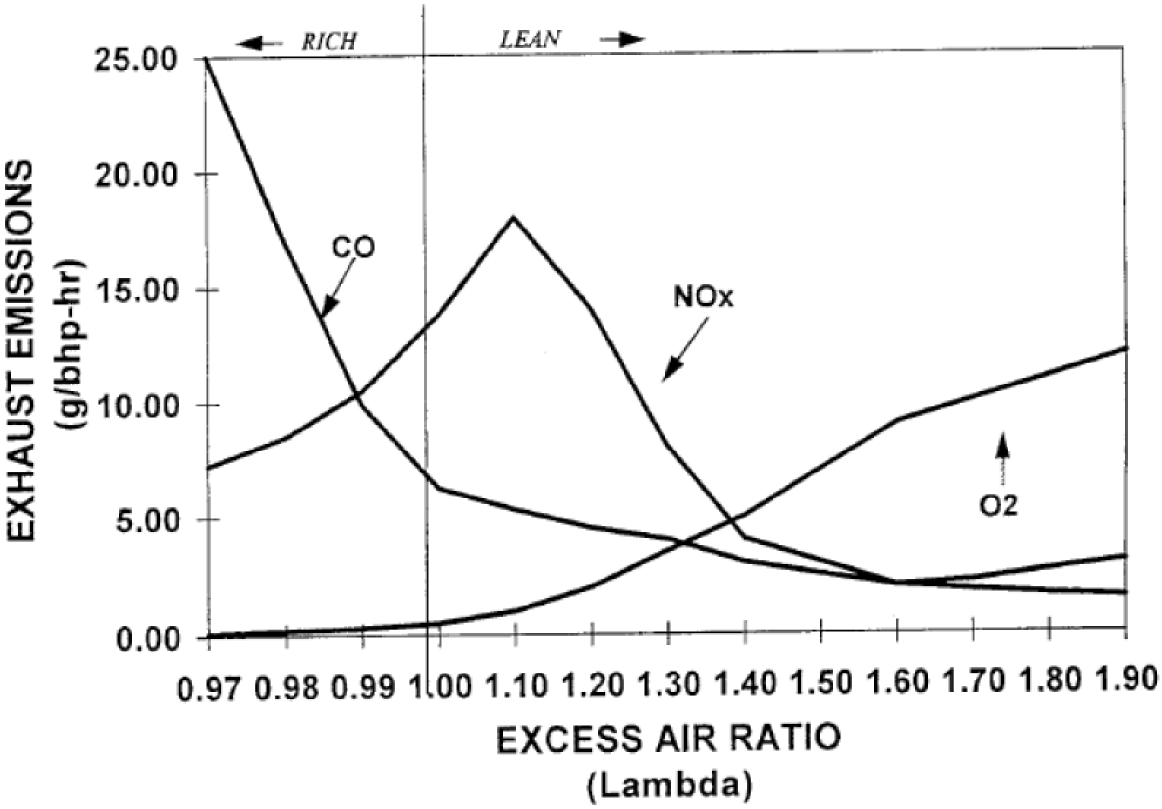


Figure 2-1: Typical exhaust gas emissions of gas fuelled reciprocating internal combustion engines (Source: Lambert, 1995).

Hydrocarbon emissions result from incomplete combustion of hydrocarbon fuels. Portions of fuel can end up in small crevices in the cylinder and avoid combustion. Also, the air and fuel mixture may be too rich or lean to oxidize all of the fuel or produce a high enough flame temperature. The unburned hydrocarbon composition will vary according to the incoming composition of the fuel. The reactivity of hydrocarbons in the atmosphere differs considerably. Compounds with a higher reactivity are of most concern due to their contribution to smog formation. Methane has a very low reactivity and is often excluded from hydrocarbon regulations and measurements. Unburned hydrocarbons are typically classified as Total Hydrocarbons (THC) or Non Methane Hydrocarbons (NMHC). A THC measurement will include all exhaust emissions of methane, ethane, propane, butane, pentane, and higher molecular weight hydrocarbons. A NMHC measurement will account for all hydrocarbons except for methane.

The greenhouse gases carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) are also components of engine exhaust. In recent years, the combined emissions of these compounds have been monitored more closely. The quantity of greenhouse gas emissions produced by spark ignited engines is closely related to the engine air-fuel ratio. Figure 2-2 compares the greenhouse gas emissions from different types of engines. Lean combustion produces fewer GHG emissions compared to rich combustion due to the reduction in fuel consumption and unburned fuel.

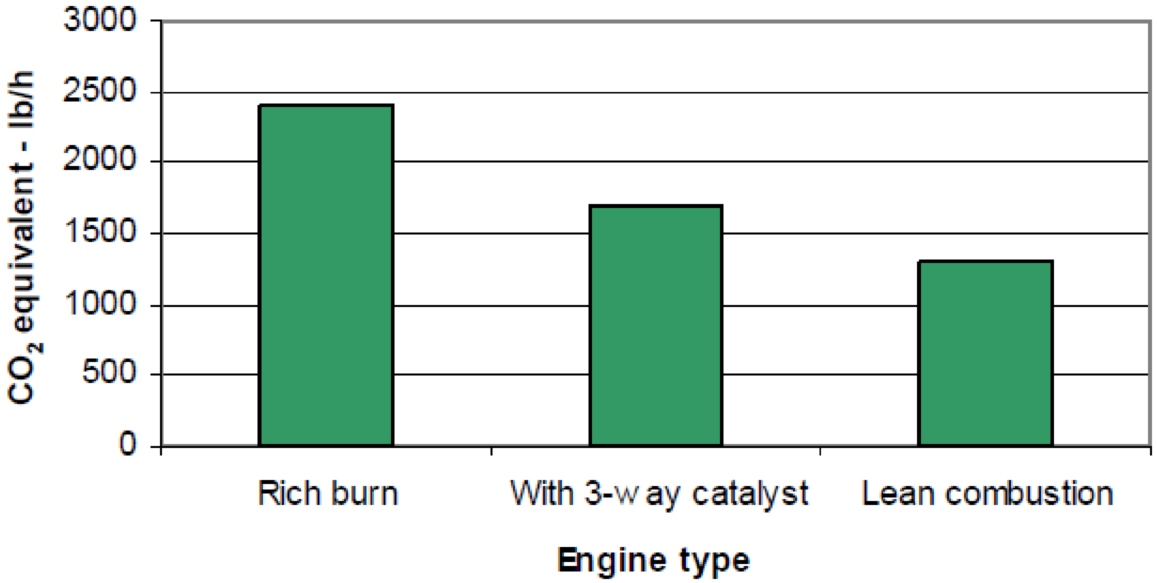


Figure 2-2: GHG emissions from gas fuelled reciprocating engines (courtesy of Spartan Controls Ltd.)

The combustion of natural gas produces virtually no particulate matter. Some particulates are produced from the combustion of engine oil. However, the quantities are usually negligible during normal engine operation.

Sulphur will be present in the exhaust of a gas engine when the fuel contains sulphur compounds. Hydrogen sulphide is the most common sulphur bearing compound found in gaseous fuels, particularly with wellhead and associated gases. However, since most engines can only tolerate small amounts of sulphur bearing compounds in the fuel, sulphur dioxide emissions are generally not an issue with natural gas engines.

There are also several hazardous air pollutants (HAP) that may be emitted from gas fuelled engines. The pollutants of most concern from this category are several aldehydes which account for most of the HAPs in the engine exhaust.

3.0 RETROFIT NO_X REDUCTION TECHNOLOGIES

There are several different types of retrofit technologies to reduce NOx emissions from gas fuelled engines. These controls can be grouped into two categories: combustion modifications and post-combustion controls. Combustion modifications include ignition timing retard, turbocharging, exhaust gas recirculation, and leaning of the AFR. In some cases, a combination of several combustion controls may be used to achieve very low NOx emissions. Post combustion controls include non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR). Table 3-1 summarizes some technically feasible emission controls for gas fuelled RICE and their NOx reduction capabilities.

Table 3-1: Emission control options for gas fuelled reciprocating internal combustion engines.

Technology	Engine Type	NOx Reduction Potential (%)
Air-Fuel Ratio Adjustment	Lean-Burn	≈ 5- 30%
Ignition/Spark Timing Retard	Lean-Burn	≈ 20%
NSCR	Rich-Burn	≈ 80 – 90%
SCR	Lean-Burn	≈ 80 – 90%

Selective non-catalytic reduction (SNCR) is not included in Table 3-1 because this technology requires a relatively high exhaust temperature to be effective, eliminating it as an applicable NOx abatement strategy for gas fuelled reciprocating engines. This technology has been proven effective on process boilers, incinerators, and other plant heaters.

3.1 Air-Fuel Ratio (AFR) Controllers

The mechanism by which an engine receives fuel and air is either by a carburetor or throttle body and fuel injectors. While the throttle body and fuel injectors are a common feature on modern automobiles, many stationary engines operating in the oil and gas industry are older and still utilize a carburetor (Beshouri et al., 2005). A disadvantage of a carburetor is that the fuel air mixture is set mechanically, typically by an adjustment screw or some other similar method. While this can be accurately done by skilled technicians for a single load and speed, there is no system for real time adjustment of the AFR. Therefore, when the load, speed, or environmental conditions change, the AFR will vary (Lambert, 1995). This constant variation of the air-fuel ratio is called an uncontrolled engine. If the excess air is uncontrolled and varying, the AFR will be uncontrolled and changing as well. To bring the engine under control, an engine can be retrofitted with an air-to-fuel ratio controller (Kennedy and Holdeman, 2006).

All engines are equipped with some form of AFR controllers to improve the performance of natural gas-fired, four-cycle, rich- and lean-burn reciprocating engines by optimizing and stabilizing the AFR over a range of engine operations and conditions. Often factory installed

AFR controllers on engines operate best at one set point. However, the range of operations in the field varies substantially. Therefore, controlling the AFR in engines over a wide range of operating conditions requires an engine management system to maximize engine efficiency.

AFR controllers use a closed-loop feedback system to automatically and continuously optimize the air-fuel mixture introduced to the engine based on various input parameters (potentially including fuel quality, engine load, flue gas O_2 levels and ambient conditions). This function provides the potential to improve engine fuel consumption and reduce engine emissions, particularly when noteworthy changes in engine load, fuel quality, or ambient conditions occur. An optimized and stabilized AFR can also improve engine performance, reduce lubrication oil degradation, and help minimize wear to major engine components.

3.1.1 Technologies in Market

3.1.1.1 REMVue Adaptive Engine/Compressor Management System

Developed by REM Technologies Inc., the REMVue is a modular engine/compressor management control system, which allows the user a variety of options. The base system permits the operation of the AFR control. Other modules for shutdown, process and environmental control can be added, depending on the application.

REM stands for reciprocating equipment management. The REMVue system can be applied to stoichiometric, lean burning and turbocharged natural gas engines, typically used to drive rotating equipment for natural gas extraction and processing. The REMVue system is an after-market product designed to replace the original manufacturers' mechanical AFR control systems. Mechanical equipment substitutions or alterations are required to link the REMVue software package to the engine. The inputs are monitored via a real-time operating system which provides prioritized multitasks of control, monitoring, communications, calculation and operator interface. REMVue systems are also being supplied to new equipment packagers at the request of the final customer, who specifies the options (safety shutdown, diagnostics, etc.).

In the case of a rich-burn retrofit, the REMVue system controls the engine's emissions by establishing lean burn conditions within a rich burn engine. REMVue does this by introducing a large air volume into an open chamber cylinder design. The original turbo bypass valve is replaced to maintain control and optimize the air manifold pressure. A mass flow fuel gas meter is used to match the optimum amount of fuel for the air volume supplied.

3.1.1.2 Altronic Engine Control Systems

Altronic Controls Incorporated manufactures AFR control systems and accessories. Their EPC control systems utilize microprocessor technology. The systems have demonstrated that they are able to provide long term AFR stability, increased engine efficiency and reduced engine exhaust emissions. The following models are available for the applications specified:

- EPC-50 is designed for use on low power carburated natural gas fuelled engines.

- EPC-110 is designed to be used with a 3-way catalytic converter on rich burn, carburated natural gas engines.
- EPC-100E is designed for stoichiometric rich burn engines and optimizing the performance of the 3-way catalytic converter.
- EPC-150 is designed for lean burn engines.
- EPC-200 is designed for turbo-charged integral compressor engines

All EPC systems operate on the basis of closed loop control using data from an exhaust-mounted oxygen sensor as feedback. With the controller set point optimized for lowest emissions, the EPC unit controls the flow of fuel through the stepper motor valve(s) to maintain the target oxygen level during engine operation.

3.1.2 Impact of the Technologies on NO_x and GHG Emissions

The benefits of a REMVue retrofit are derived from the significant reduction to site NO_x and CO_2 emissions and reduced primary fuel consumption, as illustrated by the green REMVue Low Emission area in Figure 3-1.

Fuel Consumption

A typical Waukesha L7042GSI engine using REMVue can save up to 220,000 m^3 in natural gas per year as reported in tests by Petro-Canada (Accurata 2005, Section 4.1).

Reliability

Studies show that after the REMVue system was installed, there were reductions of up to 31 percent in unscheduled downtime. This was attributed to REMVue's automated controls leading to more predictable performance (Accurata 2005, Section 4.2).

Operational Improvement

Less downtime results in reduced maintenance costs and improved production volumes. Steady-state engine operation, versus an engine experiencing variable speeds, results in less wear and stress on engine components. Reduced operating temperatures also prolong engine component life and reduce annual maintenance costs. These factors increase hours of operation and yield an increase of incremental production.

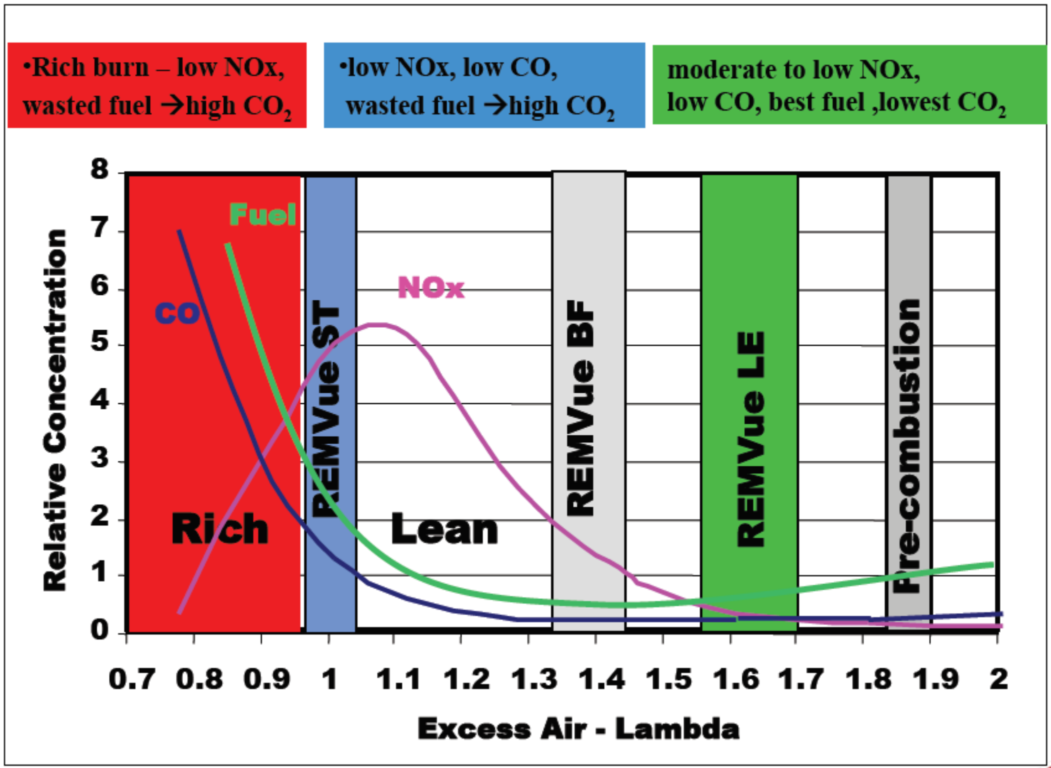


Figure 3-1: Operating zones of REMVue systems installed on gas fuelled reciprocating internal combustion engines (courtesy of Spartan Controls Ltd.).

Table 3-2 presents industry test data of pre- and post- REMVue NOx emission rates and brake specific fuel consumptions (BSFC). Most of the engines that were tested were Waukesha 7042GSI. Most engines experienced a reduction in NOx emissions. Engines that saw an increase in this category typically released relatively low pre-retrofit NOx emissions. These engines were set to an ultra-rich setting to control NOx emissions before the REMVue installation. Almost all engines from this test sample experienced a decrease in BSFC.

It is apparent from the industry test data presented above that lean-burn conversion with a REMVue installation increases fuel efficiency and substantially reduces NOx emissions from uncontrolled engines. Lean-burn conversion reduction opportunities are well known and available in the literature and from industry.

Table 3-2: Pre- and post-REMVue retrofit NOx emission rates and BSFC obtained from industry test data.

	Pre-Retrofit			Post-Retrofit			Reduction	
	Lambda	NOx Emission	BSFC	Lambda	NOx Emission	BSFC	NOx	BSFC
		g/bhp-h	btu/bhp-h		g/bhp-h	btu/bhp-h	%	%
7042GSI	1.01	13.17	8507	1.52	4.06	7962	69%	7%
7042GSI	1.00	4.96	12045	1.63	2.06	9733	59%	24%
7042GSI	1.01	17.30	10215	1.63	1.77	9494	90%	8%
7042GSI	1.02	19.26	11651	1.57	1.64	10407	92%	12%
7042GSI	1.00	10.71	9574	1.62	1.40	9034	87%	6%

Table 3-2: Pre- and post-REMVue retrofit NOx emission rates and BSFC obtained from industry test data.

	Pre-Retrofit			Post-Retrofit			Reduction	
	Lambda	NOx Emission	BSFC	Lambda	NOx Emission	BSFC	NOx	BSFC
		g/bhp-h	btu/bhp-h		g/bhp-h	btu/bhp-h	%	%
7042GSI	1.01	12.09	9803	1.58	1.57	9425	87%	4%
5790GSI	1.01	4.58	11535	1.40	10.40	9709	-127%	19%
7042GSI	1.01	1.80	12488	1.57	4.44	8885	-147%	41%
7044GSI	1.01	13.74	9748	1.53	3.30	9024	76%	8%
7042GSI	1.34	9.12	9751	1.82	1.23	9423	86%	3%
3521GSI	1.00	8.84	10981	1.50	2.15	10543	76%	4%
7042GSI	1.01	2.74	9321	1.53	3.67	7788	-34%	20%
7042GSI	1.01	2.26	10019	1.58	4.37	9341	-94%	7%
7042GSI	1.00	1.30	10868	1.63	4.25	7494	-226%	45%
7042GSI	1.02	2.54	9543	1.54	4.30	8139	-69%	17%
7042GSI	1.00	9.49	9408	1.48	3.02	8617	68%	9%
7042GSI	1.01	1.10	12400	1.52	2.88	9675	-162%	28%
7042GSI	1.00	1.24	10549	1.55	4.54	9229	-266%	14%
7042GSI	1.00	7.42	10474	1.53	4.57	9100	38%	15%
7042GSI	1.01	1.78	10318	1.54	4.13	8634	-132%	20%
9390GSI	1.01	0.56	11133	1.60	4.25	7592	-666%	47%
7042GSI	1.02	13.75	9181	1.49	4.30	9253	69%	-1%
7042GSI	1.09	23.23	8238	1.50	4.02	8014	83%	3%
7042GSI	1.00	1.86	9862	1.54	4.13	8153	-121%	21%
7042GSI	1.00	3.75	8692	1.50	3.67	7818	2%	11%
7042GSI	1.00	3.75	9661	1.50	3.87	8560	-3%	13%
7042GSI	1.00	1.85	10756	1.47	3.45	8226	-86%	31%
7042GSI	1.00	0.92	12530	1.60	4.24	8147	-359%	54%
7042GSI	1.00	3.75	8720	1.55	3.15	8085	16%	8%
7042GSI	1.01	4.77	10441	1.49	4.31	8693	10%	20%
7042GSI	1.01	11.41	10778	1.45	2.90	9534	75%	13%
16GT-825	1.45	13.42	9110	1.51	16.81	9639	-25%	-5%
9390GSI	1.01	5.38	8430	1.62	4.63	7830	14%	8%
7042GSI	1.01	13.17	8203	1.62	1.54	8317	88%	-1%
7042GSI	1.01	10.85	8372	1.56	1.17	7952	89%	5%
5108GSI	1.03	17.26	8858	1.56	4.14	8064	76%	10%
7042GSI	1.01	25.10	15000	1.82	1.23	9423	95%	59%
Average	1.03	8.11	10194	1.56	3.83	8783	-29%	16%
Std Dev	0.09	6.66	1468	0.08	2.74	799	158%	15%

Source: PIC Division of Spartan Controls.

Hutcherson et al. (1999) presented a paper at the Gas Machinery Conference which highlighted NOx reduction performance trade-offs. A relevant analysis that was performed was the relation of NOx emissions and BSFC. This provides a qualitative representation of GHG emissions. As more fuel is wasted or burned, more CO_2 is released. Figure 3-2 shows that for various 2-stroke and 4-stroke engines there is a BSFC asymptote where increasing NOx emissions does not affect BSFC. However, BSFC is affected and increases rapidly if drastic reductions in NOx emissions are required. In other words, BSFC and NOx exhibit a decaying exponential characteristic. Unfortunately, the brake specific data presented for 4 four stroke engines is quite isolated around the 2 g/bhp-hr NOx and 13 to 19 g/bhp-hr NOx emission rate, making it difficult to interpret the relationship.

The study also showed that the ignition system affected where the BSFC and other trade-offs would occur. Advanced Engine Technologies Corporation (2004) continued the study which included enhanced mixing combustion technologies (EMCT). The fundamentals of this technology include improved combustion with enhanced mixing and flame propagation. It was determined that EMCT can shift or eliminate the performance trade-offs. The test results prove that stricter NOx limits can be obtained without sacrificing performance.

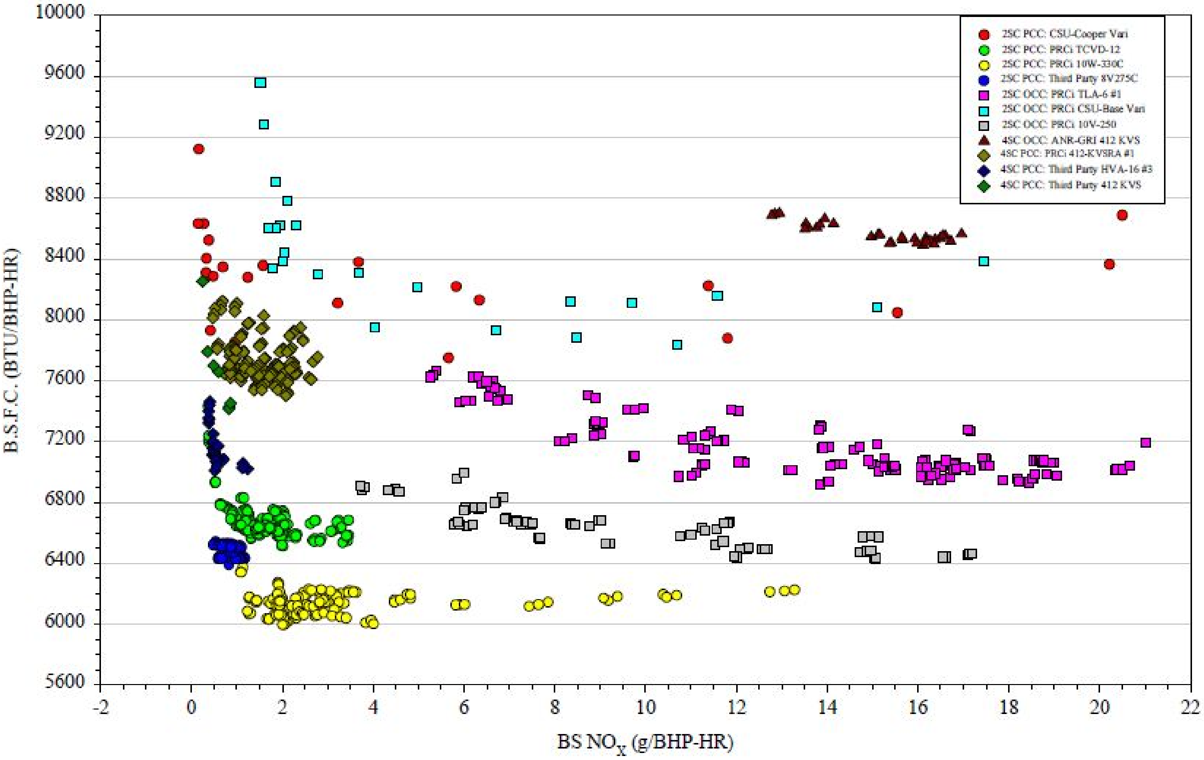


Figure 3-2: Effects of brake specific NOx emissions on brake specific fuel consumption for various 2-stroke and 4-stroke engines (courtesy of Hutcherson et. al.).

Evans and Blaszczyk (1997) studied the performance and exhaust emissions of spark ignited engines. They measured various parameters while adjusting speed, load, and the AFR. All tests were performed in a laboratory environment on a single-cylinder engine producing approximately 15 kW. Figure 3-3 and Figure 3-4 present some relevant results showing the relation of BSFC and NOx emissions for various loading conditions. As the AFR reaches the lean limit of combustion, the fuel consumption begins to increase, indicating that CO_2 emissions being to increase as the AFR point for “best emissions” approaches.

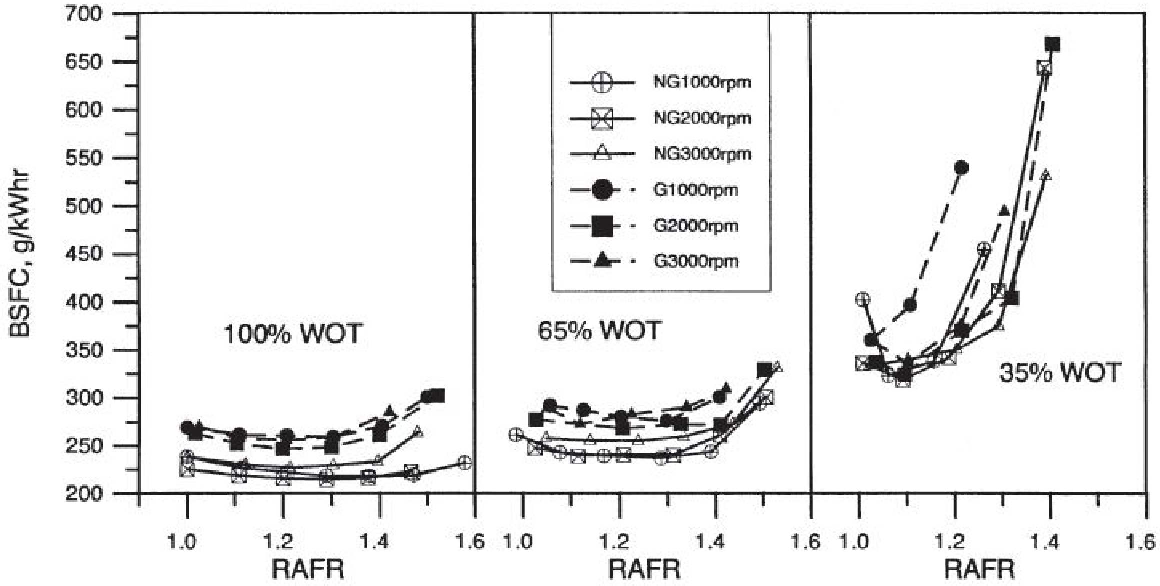


Figure 3-3: Effects of air-fuel ratio on brake specific fuel consumption for spark ignited engines fuelled by natural gas and gasoline (courtesy of Evans and Blaszczyk).

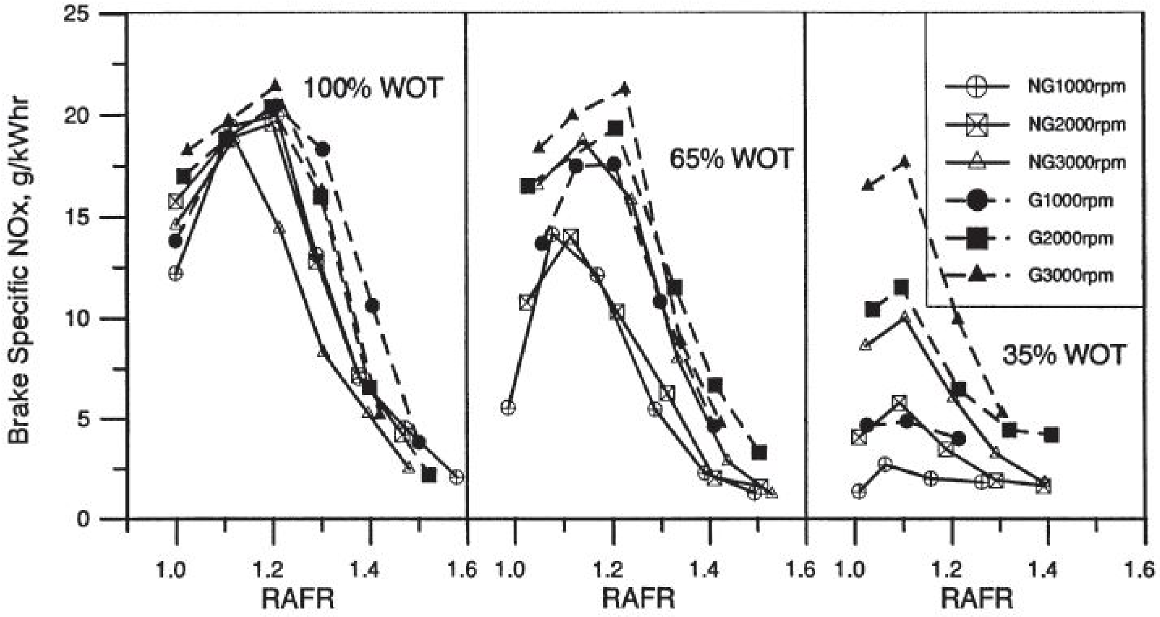


Figure 3-4: Effects of air-fuel ratio on brake specific NOx emissions for spark ignited engines fuelled by natural gas and gasoline (courtesy of Evans and Blaszyczk).

Accurata Inc. (2005) performed a study on emissions reduction and efficiency enhancements with a REMVue retrofit. More specifically, test data was gathered for a Waukesha L7042GSI equipped with a REMVue system. CO2 and NOx emissions were measured for various loads, speeds, and optimizing settings. Figure 3-5 shows that CO_2 emission begins to increase as settings are changed from “best fuel” to “best emissions”. It would be beneficial to gather similar data for more loading conditions and AFR settings.

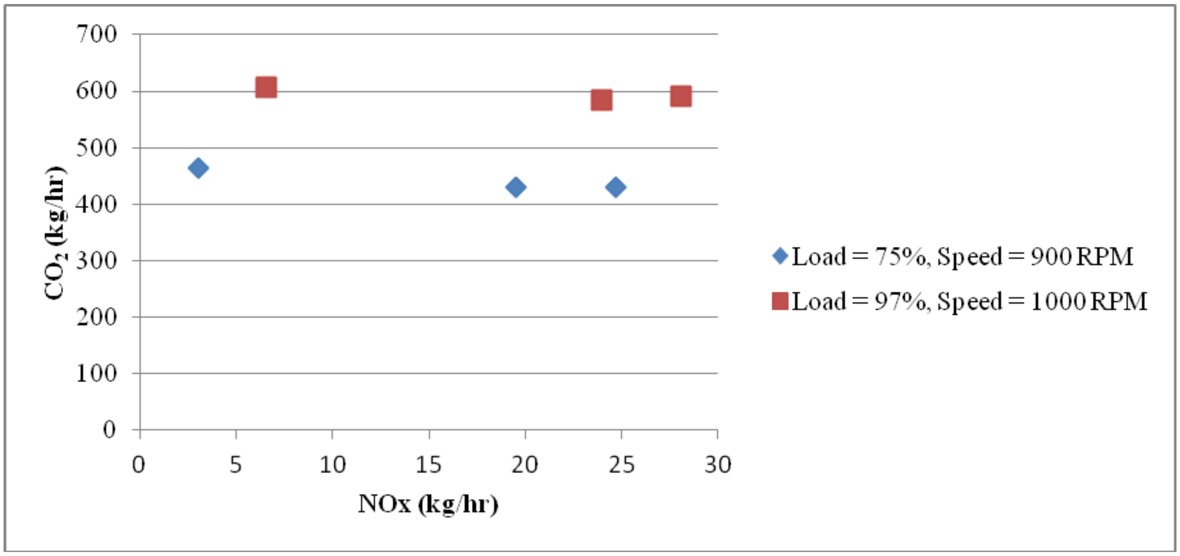


Figure 3-5: Effects of NOx reduction on CO_2 emissions for a Waukesha L7042GSI engine equipped with a REMVue system (courtesy of Accurata Inc.).

3.2 Controlling NOx Emissions with Catalysts

The basis of catalyst emission control from stationary sources is to reduce specific pollutants to harmless gases by stimulating chemical reactions in the exhaust stream (Manufacturers of Emission Controls Association. 1997). The necessary reactions depend on the composition of the exhaust gases. Different catalyst technologies are selected based on whether the engine is running rich, stoichiometric, or lean. Table 3-3 summarizes the available catalysts for different air-fuel ratios.

Table 3-3: Catalyst technologies available for gas fuelled reciprocating internal combustion engines.

Engine A/F Ratio	Emission Control Technology	Target Pollutants
Rich	NSCR	NOx, CO, NMHC
Stoichiometric	NSCR	NOx, CO, NMHC
Lean	Oxidation Catalyst	CO, NMHC
	Lean-NOx Catalyst	NOx
	SCR	NOx

Source: Manufacturers of Emission Controls Association

Non-selective catalytic reduction (NSCR) and selective catalytic reduction (SCR) are discussed in the following sections.

3.2.1 Non-Selective Catalytic Convertors (NSCR)

As shown in Table 3-3, NSCR can be applied to rich-burn engines to effectively reduce NOx, CO, and unburned hydrocarbons. Under these conditions, NSCR is also referred to as three-way conversion catalysts. The catalytic materials typically consist of precious metals from the platinum group. The simplified chemical reactions that occur during NSCR are as follows:

$$CO + O_2 \rightarrow CO_2 \qquad (1)$$

$$C_xH_y + O_2 \rightarrow CO_2 + H_2O \qquad (2)$$

$$H_2 + O_2 \rightarrow H_2O \qquad (3)$$

$$NO_x + CO \rightarrow CO_2 + N_2 \qquad (4)$$

$$NO_x + H_2 \rightarrow H_2O + N_2 \qquad (5)$$

$$NO_x + C_xH_y \rightarrow CO_2 + H_2O + N_2 \qquad (6)$$

The engine must operate within a relatively small AFR range for the NSCR catalyst to remain effective at converting the three target pollutants (Manufacturers of Emission Controls Association, 1997). More specifically, oxygen levels in the exhaust stream must be sufficient for the oxidation reactions (equations 1 to 3) to occur. There must also be sufficient CO and hydrocarbons in the exhaust for the reduction reactions (equations 4 to 6) to proceed. As shown in Figure 3-6, this combination creates a relatively narrow window where a typical engine must operate within to achieve the targeted emission rates. Therefore, AFR controllers must be used in conjunction with NSCR catalysts to keep three-way conversion efficiencies high.

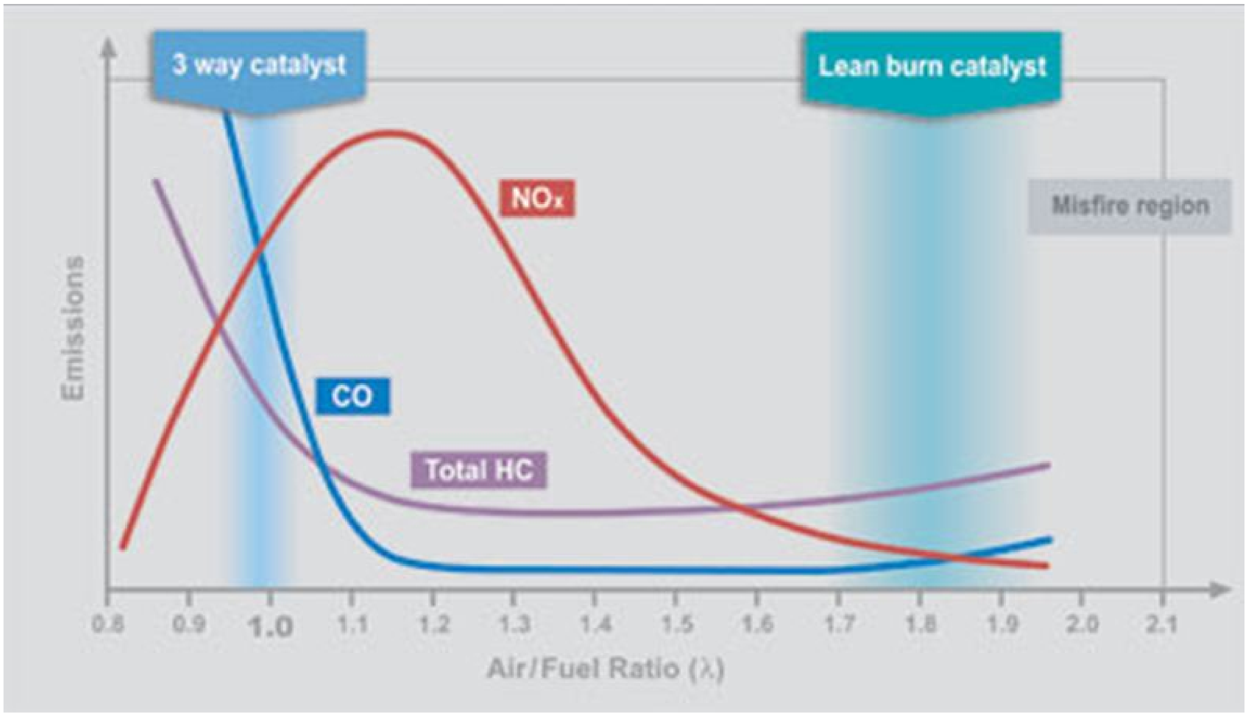


Figure 3-6: Effect of air-fuel ratio on emissions from gas fuelled reciprocating internal combustion engines (courtesy of Johnson Matthey).

3.2.1.1 NSCR Technologies in Market

Johnson Matthey offers NSCR catalysts in a variety of sizes for internal combustion engines. These multi-element catalytic converters are designed so elements are easily accessible. If regulations change or the unit requires maintenance, elements can be added or replaced without removing the converter. Each layer of the catalyst substrate is connected by brazing, which is intended to resist element sagging and distortion. These catalytic converters have a unique design which reduces back pressure to increase fuel savings and extend engine life. They are manufactured using dispersed platinum group metals to increase catalytic activity and resist poisoning. The CXX model is designed for engines between 50 and 500 hp and the BXX model can be installed on engines sized from 250 to 2,500 hp.

Emerachem ADCAT three-way catalysts include a diffusion-bonded nickel alloy substrate, resulting in a unit which is durable and resilient to high temperatures (350^{o}F – 1200^{o}F). The substrate has a high catalytic surface area which reduces pressure loss, increases catalytic activity, and eliminates blowout and sagging. These catalytic converters can be manufactured in custom sizes and cell densities to adapt to any engine.

Miratech IQ and RCS/RHS NSCR catalytic converters can be applied to natural gas engines sized from 200 to 8,000 hp. “NEXT” catalyst substrates are available on these models which have a channel designed to create a turbulent flow and promote more surface contact and pollutant breakdown. Miratech also supplies custom three-way catalyst elements which can be manufactured to any space requirements or brand of catalytic converter.

3.2.2 Selective Catalytic Convertors

SCR is a technology to reduce NOx emissions from lean-burn internal combustion engines. This technology is named "selective" since it targets only NOx emission. However, SCR can be used in conjunction with oxidation catalysts to also reduce CO and hydrocarbon emissions under these conditions. Lean-burn conditions result in an oxygen rich exhaust with relatively low concentrations of CO and hydrocarbons, thereby eliminating NSCR technology as an option to reduce NOx emission (Manufacturers of Emission Controls Association, 1997). The principal of SCR involves injecting a reducing agent (reagent), such as ammonia or urea, to reduce NOx to harmless gases (Southern California Gas Company, 2008). The resulting SCR chemical equations are as follows:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$$

The reactions to reduce NOx and ammonia to nitrogen and water occur spontaneously between 1500^{o}F and 2200^{o}F. With the introduction of a catalyst, these reactions can occur at temperatures more commonly seen from stationary internal combustion engines. Different catalyst materials may be used depending on the exhaust temperature. Precious metal catalysts are used for lower temperatures (350^{o}F to 550^{o}F), zeolite catalysts are for higher temperatures (675^{o}F to 1100^{o}F), and base metals catalysts, made from vanadium and titanium, can be used for temperatures within 450^{o}F to 800^{o}F (Manufacturers of Emission Controls Association, 1997). Figure 3-7 displays a typical SCR system combined with an oxidation catalyst.

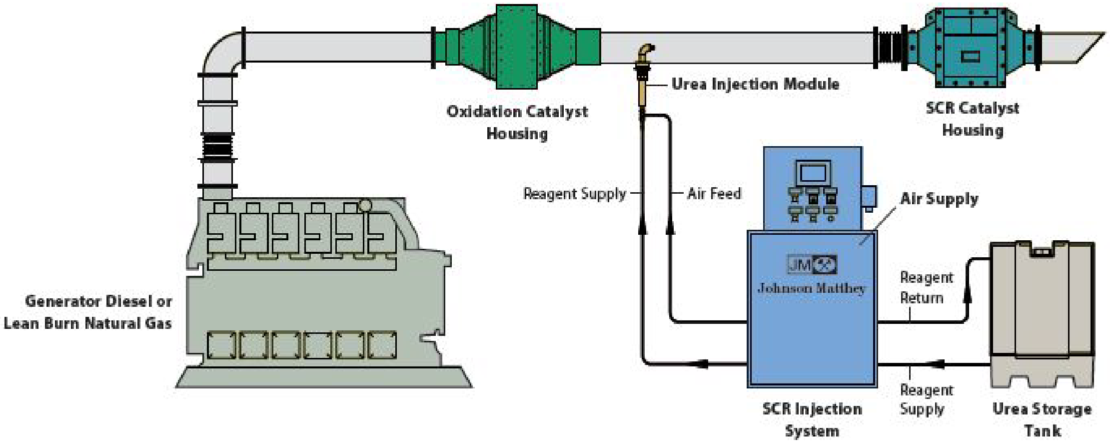


Figure 3-7: SCR system combined with an oxidation catalyst (courtesy of Johnson Matthey).

3.2.2.1 Technologies in Market

Johnson Matthey supply SINOx SCR systems consisting of a SCR catalytic converter, mixing duct, injection system, and a control unit. The control unit regulates the injection of the reagent based on engine loading or feedback from a continuous emission monitoring system. This system guarantees precise control of the reagent injection to comply with emission limits and minimize operational costs. Various catalyst materials are available to accommodate exhaust temperatures from 335°F to 950°F. The reagent nozzle can be quickly disconnected for easy cleaning.

The CleanAIR ENDURE SCR catalyst, supplied by CleanAIR Systems, uses a substrate coated with a non-vanadium, zeolite-enhanced base, making it effective over a large temperature range of 302°F to 1004°F. The ENDURE's reagent injection system continuously monitors NOx levels for reagent control. It is compatible with ammonia and urea. CleanAIR Systems claim that a downstream NH_3 catalyst is not needed due to the accuracy of this reagent injection and NOx monitoring system. To optimize space, the ENDURE SCR system can be combined and assembled in a stainless steel housing, called the E-POD. The control panel for the injection and monitoring system can be installed separate from the E-POD housing.

Miratech SCR catalyst housings contain staged catalyst layers. As shown in Figure 3-8, the first stage is a NOx reduction stage and the second is an oxidation stage for CO and hydrocarbon reduction. It is compatible with either ammonia or urea. As with other Miratech catalyst housings, the SCR housing has easy access doors to facilitate maintenance of the catalyst elements and injection nozzle.

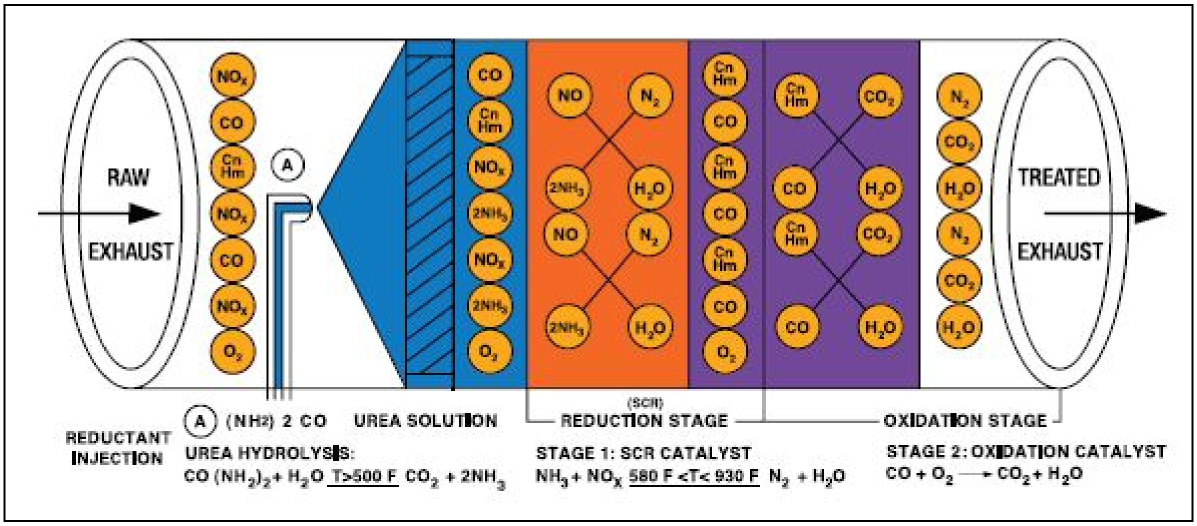


Figure 3-8: Miratech SCR Catalyst Housing (courtesy of Miratech Corporation).

3.2.3 Impacts of Catalyst Technology

As shown in Figure 3-9, a Johnson Matthey BX three-way catalytic converter can reduce NOx, CO, and hydrocarbon emissions by around 95 percent. More specifically, after the retrofit of a

Johnson Matthey NSCR catalytic converter, emissions can be reduced to NOx: 0.7 g/hp-hr, CO: 0.5 g/hp-hr, HC: 0.5 g/hp-hr.

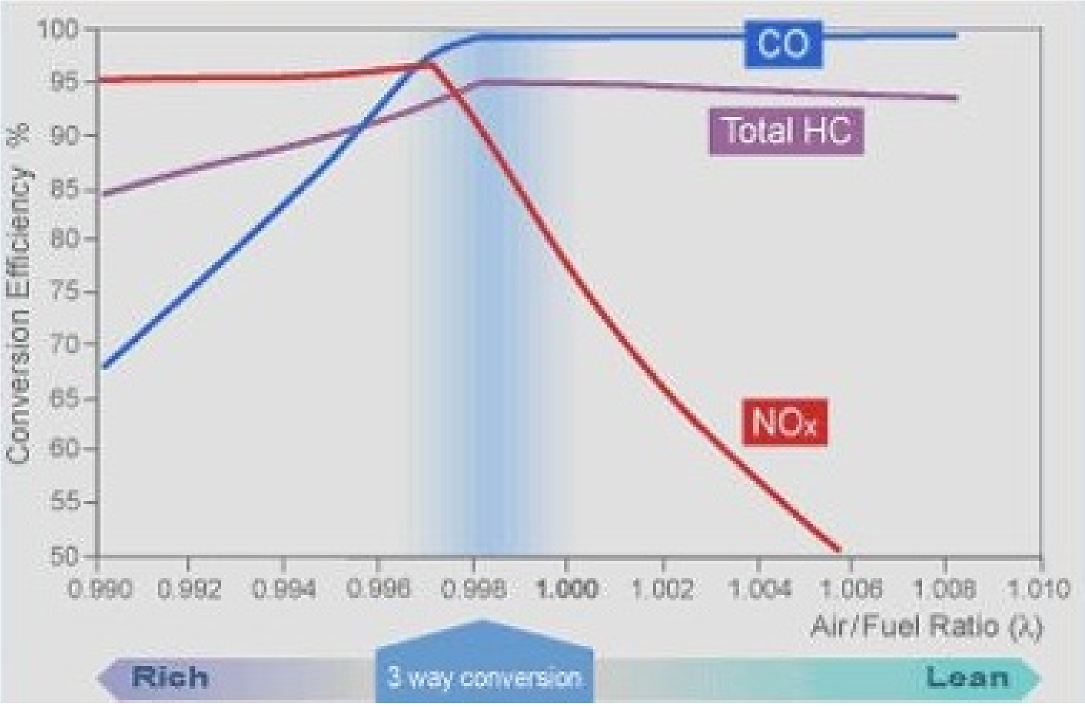


Figure 3-9: Conversion efficiency of Johnson Matthey NSCR technology on gas fuelled reciprocating internal combustion engines (courtesy of Johnson Matthey).

Miratech IQ and RCS/RHS 3-way catalytic converters with "NEXT" elements can reduce NOx and CO emissions by up to 99 percent. As shown in Figure 3-10, the Southern California Gas Company also claims up to 99 percent reductions in NOx and CO emissions with a Miratech NSCR catalyst. However, when operated within the compliance window to effectively reduce all target pollutants, the catalyst performance decreases to approximately 90 percent.

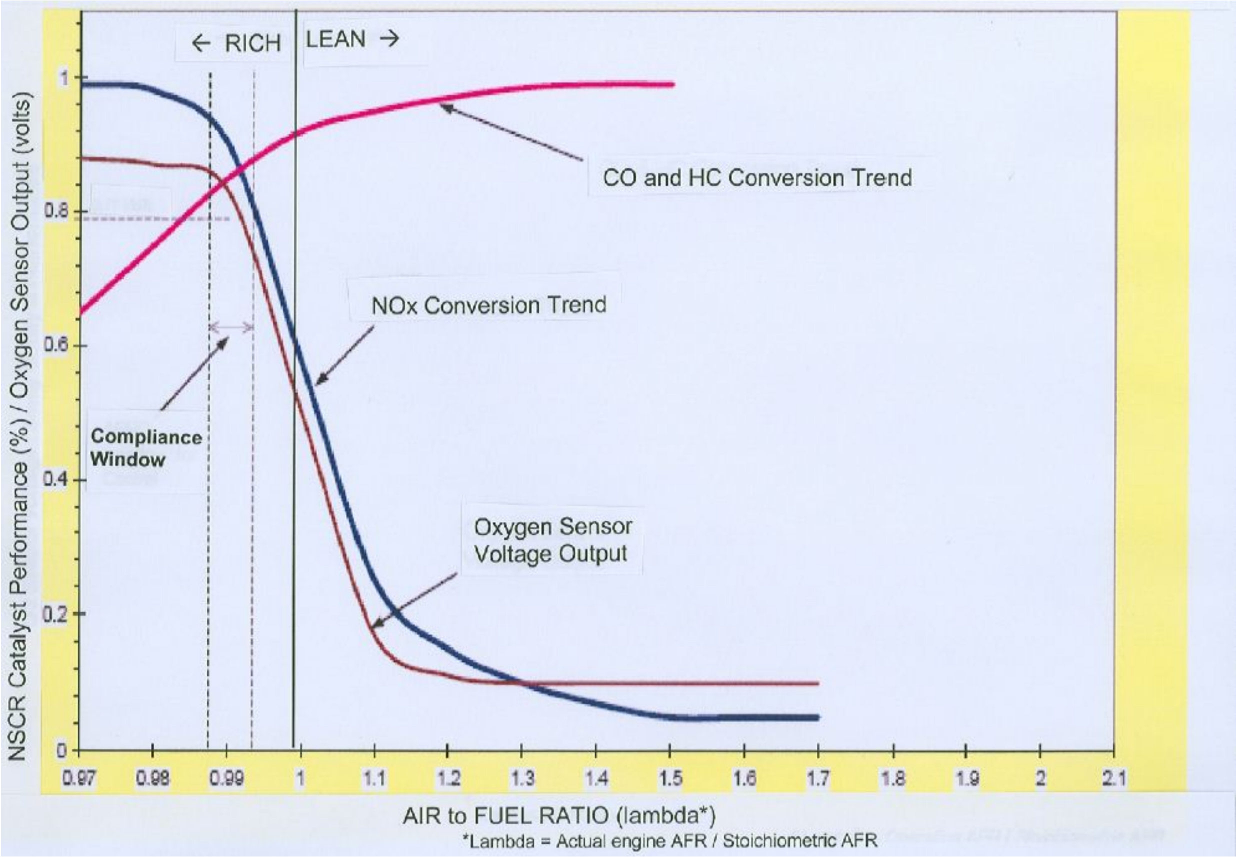


Figure 3-10: Miratech NSCR catalyst conversion efficiencies on gas fuelled reciprocating internal combustion engines (courtesy of Southern California Gas Company).

Environ presented a study on five Caterpillar reciprocating compressor engines. The NOx emission rates were determined before and after the installation of an AFR controller and NSCR catalytic converter (Environ 2005). Table 3-4 summarizes the results.

Table 3-4: NOx emission rates from reciprocating compressor gas engines before and after the installation of an air-fuel ratio controller and NSCR catalytic converter.

Engine Make and Model No.	Rated HP	Pre-Installation		Post-Installation		NOx Reduction Efficiency (%)
		HP	g/hp-hr	HP	g/hp-hr	
CAT G342NA	225	116	11.6	137	0.3	97
CAT 3306TA	225	122	13.0	58	0.5	96
CAT G342TA	265	142	13.3	130	0.5	96
CAT 3306TA	220	125	12.7	125	0.4	97
CAT 3306NA	145	96	12.4	96	0.5	96

Source: Environ 2005

Presented in Table 3-5, the Manufacturers of Emission Controls Association determined some typical reductions that can be achieved with NSCR technology. The reduction efficiencies for a rich burn engine are comparable to those previously presented from other sources. However, the stoichiometric reduction efficiencies (NOx: 98%) seem to be optimistic when compared to the results from vendors. Johnson Matthey and Miratech Corporation claim that NOx reduction efficiencies decline as the stoichiometric point is reached (60 to 75%).

Table 3-5: Typical emission reductions using NSCR technology on gas fuelled reciprocating internal combustion engines.

Engine Operation	**Reduction Efficiency (%)**		
	NMHC	**CO**	**NOx**
Rich	>77	>90	>98
Stoichiometric	>80	>97	>98

Source: Manufacturers of Emission Controls Association

Based on typical emission reductions, the US EPA has concluded that NSCR is an effective option to reduce NOx and other harmful emissions from rich-burn gas engines. The U.S. EPA identified NSCR as the most capable emission control in the near term with capital costs estimated to be approximately $10,000 for each engine (Environ 2005).

Kansas State University's Gas Machinery Laboratory (2009) collected emission data semi-continuously from 4-stroke rich-burn engines equipped with NSCR technology. The engines selected for testing were rated at 57 hp, 23 hp, and 1467 hp. It was observed that the 3-way catalysts had difficulties in consistently maintaining low emission rates. For the 1467 hp engine, performance was related to CO emission levels as summarized in Table 3-6.

Table 3-6: Percent of time various emissions levels were maintained on the 1467 hp engine.

	CO < 2 g/hp-hr	2 <CO < 4 g/hp-hr	CO > 4 g/hp-hr	All CO Levels
NOx < 0.5 g/hp-hr	38 (+2 or -4)%	1.0 (+2 or -2)%	0.9 (+0.1 or -0.2)%	40 (+2 or -4)%
0.5 < NOx < 1 g/hp-hr	15 (+4 or -3)%	0.0 (+0.1)%	0.0 (+0.1)%	15 (+4 or -3)%
1 < NOx < 2 g/hp-hr	11 (+2 or -1)%	0.0 (+0.007 or -0.001)%	0.0 (+0.002)%	11 (+2 or -1)%
NOx > 2 g/hp-hr	34 (+1 or -1)%	0.11 (+0.01 or -0.01)%	0.0 (+0.01)%	34 (+1 or -1)%
All NOx Levels	98 (+0.1 or -0.1)%	1.1 (-0.2)%	0.9 (+0.1 or -0.1)%	100.0%

Source: Table 7 of Kansas State University National Gas Machinery Laboratory 2011

Changes in emission levels typically corresponded to changes in the signal from the oxygen sensor. The oxygen sensor required tuning on multiple occasions. Seasonal variations were also observed. NOx emissions decreased as the ambient temperature increased. This may be attributed to the inability of the AFR controller to monitor the change in air density. As the ambient temperature increases, the air density decreases, potentially causing the engine to run slightly richer, improving NOx reduction efficiencies. The conclusions which can be reached from this study is that NSCR can achieve very strict NOx limits; however, this technology has difficulties in reaching these limits on a consistent basis.

With proper engine control and regular monitoring, NSCR technology is known to be relatively reliable. Provided the engine is not overloaded and the fuel supply is not excessively contaminated, maintenance tasks typically include catalyst cleaning every 2 years and oxygen sensor replacement four times a year. Environ (2005) provided a cost estimate for their study on five Caterpillar engines rated from 145 hp to 265 hp. The costs were estimated as follows:

- Catalytic converter = $2,000 respectively
- AFR controller = $4,290
- Solar panel and batteries = $1,450
- Installation for 5 engines = $6,400

This results in an average capital cost $8,950. The annual cost for maintenance was estimated to be $400, assuming that unpredicted problems would not occur. Conservatively assuming a five year life and a discount rate of 3 percent, the total annual cost for these NSCR catalysts are $2,250. A properly sized and maintained catalyst should not reduce flow or cause a substantial pressure drop, thereby not affecting the energy consumed. However, many rich-burn engines are tuned to run slightly on the lean side of the stoichiometric point to improve fuel efficiency. When NSCR technology is installed, the AFR controller needs to maintain the AFR slightly rich to maintain high reduction rates, thereby reducing fuel efficiency. Increases in fuel consumption should be included in this cost estimate. Capital costs are also based on engine size. Johnson Matthey estimates the cost of a NSCR catalyst to be $15/hp.

Table 3-6 summarizes SCR NOx conversion efficiencies collected from various vendors.

Table 3-7: SCR NOx conversion efficiencies for gas fuelled reciprocating internal combustion engines provided by various vendors.

Manufacturer	NOx Conversion Efficiencies (%)
Johnson Matthey	> 90
CleanAIR Systems	up to 95
Miratech Corporation	up to 99

Figure 3-11 presents the NOx conversion efficiencies of Johnson Matthey SCR catalysts. This shows that there is an effective catalyst material for a wide range of exhaust temperatures. However, at the lower end of the temperature range (400°F to 500°F), the maximum NOx reduction efficiency that can be obtained is approximately 75 percent.

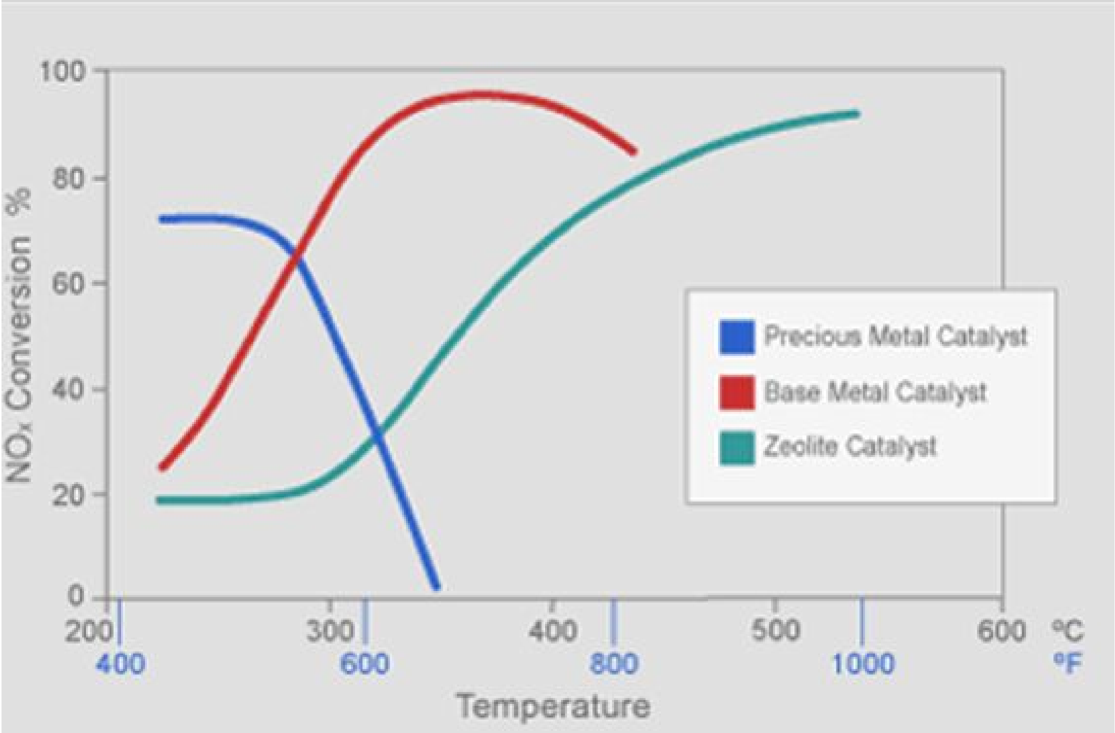


Figure 3-11: SCR NOx conversion efficiencies of various catalyst materials for gas fuelled reciprocating internal combustion engines (courtesy of Johnson Matthey).

4.0 RICE REGULATORY REQUIREMENTS

4.1 Canadian Regulations

Canada is following the United States in introducing stricter regulations governing the emissions from stationary reciprocating internal combustion engines (RICE). Presently, there are no Canada wide standards that specify limits for stationary RICE emissions as a point source. In some provinces, engine emissions may be regulated indirectly through the permitting process if there is a limit imposed on total emissions for a facility. Ambient levels of NOx are governed by air quality standards established and regulated by the individual provinces.

Alberta introduced a low NOx standard for stationary new and upgraded RICE in 1996 as outlined in the "Environmental Code of Practice for Compressor and Pumping Stations and Sweet Gas Processing Plants". The practice requires that any new or reconstructed natural gas-fuelled reciprocating engines of a size greater than 600 kW at full load emit less than 6 grams NOx/kWh. The Canadian Council of Ministers of the Environment (CCME) adopted this standard as part of the national NOx/VOC Management Plan which was introduced in 1996, but the requirement was not formally legislated.

BC introduced Oil and Gas Waste Regulation B.C. Reg. 254/2005 that includes NOX requirements for engines operating more than 200 hours per year and greater than a combined power of 600 kW. The regulation does not include facilities with a combined power output of 3000 kW. For those between 600 and 3000 kW, the applicable NOx emissions limit is 2.7 g/kWh.

In order to improve air quality management across the country, Canada is finalizing the new Air Quality Management System (AQMS). When implemented, the AQMS will include: New Canadian Ambient Air Quality Standards (CAAQS), Air Zone Air Quality Management & Regional Airsheds, and Base Level Industrial Emissions Requirements (BLIERs). The CAAQS will be established under Canadian Environmental Protection Act 1999, and will replace the existing Canada-wide Standards under CCME. Six regional airsheds, together covering all of Canada, will be established to coordinate efforts to reduce transboundary air pollution flows and report on regional air quality. Coordinating mechanisms will be built on existing mechanisms or established as needed to address air pollution issues, including transboundary pollution from the United States, and across interprovincial and inter-regional boundaries. BLIERs will specify emissions standards applicable to major industrial sectors and some equipment types.

BLIERs development has focused on the reduction of NOx, SO_2, VOCs and particulate matter emissions in 13 individual industry sector groups and 3 equipment groups. The Reciprocating Engine Expert Group is one of the 3 equipment groups.

The Upstream Oil and Gas sector is responsible for 48% of industrial NOx emissions in Canada and 85% of these emissions are contributed by reciprocating internal combustion engines, (CAPP 2004). The BLIER for reciprocating engines will specify NOx emissions limits for new and existing natural gas-fuelled spark ignited engines.

The subgroup developing the reciprocating engine BLIER is working to obtain a consensus on what the achievable emission limits are for existing engines. The limits proposed in the 2009 CAMS process are detailed in Table 4-1.

Table 4-1: Upstream Oil and Gas BLIER for Natural Gas Fuelled RICE.

Description	Proposed NOx Emission Limit	Basis of BLIER
New Engines		
≥100 or ≥ 600 kW	1.3 – 2.7 g/kWh	BC Provincial regulation and US Federal Limits
Existing Rich Burn		
≥100 or ≥ 600 kW	2.7 – 6.0 g/kWh	AB and BC Provincial regulation and US Federal Limits (technical feasibility)
Existing Lean Burn		
≥100 or ≥ 600 kW	TBD	Determination of whether there is a need for a limit is being discussed

4.2 Stationary RICE Emission Regulations in the United States

The US EPA recently introduced updated regulations for stationary internal combustion engines. There are two sets of regulations at the federal level governing emissions from stationary RICE. The new source standards of performance (NSPS) regulate emissions of criteria air pollutants such as NOx from new and reconstructed engines. The stationary RICE National Emissions Standard for Hazardous Air Pollutants (NESHAP) specifies limits for emissions of hazardous air pollutants such as formaldehyde. The NSPS and NESHAP serve as the national requirements, leaving states with the authority to regulate more stringently as might be required in unique situations. The updated NSPS and NESHAP do not specify NOx emission limits for existing engines.

Similar to the AQMS in Canada, air quality in the United States is managed through the establishment of zones are attainment areas. Particular attention is paid to areas where ambient air quality objectives are not being met. These areas are identified as non-attainment areas. Federal regulations require each state to implement a plan to bring areas of non-attainment into compliance. A review at the federal level may also be required if emissions from a facility in an attainment area exceed certain limits. The US EPA provides standards for Reasonably Achievable Control Technology (RACT), Best Achievable Control Technology (BACT), and Maximum Achievable Control Technology (MACT) to guide the process.

There are considerable differences in the approaches taken by individual states to regulate emissions from stationary RICE and manage air quality within their jurisdictions. These differences are based primarily on whether there are serious air quality issues and non-attainment areas that need to managed more aggressively. In most cases, the states specify emissions limits for each pollutant of concern, but no not mandate which control technology must be used. There are exceptions, however. For example, the State of Colorado requires the use of three-way catalytic converters on rich-burn stationary RICE to meet the NOx emission limit.

5.0 RECOMMENDATIONS

As previously mentioned, information on NOx and other emission reduction opportunities using retrofit control technologies is readily available in literature and from industry. However, it was difficult to obtain data showing the impact or trade-offs of drastic NOx reductions on GHG emissions using AFR controllers and engine management systems, particularly REMVue systems. Information on the performance of NSCR technology under changing conditions was also limited. The gathered information was either incomplete or based on laboratory environments and engines not seen in the upstream oil and gas industry. Either way, it is believed that the amount of information is insufficient for government decision making. Therefore, this study should perform a complete emission analysis on common engines over a wide range of loads, speeds, and engine settings to understand what these technologies are capable of, and the resulting impact on fuel efficiency and GHG emissions. Typical performance and emissions levels can then be established for engines equipped with REMVue systems.

As discussed in Section 1.2.4, the engines selected for testing should represent the engine fleet from the upstream oil and gas industry as well as possible. Therefore, common engines should be selected. Rich-burn engines comprise the majority of the gas fuelled engines powering reciprocating compressors. Also, rich-burn engines typically release more NOx and GHG emissions than their lean-burn counterparts and provide more reduction opportunities. Rich-burn engines should be the focus of the study. Based on the Clearstone database (Figure 1-3, Figure 1-4 and Figure 1-5), some common rich-burn engines are Waukesha L7042GSI, Waukesha F3521GSI, Caterpillar G3408TA, Caterpillar G3406TA, Caterpillar G3306TA, and White Superior 8G-825. Also, these engine models cover a wide range of rated power (150 kW to 1100 kW respectively).

Due to the limited time frame for testing, it would be beneficial to select engines that are already scheduled for an emission control retrofit. Based on conversations with REM Technology, a REMVue retrofit would take approximately 1 to 2 weeks, allowing for pre-and post-results to be obtained in the same time frame.

Emissions and fuel consumption needs to be measured for a combination of parameters. The selected engines should be flexible at the time of testing so loading, speed, engine settings, etc. can be changed without disrupting facility operations. Engines should be equipped with a fuel gas meter for pre-retrofit measurements. It is believed that the pressure of inlet fuel gas is too low for ultrasonic flow measurements.

The selected engines should be different ages to determine the effects of engine life on performance and emissions.

Engines in proximity to Calgary should be selected to reduce travel time and depletion of the project budget.

6.0 REFERENCES

Accurata (2005). Emissions and Efficiency Enhancements with REM AFR Systems report for PTAC completed by Accurate Inc.

Advanced Engine Control Technologies Corporation (2004). Carbon Pollutant Emissions and Engine Performance Trade-Offs vs NOx Emissions for Reciprocating Internal Combustion Engines Fitted with Enhanced Mixing Combustion Technologies Utilized in Gas Transmission Service. Prepared for INGAA Foundation.

Beshouri G., Willson, B., & Chapman, K. S. (2005). *Pipeline Engine Emissions Control Roadmap*

Bhardwaj, Sachin, (2002) Inventory of Nitrogen Oxide Emissions and Control Technologies in Alberta's Upstream Oil and Gas Industry

Caterpillar (2007). Gas Engine Emissions. Application and Installation Guide.

CleanAIR Systems (2007). CleanAIR Endure SCR Catalyst Brochure. http://www.cleanairsys.com/products/scr/ENDURE-Lean-Burn.pdf

CleanAIR Systems (2010). The CleanAIR E-POD System Brochure. Selective Catalytic Reduction Technology. www.cleanairsys.com

Emerachem (2009). NSCR Catalyst. ADCAT Three-Way (NSCR) Catalyst for VOC, CO, and NOx Reduction. Stationary Internal Combustion Engine Applications. www.emerachem.com

Environ (2005). A Pilot Project to Assess the Effectiveness of an Emission Control System for Gas Compressor Engines in Northeast Texas prepared for NETAC by Environ International Corporation.

Evans R.L., Blaszczyk J., (1997). A Comparative Study of the Performance and Exhaust Emissions of a Spark Ignition Engine Fuelled by Natural Gas and Gasoline. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering.* 1997, 211:39

Hutcherson G., Fletcher C., Beshouri G., (1999). Carbon Pollutant Emissions and Engine Performance Trade-Offs vs NOx Emissions for Reciprocating Internal Combustion Engines Utilized in Gas Transmission Service. *1999 Gas Machinery Conference*. Houston, Texas.

Johnson Matthey (2009). BXX and CXX Catalytic Converters Datasheets. Emission Control Technologies. Stationary Source Literature. www.matthey.com

Johnson Matthey (2009). Gas Engine Emissions Control Datasheet. Emission Control Technologies. Stationary Source Literature. www.matthey.com

Johnson Matthey (2009). SCR – Maximum NOx Control for Stationary Diesel and Gas Engines Brochure. Emission Control Technologies. Stationary Source Literature. www.matthey.com

Johnson Matthey (2009). SINOx Honeycomb Catalysts Brochure. Emission Control Technologies. Stationary Source Literature. www.matthey.com

Kennedy, K., & Holdeman, T. (2006). Application of Full Authority Fuel Control Valve for Non Selective Catalytic Reduction on Large-Bore, Four-Stroke Cycle, Natural Gas Fired Reciprocating Engine. *Gas Machinery Conference,* Oklahoma City, OK.

Lambert, D. C. (1995). Current Design, Operation, Performance, and Costs of 3-Way Catalysts on Stationary Natural Gas Engines. *1995 Fall Technical Conference of the ASME Internal Combustion Engine Division, , 4*(25) 91.

Manufacturers of Emission Controls Association (1997). Emission Control Technology for Stationary Internal Combustion Engines.

Miratech Corporation (2009). Emission Control Solutions for the Natural Gas Industry. Gas Compression Brochure. www.miratechcorp.com

Miratech Corporation (2009). IQ and RCS/RHS Catalyst Housings Flyer. www.miratechcorp.com

Miratech Corporation (2009). SCR: Selective Catalytic Reduction Brochure. www.miratechcorp.com

Southern California Gas Company (2008). Operating Catalytic Emission Reduction Systems. Presentation at the *Gas/Electric Partnership 2008 Workshop*. Houston, Texas.

Tice, J. K. (2007). Exhaust Gas After-Treatment: Catalyst Systems. Paper presented at the *Gas Machinery Conference*, Dallas, TX.

Toema M., Nuss-Warren S., Chapman K.S., (2009). Long-Term Emissions Performance of Stationary Natural Gas Engines Equipped with NSCR System.

Kansas State University National Gas Machinery Laboratory (2011). Final Report: Cost-Effective Reciprocating Engine Emissions Control and Monitoring for E&P Field and Gathering Engines by K. Hohn and S.R. Nuss-Warren. DOE Contract DE-FC26_02NT15464.

PIC Division of Spartan Controls (2011). Pre and Post REMVue engine data collected from installations in the oil and gas industry. Calgary, Alberta.