THESIS

PERFORMANCE EVALUATION OF AN ADVANCED AIR-FUEL RATIO CONTROLLER ON A STATIONARY, RICH-BURN NATURAL GAS ENGINE

Submitted by

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ABSTRACT

PERFORMANCE EVALUATION OF AN ADVANCED AIR-FUEL RATIO CONTROLLER ON A STATIONARY, RICH-BURN NATURAL GAS ENGINE

The advent of an era of abundant natural gas is making it an increasingly economical fuel source against incumbents such as crude oil and coal, in end-use sectors such as power generation, transportation and industrial chemical production, while also offering significant environmental benefits over these incumbents. Equipment manufacturers, in turn, are responding to widespread demand for power plants optimized for operation with natural gas. In several applications such as distributed power generation, gas transmission, and water pumping, stationary, spark-ignited, natural gas fueled internal combustion engines (ICEs) are the power plant of choice (over turbines) owing to their lower equipment and operational costs, higher thermal efficiencies across a wide load range, and the flexibility afforded to end–users when building fine-resolution horsepower topologies: modular size increments ranging from 100 kW – 2 MW per ICE power plant compared to 2 – 5 MW per turbine power plant.

Under the U.S. Environment Protection Agency's (EPA) New Source Performance Standards (NSPS) and Reciprocating Internal Combustion Engine National Emission Standards for Hazardous Air Pollutants (RICE NESHAP) air quality regulations, these natural gas power plants are required to comply with stringent emission limits, with several states mandating even stricter emissions norms.

In the case of rich-burn or stoichiometric natural gas ICEs, very high levels of sustained emissions reduction can be achieved through exhaust after-treatment that utilizes Non Selective Catalyst Reduction (NSCR) systems. The primary operational constraint with these systems is

the tight air-fuel ratio (AFR) window of operation that needs to be maintained if the NSCR system is to achieve simultaneous reduction of carbon monoxide (CO), nitrogen oxides (NOx), total hydrocarbons (THC), volatile organic compounds (VOCs), and formaldehyde (CH_2O). Most commercially available AFR controllers utilizing lambda (oxygen) sensor feedback are unable to maintain engine AFR within the required range owing to drift in sensor output over time.

In this thesis, the emissions compliance performance of an AFR controller is evaluated over a 6-month period on an engine driving a gas compressor in an active natural gas production field. This AFR controller differentiates itself from other commercially available products by employing a lambda sensor that has been engineered against sensor drift, making it better suited for natural gas engine applications. Also included in this study are the controller's responses to transient loads, diurnal performance, adaptability to seasonal variations in ambient temperature, fuel quality variations (in wellhead gas), engine health considerations for proper AFR control, and controller calibration sensitivity when replacing lambda sensors.

During the first three months of operation and subsequent diurnal tests, the controller's performance as a multi-point AFR control system was consistent, demonstrating appropriate AFR adjustments to variation in engine operation, over a wide range of ambient conditions, despite high consumption rate of engine lubrication oil. For the remainder of the test, high levels of lubrication oil consumption compromised the ability to verify controller performance.

ACKNOWLEDGEMENTS

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On a personal note, I am indebted to the Kochuparampil, Tshering–Copeland, Manriquez, and Ihde–Ksug families for their love, good counsel, and friendship.

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1. Introduction

Natural gas is used extensively in power generation and is becoming increasingly competitive with incumbent fuel sources, such as crude oil, in other end-use sectors such as transportation and industrial chemical production, while also offering notable environmental benefits over these incumbents.

1.1 The Golden Age of Natural Gas

The factors that drive natural gas demand and supply increasingly point to a future in which natural gas plays a greater role in the global energy mix. Global uncertainties afflicting the energy sector can be seen as opportunities for natural gas. When replacing other fossil fuels, natural gas can lead to lower emissions of greenhouse gases and other pollutants while diversifying the energy supply, thereby leading to improved energy security. It is capable of providing the flexible backup capacity required to augment higher grid penetration of renewable power sources such as wind and solar. Gas is a particularly attractive fuel for regions like China, India, and the Middle East, that are experiencing rapid urban development, causing a surge in energy demand [24].

The global resource base for natural gas is vast and widely dispersed (geographically). Conventional recoverable resources are equivalent to more than 120 years of current global consumption, while total recoverable resources could sustain current production levels for over 250 years. All major regions have recoverable resources equivalent to a minimum of 75 years of current consumption. Timely and successful development depends on a complex set of factors, including policy choices, technological capability, and market conditions. Once discovered, major gas resources can take several decades to reach production [24].

The use of horizontal drilling in conjunction with hydraulic fracturing has greatly expanded the ability of producers to profitably recover natural gas and oil from low-permeability geologic basins – particularly shale formations. The gas recovered from such geological formations (shown in Figure 1) is termed as unconventional gas and is now estimated to be as large as conventional resources, constituting 60% of domestic production in the United States [25].

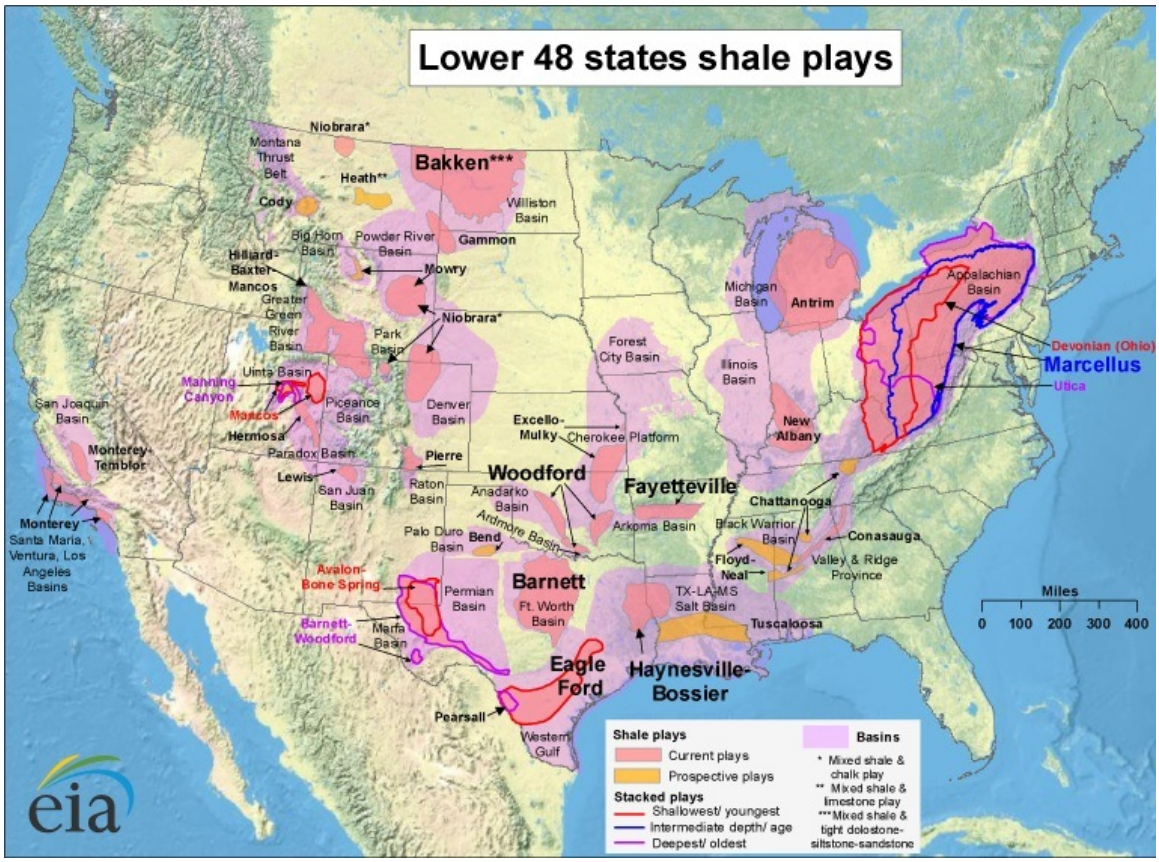

Figure 1: Map of U.S. shale gas and shale oil plays in the lower 48 states [25].

Over the past decade, advances in technology and knowledge have led to increasingly effective directional drilling capabilities, contributing to the ability to drill horizontal wells. Drilling a horizontal well involves curving the path of the well, gradually moving from a vertical to a horizontal path. Technological advances in drilling allow for steerage of drilling equipment

away from the straight vertical trajectories observed in traditional wells, instead deviating to reach a point that could be up to two miles away from the entry site [26].

One of the key enablers of this technique is measurement-while-drilling technology, or borehole telemetry, which permits engineers and geologists to monitor, in real-time, the progress of a drilling operation deep beneath the surface. Using this technology, the trajectory of a well can be accurately plotted and managed, as it curves from a vertical to a horizontal path. Another important enabler is the steerable downhole motor assembly. Conventional drilling of vertical wells occasionally require downhole motors, placed above the drill bit, to help penetrate particularly hard rock formations. Supplementing this with the capability to steer these motors implies that a given well-path can be redirected during real-time drilling operation, allowing for introduction of controlled deviation of the well-path, eventually steering the drill bit into a horizontal path [26].

Hydraulic fracturing is a process of creating fractures in tight rock formations, using high-pressure water containing a mixture of sand and other chemicals, to release the oil and natural gas trapped inside the rock formation. Pumping this pressurized fluid into a drilled well opens up tiny fissures in the rock formation, up to several tenths of an inch wide, allowing oil and natural gas trapped within to flow back to the surface (Figure 2). This technique has been used to extract oil and natural gas for decades, having been first deployed in Kansas in 1947 [26].

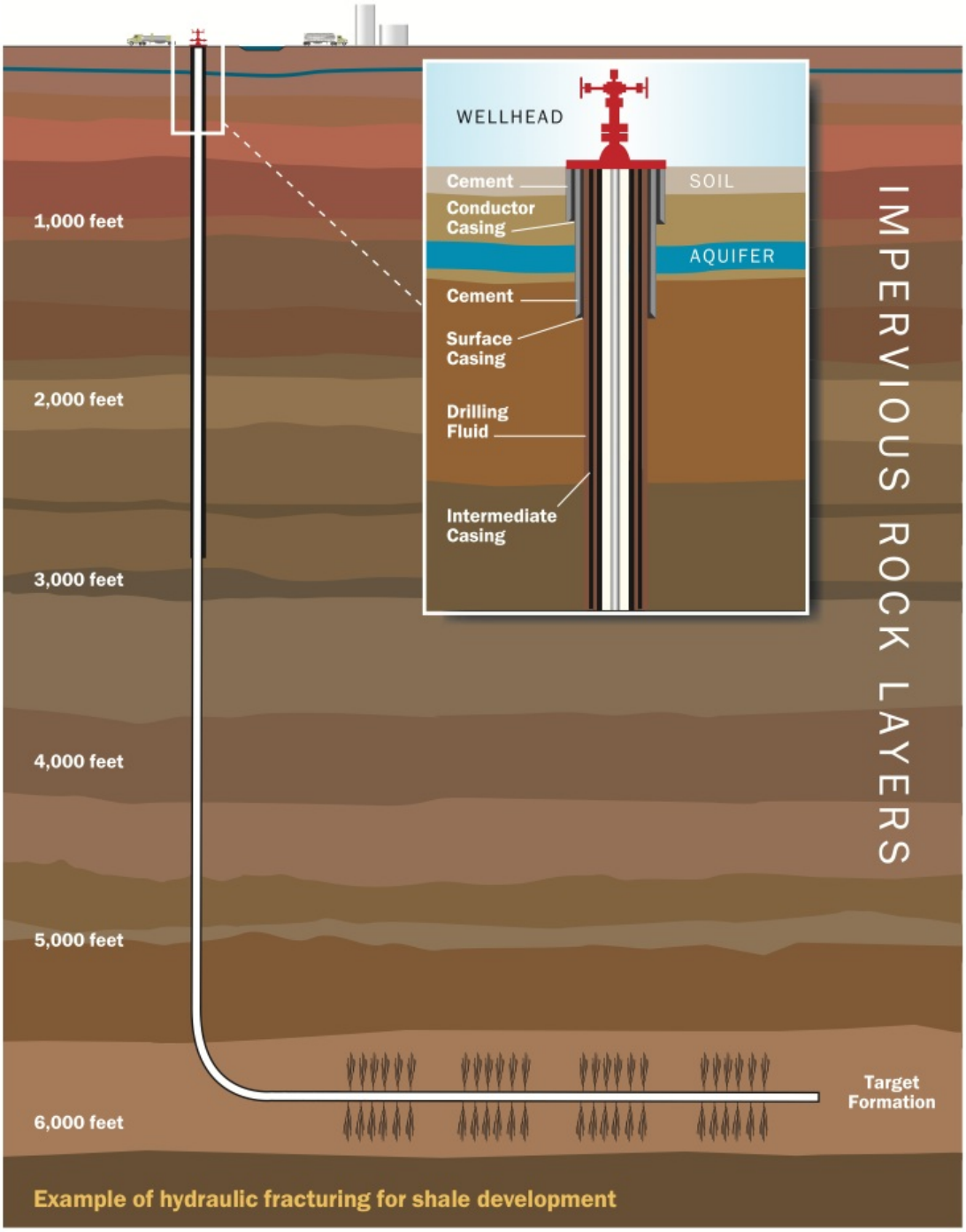

Figure 2: Cross-section of a horizontal well, showing hydraulically fractured fissures within the target formation [26].

The use of hydraulic fracturing in the production process has raised serious environmental concerns, pushing the boundaries of the existing regulatory framework for this industry. However, best practices applied to production, through effective regulation and

monitoring, can mitigate potential environmental risks such as excessive water use, contamination, and disposal. Development of other unconventional gas resources, such as coal-bed methane, is growing in Australia, while unconventional gas projects in China, India, and Indonesia are in their early stages [24].

All these factors point to a coming era in which natural gas will hold greater dominance as a global fuel of choice, increasingly recognized as the golden age of natural gas. In order to take advantage of this era, primemovers such as turbines and internal combustion engines (ICEs) will be optimized to utilize this fuel and deployed in greater numbers in applications relating to power generation and transportation.

1.2 Classification of Internal Combustion Engines

Owing to their efficiency, robustness, and power density, stationary reciprocating ICEs are the primemover of choice in a variety of applications including distributed power generation, gas transmission, and water pumping (irrigation). Regulatory bodies continue to reduce emissions limits on this class of primemover, requiring development of new technologies for emissions reduction. The type of emission reduction technology deployed in a given situation is closely related to the type of engine used in that situation. Air-Fuel Ratio (AFR) is a key factor influencing engine efficiency, emissions and overall operation. Therefore, an ICE is classified based on the range of AFR within which it is designed to operate: lean-burn engines are optimized to utilize excess air during the combustion process; stoichiometric engines, use chemically balanced measures of air and fuel during combustion; rich-burn engines use (marginally) less air than stoichiometry for combustion. In general, rich-burn engines can operate in a stoichiometric configuration but lean-burn engines are not capable of such flexibility. In the

natural gas industry, rich-burn engines are actually stoichiometric engines [27]. From basic study of combustion chemistry, it is known that the emissions produced during combustion in an excess-oxygen environment are markedly different than those from a fuel-rich environment. Therefore, it follows that the pollutant species, and by extension, the exhaust after-treatment deployed on an engine, is primarily guided by the type of engine being used ie. lean, stoichiometric, or rich-burn. A common parameter used to monitor and control engine AFR is the real-time equivalence ratio (ϕ), defined as:

$$\phi = AFR_{stoic} / AFR_{act} \text{ , where}$$

AFR_{stoic} = mass-based stoichiometric air-fuel ratio

AFR_{act} = mass-based actual air-fuel ratio.

Figure 3 shows the relationship between concentrations of different exhaust constituents, for varying values of ϕ (known as a ϕ sweep). It can be noticed that engine operation at rich and stoichiometric conditions produces higher amounts of NOx, CO, and HC as compared to that during lean operation. However, it can also be seen that, for constant values of pressure and temperature in the intake manifold, peak engine power occurs in a region of rich operation. Therefore, for a given application, considerations between engine power versus emissions determine the type of engine that is selected. It is worth noting that since NOx formation is exponentially linked to in-cylinder temperature [17], the NOx curve in Figure 3 can also be interpreted as representative of engine temperature across the λ sweep.

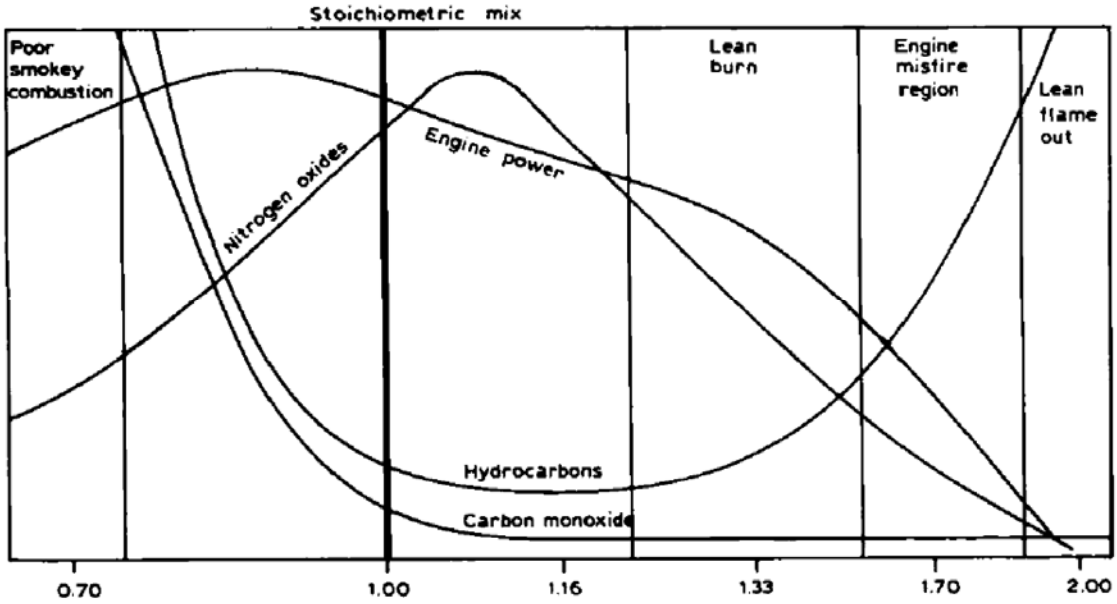

Figure 3: Engine-out emissions of various constituents and engine power output (on y-axis) produced during a λ sweep (on x-axis) [Reprinted from 10].

Using improved component designs, advanced system topology, and sophisticated control techniques, great strides have been made in improving the combustion efficiency of an ICE, leading to very impressive reductions in the emissions footprint of these primemovers. However, ever-tightening air quality regulations require the use of exhaust after-treatment systems to meet these stringent norms.

1.3 Exhaust After-Treatment Systems

Appropriate selection of an exhaust after-treatment system is primarily dependent on the type of engine (CI, SI, lean, rich) and whether it is for a mobile or stationary application. Table 1 provides an overview of commercially available exhaust after-treatment technologies.

1.3.1 Catalytic Considerations

When designing an exhaust after-treatment system, two additional parameters need to be considered if a catalyst is used, namely: Light-off Temperature and Space Velocity.

Since catalysts are designed to operate within a specified temperature range, the light-off temperature of a catalyst, which is the minimum temperature at which reduction efficiency is at least 50%, is critical when designing a catalytic treatment system [27].

Space Velocity is the ratio of the volumetric flow rate of the exhaust gas stream at the inlet of the catalyst housing to the volume of the catalyst bed. It can be calculated either based on standard conditions (STP), referred to as Standard Space Velocity, or actual gas stream temperature and pressure, and referred to as the Actual Space Velocity. It is equivalent to the reciprocal of gas stream residence time in the catalyst-bed and is commonly denoted using units of hr^{-1}. In addition to gas flow rate and reactor volume, cell density of the catalyst substrate (which is a commonly used metric for designating the amount of catalyst material in an element) influences pressure drop across the catalyst element and its space velocity [27].

Long-term durability of catalyst reduction efficiency is influenced by the thermal and chemical environments within which a given catalyst element operates. Degradation due to thermal aging is typically associated with sintering, which causes wash coat destruction, in turn encapsulating active catalyst material, thereby decreasing catalytic activity of the precious metal coat. Chemical aging is brought about two phenomena: fouling and poisoning. The former occurs when particulates in the exhaust stream accumulate within the substrate channels, effectively blocking the channels and restricting the reaction of constituents in the exhaust gas stream at active catalyst sites. The latter is primarily associated with sulphur and phosphorus compounds, originating in the fuel or lubrication oil, that become reactive during combustion and proceed to chemically bond with catalyst precious metals, causing a reduction in the number of active sites available for catalysis [20, 21, 22, 23].

Table 1: Overview of currently available exhaust after-treatment systems [7, 16, 17, 18, 19].

Oxidation Catalyst [17]	• Used on SI or CI lean-burn and stoichiometric engines • Oxidizes THC and CO into CO_2 and H_2O, using O_2 available from lean operation. In the case of stoichiometric operation, additional O_2 is introduced to the exhaust stream using an external blower/compressor • Catalyst bed is constructed of noble metals (Platinum and Palladium)
Selective Catalytic Reduction [18]	• Designed for operation with CI and SI lean-burn engines • A reagent (urea, NH_3) is injected into the exhaust manifold, upstream of the catalyst, facilitating reduction of NOx into chemically benign N_2 and H_2O
Lean NOx Traps [16]	• Designed to reduce NOx on lean-burn SI and CI engines • Catalyst bed comprises of materials for oxidation (Platinum), adsorption (Barium), and reduction (Rhodium) • Requires periodic regeneration
Non-Selective Catalytic Reduction [7]	• Designed to simultaneously reduce NOx while oxidizing THC and CO on stoichiometric SI engines • High reduction efficiencies require operation within a narrow range of AFRs, near stoichiometry. Cyclic variation (~1 Hz) of AFR (dithering) widens this operational range • Closed loop control via an O_2 or NOx sensor is required

	• Rich operation produces NH_3 across catalyst • Catalyst bed is constructed of Rhodium and Platinum
Exhaust Gas Recirculation [17]	• Designed for reduction of NOx emissions by recirculating exhaust gases containing inerts into the intake manifold, effectively reducing peak combustion temperature, which is a key factor in NOx formation.
Thermal Reactors [19]	• Designed for operation on rich-burn engines coupled with auxiliary air injection into the exhaust stream • Oxidizes CO and THC, typically in an enlarged exhaust manifold • Efficacy is dependent on temperature, oxygen availability, and residence time in the reactor
Particulate Filters [19]	• Designed to reduce particulate emissions from CI engine exhaust stream • Demonstrated removal efficiencies of 60-90% • Filter element, constructed from ceramic in a mat or mesh structure, requires periodic regeneration

1.3.2 Oxidation Catalysts

Oxidation catalysts are typically employed on lean-burn engines, such as diesels, to control emissions of HC, CO, and PM. These catalysts, deployed in the exhaust stream, contain precious metals impregnated onto a carrier having a high geometric surface area.

Oxidation catalysts can achieve greater than 98% reduction of CO and over 90% of THC, depending on engine type and fuel. For example, oxidation catalysts are ineffective at reducing CH_4, which is the primary species in THC emissions from natural gas engines. They can also reduce particulate emissions from diesel engines by oxidizing the soluble organic fraction of the particulate – reductions of over 30% have been reported [12] – serving the dual purpose of also eliminating the characteristic odor associated with diesel exhaust (through oxidation of aldehyde and acrolein).

1.3.3 Selective Catalytic Reduction (SCR)

SCR is an effective method for controlling NOx emissions from lean-burn stationary ICEs and is termed as such because in the presence of a reducing agent, the catalyst selectively reduces NOx, typically achieving reduction efficiencies greater than 90%. Since its introduction in 1959, this technology has been successfully applied
at hundreds of NOx generating sources worldwide, some of which have been stationary ICEs.

This process reduces NOx emissions to N_2 in the presence of a reducing agent such as anhydrous NH_3, aqueous NH_3, or aqueous urea [13]. In all cases of practical significance, the chemically active reagent species is NH_3. Lean-burn engines are characterized by an oxygen-rich exhaust, thereby making the reduction of NOx virtually impossible using NSCR catalyst technology. However, introduction of NH_3 facilitates the necessary chemical reactions [14], as shown below:

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

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

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O.$$

1.3.4 Lean NOx Trap (LNT)

Another technology designed for exhaust stream NOx control from lean burn ICEs is LNT, also referred to as a NOx storage reduction catalyst. In this process, the first step occurs during lean operation, when NOx is removed from the exhaust stream and stored (adsorbed) on an alkaline-earth metal oxide bed in the form of nitrites and nitrates. When this storage bed is saturated, a NOx sensor, installed downstream of the catalyst bed will switch the engine to rich operation (or activate fuel injection into the exhaust stream) in order to generate reductants such as CO, H_2, and HCs, which stimulate NOx release (desorption) from the storage bed, followed by catalytic reduction to N_2, CO_2, H_2O, and in some cases, NH_3 [15].

1.3.5 Non-Selective Catalytic Reduction (NSCR)

NSCR, or three-way catalytic (TWC) after-treatment is effective at simultaneously reducing NOx, CO, volatile organic compounds (VOCs), and formaldehyde (CH_2O) emitted from rich-burn natural gas engines. To accomplish this, ϕ must be precisely controlled within a narrow range near stoichiometric conditions, as depicted in Figure 4. Due to this, it cannot operate in conjunction with CI, 2-stroke, or other types of lean-burn ICEs.

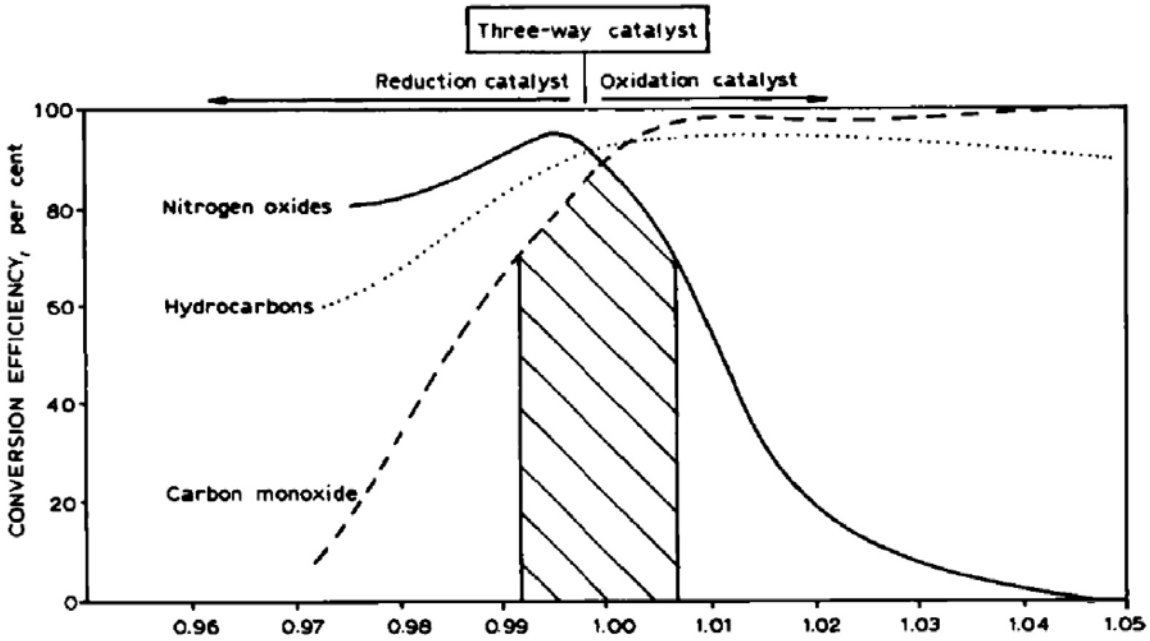

Figure 4: NSCR (or TWC) conversion efficiencies (on y-axis) for various constituents over a range of operational ϕ (on x-axis) [Reprinted from 11].

Studies [1, 2] have shown that NSCR after-treatment of exhaust gas streams from natural-gas fueled industrial engines require engine operation within a tightly controlled range of equivalence ratios for effective reduction of NOx, CO, and non-methane hydrocarbons (NMHCs). It should be noted that conversion efficiency of a catalyst, denoted by $\eta_{catalyst}$, is defined as:

$$\eta_{catalyst} = \frac{\text{(Pre-catalyst Emissions – Post-catalyst Emissions)}}{\text{Pre-catalyst Emissions}} \times 100$$

The global chemical reactions that occur within a NSCR catalyst are as follows [7]:

Oxidation reactions (using O_2 as the reagent)

$$CO + \tfrac{1}{2}\, O_2 \rightarrow CO_2$$

$$HC + \tfrac{1}{2}\, O_2 \rightarrow CO_2 + H_2O$$

$$HC + ½\ O_2 \rightarrow CO + H_2O$$

$$H_2 + ½\ O_2 \rightarrow H_2O.$$

Oxidation and reduction reactions (using NO as reagent)

$$CO + NO \rightarrow ½\ N_2 + CO_2$$

$$HC + NO \rightarrow N_2 + H_2O + CO_2$$

$$HC + NO \rightarrow N_2 + H_2O + CO$$

$$H_2 + NO \rightarrow ½\ N_2 + H_2O$$

$$H_2 + 2\ NO \rightarrow N_2O + H_2O$$

$$5\ H_2 + 2\ NO \rightarrow 2\ NH_3 + 2\ H_2O$$

$$2\ NO + 2\ NH_3 + ½\ O_2 \rightarrow 2\ N_2 + 3\ H_2O.$$

Water-gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2.$$

Reforming reactions

$$HC + H_2O \rightarrow CO_2 + H_2$$

$$HC + H_2O \rightarrow CO + H_2.$$

DeFoort et al. showed, on a Superior 6G-825 industrial natural gas engine, that the equivalence ratio range from 1.015 to 1.020, representing a ϕ control range of ±0.5%, produced a catalyst reduction efficiency of 90% for NOx and CO. In field operations however, it is challenging to consistently achieve a ϕ control range of ±0.5% over an extended duration, owing primarily to drift in the output signal from the oxygen sensor. Also, it should be noted that there is an inverse relationship between the ϕ control window and the magnitude of reduction efficiency being sought. Other parameters that impact the ϕ control window and maximum achievable catalyst efficiency are (i) space velocity, which is inversely proportional to the volume of NSCR catalyst used and (ii) catalyst operating temperature. It has been shown by Amadu et al. that lower space velocity and higher catalyst temperature widens the ϕ compliance window of an NSCR catalyst.

The work by DeFoort et al. also examines the benefits of equivalence ratio dithering. Dithering has been shown to widen the control window of a catalyst, effectively increasing the equivalence ratio range of operation. DeFoort et al. found that a 1% variation in equivalence ratio at 0.2 Hz (dithering) widened, by approximately 20%, the catalyst window for 80% reduction efficiency. This phenomenon can be ascribed to the oxygen storage capacity of a catalyst, which regulates the available O_2 present on the catalyst bed. A common material used for this application is ceria (CeO_2), owing to its excellent oxygen adsorption and desorption properties, explained by the following reactions [4]:

$$Ce_2O_3 + ½\ O_2 \rightarrow 2CeO_2 \text{ [oxidation to } CeO_2 \text{ via adsorption]}$$

$$2CeO_2 + CO \rightarrow Ce_2O_3 + CO_2 \text{ [reduction to } Ce_2O_3 \text{ via desorption]}$$

The ability of AFR control systems to consistently maintain engine equivalence ratio in the required narrow operating range over the long-term, under field conditions has not been

established. Another study [3] which sought to better understand the limitations of current commercially available AFR control systems for rich-burn engines with NSCR catalysts concluded that the AFR controller evaluated during that study exhibited poor control for NSCR operation, owing primarily to drift in oxygen sensor calibration.

In response to these issues faced by the natural gas industry, Woodward, Inc. developed and commercialized a new Heated Exhaust Gas Oxygen (HEGO) sensor (commercially referred to as StableSense™), tailored for the rigors of industrial gas engine applications. Compared against automotive-grade O_2 sensors that were traditionally used on AFR control systems for industrial gas engines, the StableSense™ HEGOs exhibited drastic reductions in signal drift, even when operated in environments containing unburned CH_4 and H_2 [4]. Signal response of the StableSense™ HEGO sensor is similar to that of the upstream sensor described in the work by Mizutani et al. The primary difference between HEGO sensors for automotive applications versus the StableSense™ HEGO for industrial gas engines is that the design for the latter application utilizes special sensor packaging features that accommodate the operational requirements of high vibration and near-100% duty cycle [6].

Coupling this advanced sensor capability with 32-bit microprocessor functionality, a very robust control architecture was developed that enabled optimal NSCR operation. This control system, commercialized by Woodward, Inc. is known as the E3 Rich-Bun Air-Fuel Ratio Control with StableSense™. In this report, it is referred to as the E3RB. It should be noted that the E3RB must utilize StableSense™ HEGOs; alternate types or brands of HEGO sensors are not acceptable substitutes in the E3RB system.

Following on the heels of very recent work [4], this thesis elucidates on the results of a long-term study (6-months) conducted on the E3RB AFR control system. In particular, this

project was intended to evaluate performance of the E3RB while maintaining optimal NSCR operation and durability of StableSense™ HEGOs over a wide range of ambient and engine load conditions. Existing literature does not contain performance data on the E3RB or the StableSense™ HEGO sensors.

2. Site Overview

This field study was conducted on a Waukesha VHF-series L7044GSI engine, sited at Encana Corporation's Frenchie Draw operation, in Wyoming's Wind River Basin, located 6,000 feet above sea level. This engine, deployed at a compressor station, powers a gas compressor for a gas gathering application (Figure 5, Figure 6, Figure 7, and Figure 8).

Figure 5: Compressor station external view, with engine room (in foreground) and exhaust stack/tailpipe on elevated catwalk (in background)

The Waukesha L7044GSI, designed for operation at a stoichiometric AFR, is categorized as a rich–burn engine. The engine design utilizes a cross-turbo configuration, which flows exhaust gases from the right cylinder bank into the left turbocharger and vice versa. Complete engine specifications are provided in Appendix A. The compressor coupled to this engine is manufactured by Ariel and is a 4-cylinder, 4-throw model having a maximum allowable working pressure of 1500 psig.

The air quality permit issued for this site allows up to 0.7g/bhp-hr of CO and NOx brake-specific emissions from this engine at a nominal speed and load condition of 1150 RPM and 1480 bhp, respectively. This nominal speed/load engine operating point will, in later sections, be referred to as High Speed/High Load (HS/HL) condition. In order to meet these regulatory limits, an NSCR exhaust after-treatment system is deployed.

The NSCR catalyst elements used on this engine are manufactured by Emit, with physical dimensions of Φ 33.5" × 3.5" thickness (Figure 9). Two such elements, placed back-to-back, providing a total space velocity of ~ 141,000 hr^{-1}, were deployed to obtain adequate engine-out exhaust after-treatment (Figure 10). The Space Velocity was calculated at an engine operating load of 1480 bhp.

The AFR controller under evaluation at this site (the E3RB) can control speed/load, AFR, and ignition timing, for a wide variety of rich-burn gas-engines in many different applications. It can be deployed on carbureted four-stroke, mono-bank (or stereo-bank), naturally aspirated (or turbo-charged engines) over a wide band of power outputs.

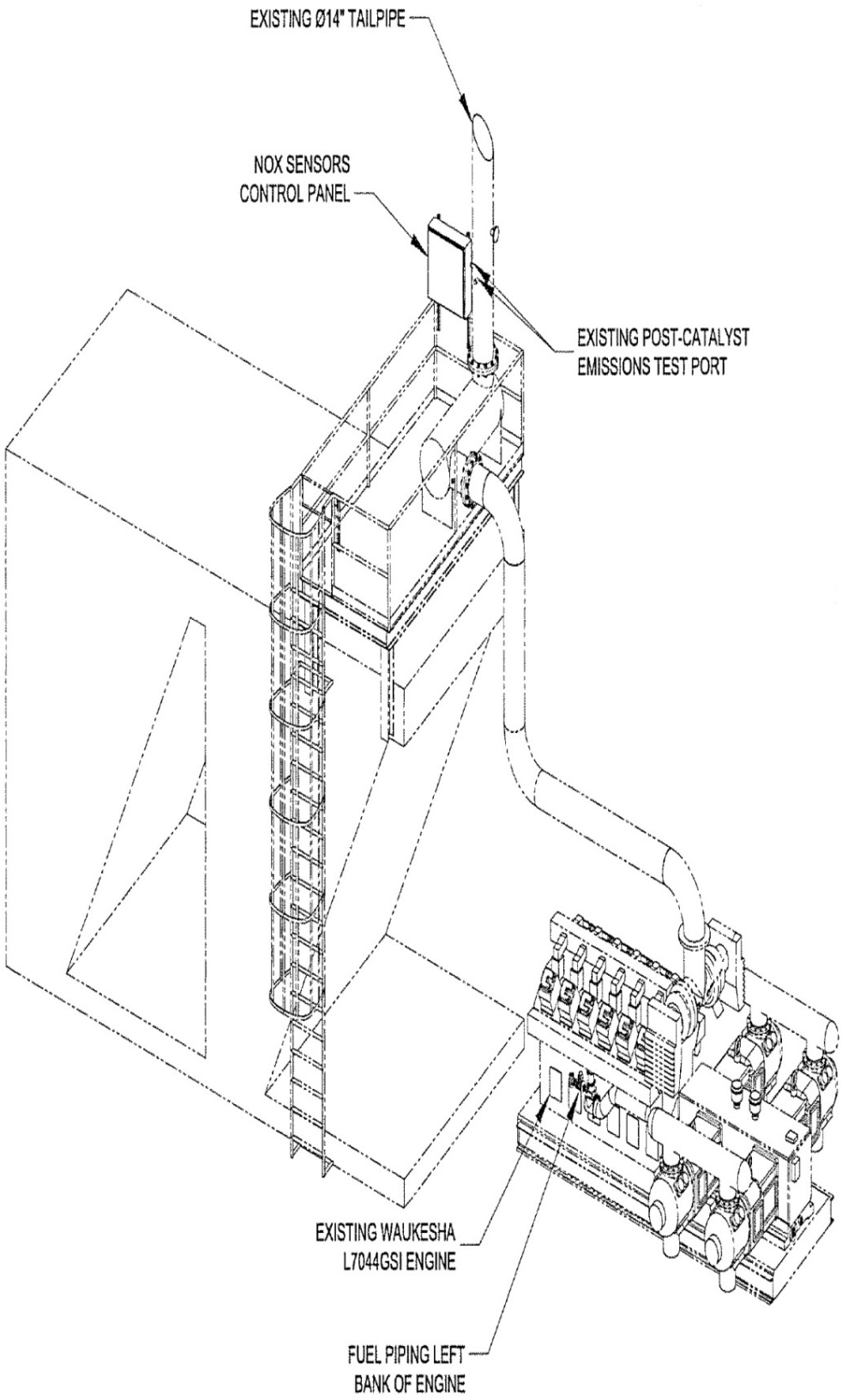

Figure 6: Schematic of compressor station layout, comprising engine, compressor, piping from exhaust manifold to catalyst housing, and stack. The catwalk is mounted atop the cooling fan housing structure

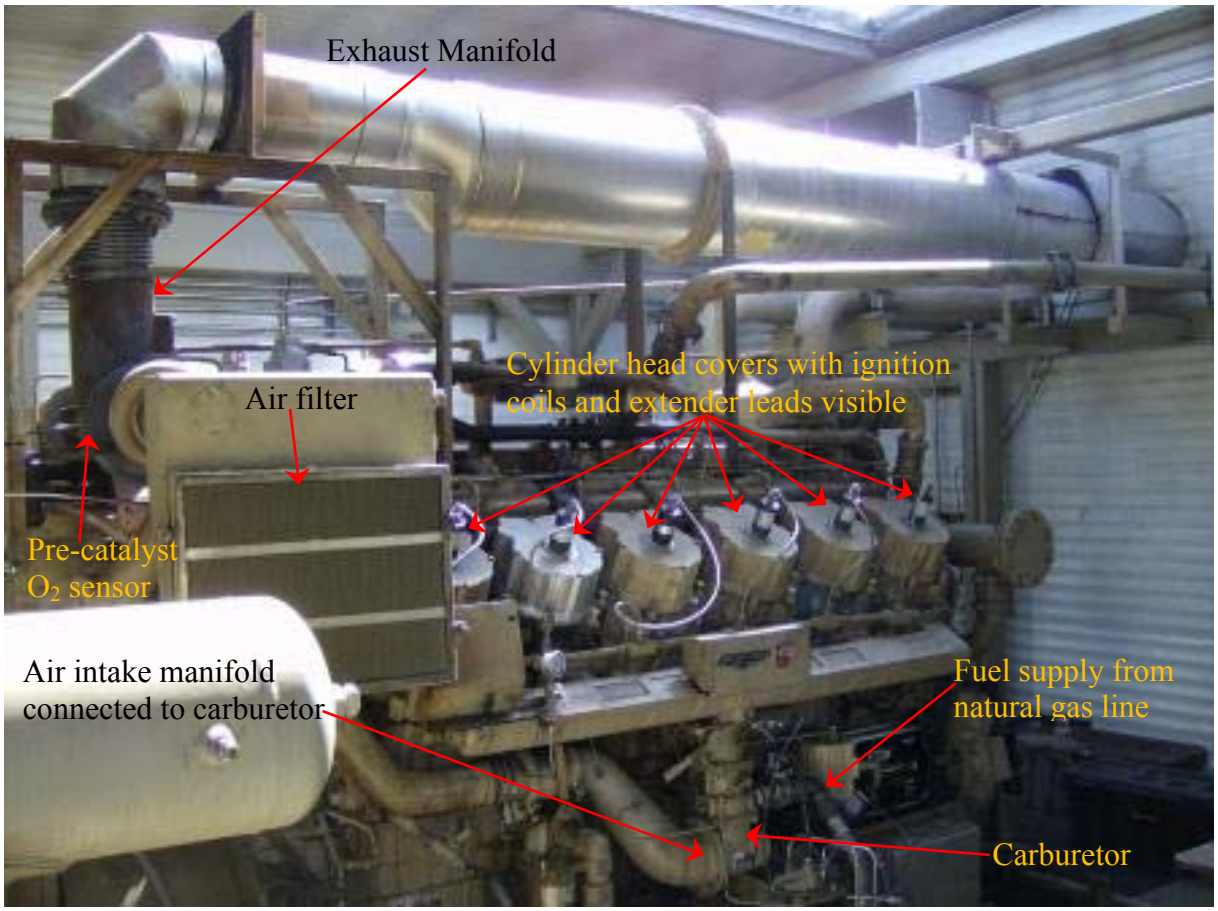

Figure 7: Profile view of the Waukesha L7044GSI engine inside the compressor station with left bank components labeled.

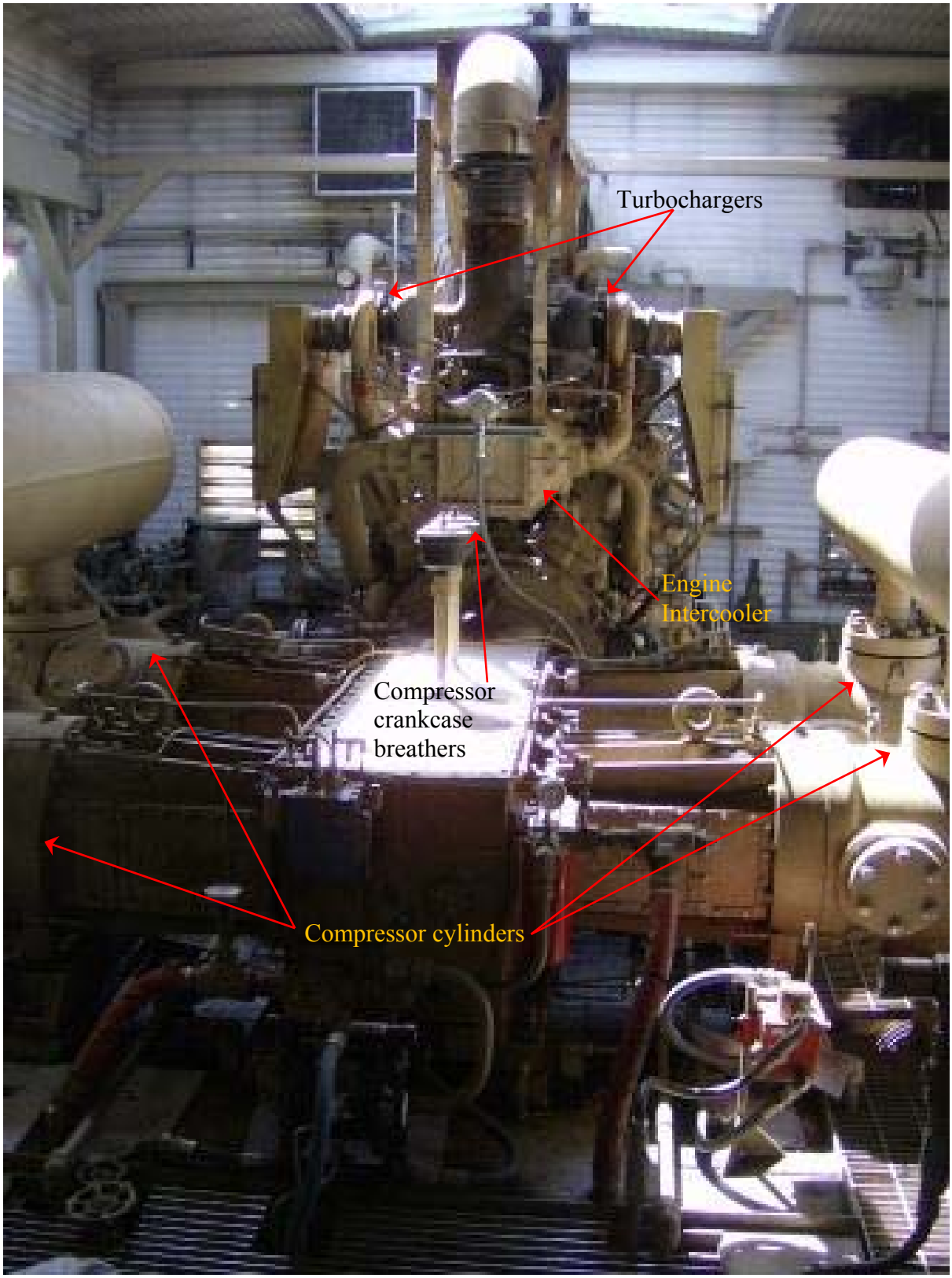

Figure 8: Gas compressor (in foreground) coupled to the engine (in background)

Figure 9: Lagging catalyst element (with ash on front face) being removed from the housing for cleaning.

Figure 10: Emit elements in the catalyst housing (leading element is on the right), with thermal-wrap around the frame for proper sealing. Direction of exhaust gas flow is from right to left.

2.1 Control Architecture

The E3RB was installed at this site (Figure 11) per guidelines obtained from Dresser-Rand Enginuity and Woodward, Inc.; personnel from both these organizations participated in the installation process. A schematic of the sensors required to facilitate E3RB operation is shown in Figure 12; complete installation specifications for this site are provided in Appendix F. An overview of the E3RB's control architecture is provided below [8].

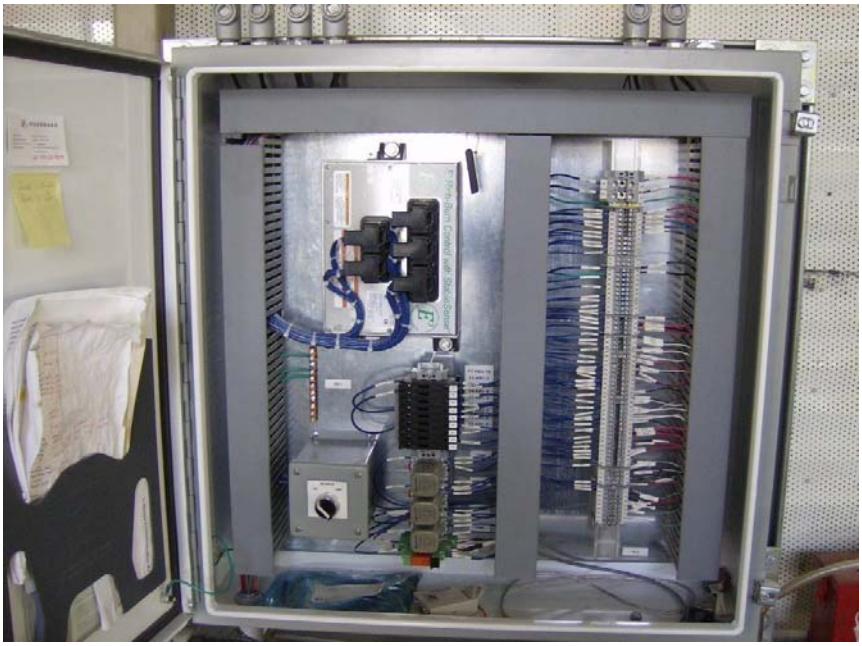

Figure 11: The E3RB control module installed inside the compressor station at the test site.

The E3RB is a microprocessor-based control for carbureted, four-stroke, gaseous-fueled engines operating at a near-stoichiometric AFR. It is designed to work in conjunction with a NSCR catalyst – one that simultaneously eliminates hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NOx) – to effectively treat exhaust emissions from rich-burn engines.

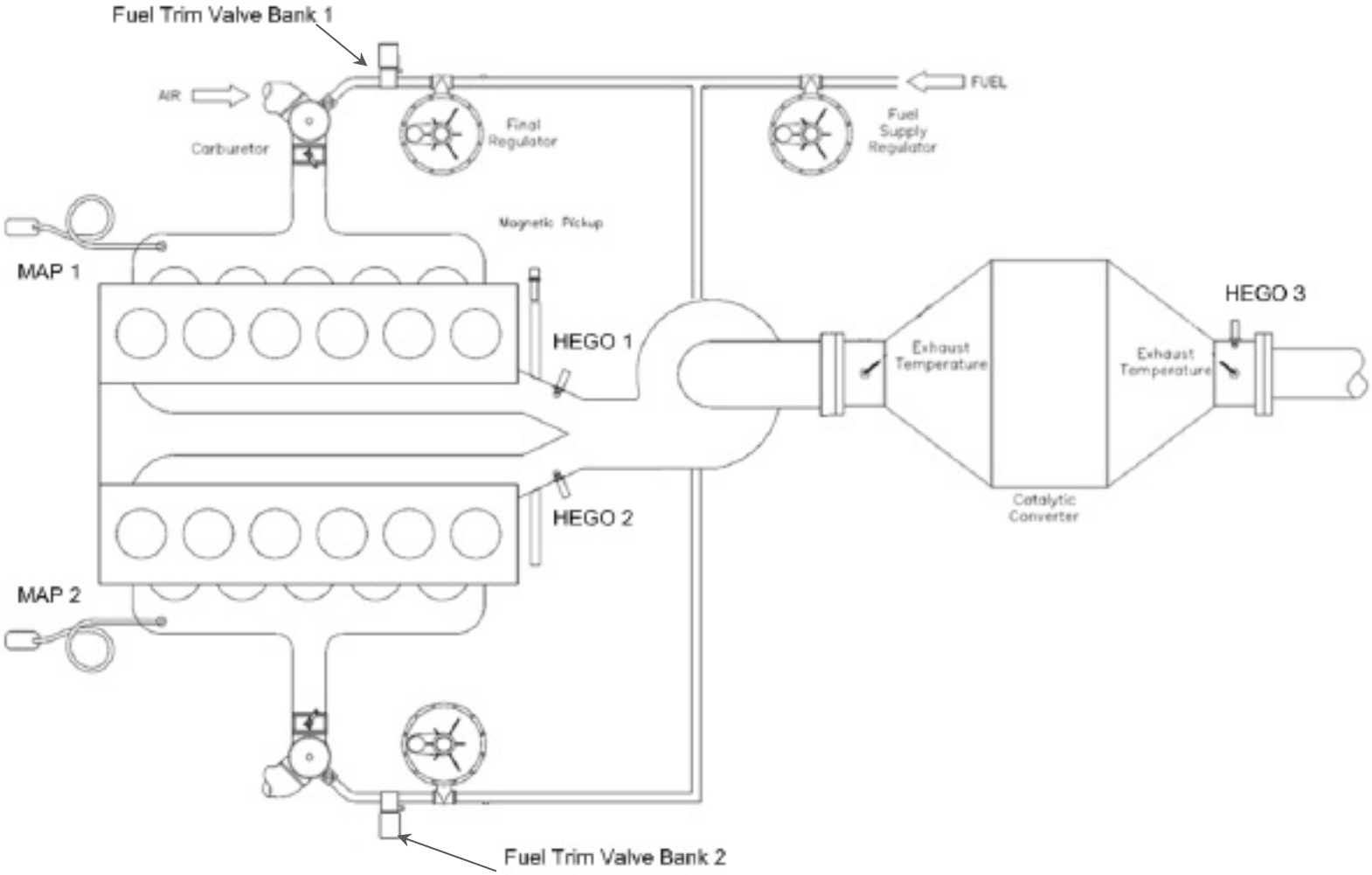

Figure 12: Layout of sensors and actuators for E3RB operation of a dual-bank engine (stereo control) [8].

By continuously adjusting for optimal air/fuel mixtures, emissions compliance can be achieved while simultaneously maximizing catalyst life and minimizing supervisory oversight by operations staff. For optimal performance and to protect the catalyst element from premature aging or damage, precise control is required of the AFR window of operation. When an engine consistently operates within this control window, optimal exhaust after-treatment can be achieved.

In the E3RB, the StableSense™ HEGO sensors generate a voltage signal that is characteristic of this ideal control window, with the controller utilizing this voltage value to keep the engine at the desired air/fuel ratio. It should again be noted that the E3RB must utilize StableSense™ HEGOs – alternate brands are not acceptable substitutes for the E3RB system. Optimized for Full-Flow Trim operation, the carburetor remains in place on the engine, the base AFR is adjusted slightly rich, and the trim valve restricts fuel flow to the carburetor so as to adjust the air/fuel mixture to the precise value that will maximize catalyst efficiency. The given engine being a dual bank design, optimal inlet conditions to the NSCR catalyst are maintained by way of stereo control, which uses two pre-catalyst HEGO sensors (one in each bank) for closed loop, exhaust oxygen feedback control and one post-catalyst HEGO sensor for post-catalyst, exhaust oxygen cascade feedback control (Figure 13). Fluctuations in engine load are managed by varying the post-catalyst HEGO sensor's base setpoint value, as tabulated in the post-catalyst setpoint table. The operational range of the feedback algorithm and HEGO sensors cover a wide spectrum of gas compositions, including LPG, pipeline natural gas, and coal-bed gas. In addition, the algorithm incorporates fuel valve dithering in order to maximize flexibility of catalyst operation. Changes in gas quality and the ambient environment during normal engine operation are compensated by post-catalyst closed loop HEGO control. In the event of a critical oxygen

sensor malfunction, the control reverts to an open loop strategy, during which time the valve position is determined using pre-assigned values from an open loop table. The fuel metering subsystem consists of a carburetor combined with an in-line fuel trim valve. Additional details follow on control terminology used in the above overview.

Stereo Control

Stereo AFR control systems are used on dual bank engines and utilize two Pre-Cat HEGO sensors (one on each bank) and two Fuel Trim Valves (one on each bank). Stereo control poses more challenges owing to twice the number of components deployed but does present the opportunity to improve the catalyst efficiency by dithering the AFR in each bank to be out of phase with each other, thereby simultaneously providing the NSCR catalyst with exhaust gas constituents required for both oxidation and reduction reactions.

Pre-Catalyst Exhaust Oxygen Control

Primary AFR control is achieved using the pre-catalyst oxygen sensors, via the Fuel Trim Valves, which increase or decrease fuel flow to the engine, so as to hold the average voltage signal of the pre-catalyst sensors at a preset target.

Post-Catalyst Exhaust Oxygen Control

As ambient conditions vary and the catalyst element ages, optimal catalyst performance is assured by means of a “Cascade” control loop that uses feedback from a second oxygen sensor in the exhaust, downstream of the catalyst element. This post-catalyst control loop adjusts the primary pre-catalyst control setpoint to changes in fuel composition, catalyst efficiency, and environmental conditions that are detected in the post-catalyst oxygen concentration.

Post-Catalyst Setpoint Table

The Post-Catalyst Setpoint Base value may vary several millivolts from engine to engine, catalyst to catalyst, and load to load. Additionally, as some engines operate with varying loads, optimum catalyst performance is obtained by adjusting the Post-Catalyst Setpoint. During initial tuning and system commissioning activities, the required setpoints are entered into the Post-Catalyst Setpoint table so that the pre-catalyst setpoint target can be changed at different loads to ensure compliance throughout the engine load range. The E3RB tracks engine load by monitoring engine speed, intake manifold pressures, and temperatures (MAP and MAT, respectively). Combining these parameters with an assumed volumetric efficiency (which varies as a function of speed), an approximate engine charge flow (Qmix) is calculated and used as the indicator of engine load. The load range of the engine is divided into eight segments and a Post-Catalyst Setpoint value can be manually assigned for each of these levels.

Fuel Valve Dithering

As discussed earlier, dithering the AFR into the engine enhances catalyst performance. The E3RB system includes parameters to adjust the dither amplitude and frequency so as to optimize the oxygen storage capacity of the catalyst. This strategy widens the window of operation and permits greater drift tolerance whilst maintaining acceptable reduction efficiencies.

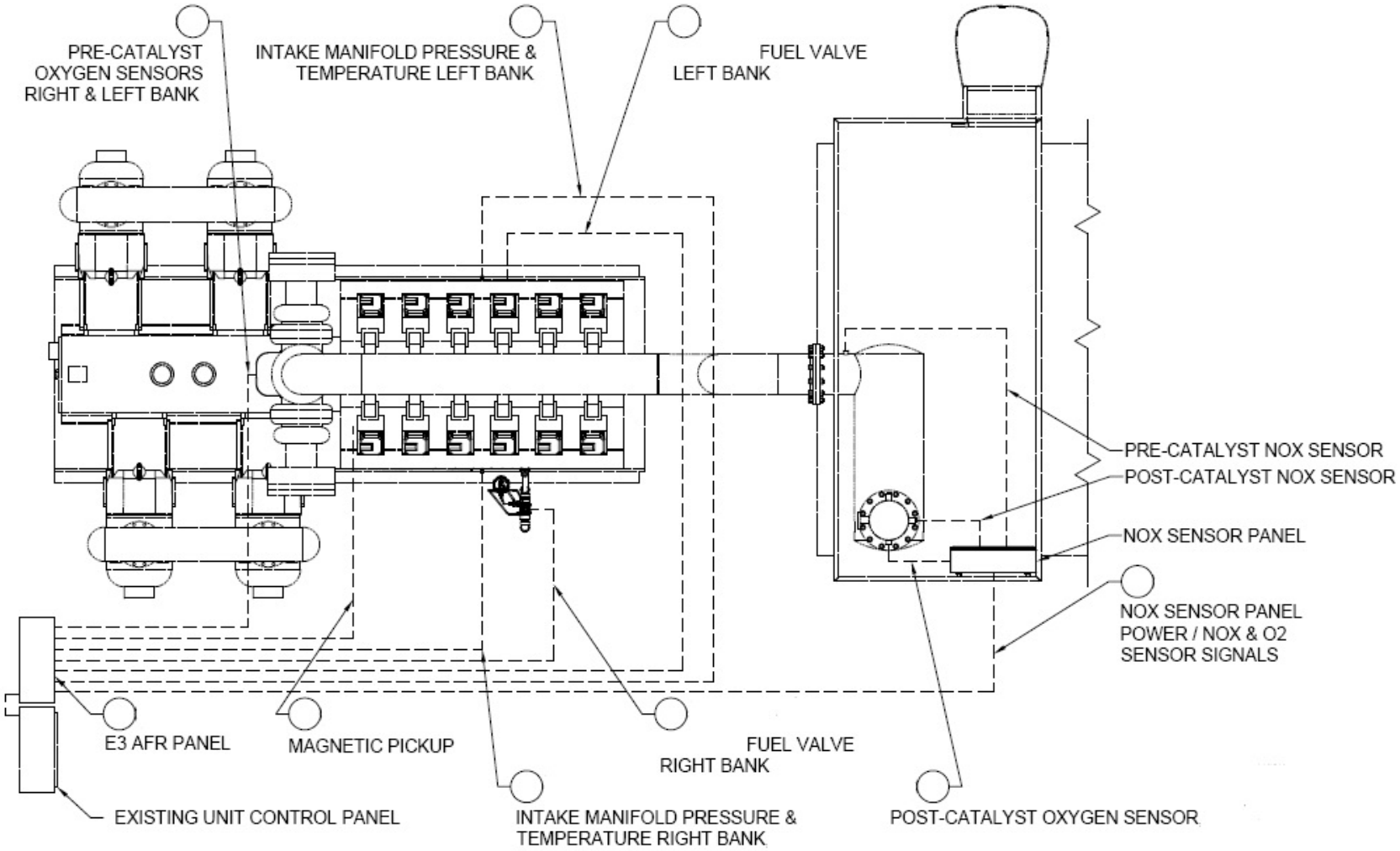

Figure 13: Schematic of valves and sensors installed on the field engine to facilitate E3RB operation. NO_x sensors, coupled to onsite SCADA, provided remote emissions monitoring capability (not required by the E3RB system).

Open Loop Control Mode

The open loop mode will control the coarse air/fuel ratio of the engine without the closed loop pre and post-catalyst sensor measurement; it is less accurate than the closed loop mode but is more accurate than using a stand-alone carburetor. This mode draws from the Open Loop Table, which correlates Fuel Trim Valve Position to the engine load parameter, Qmix. This table contains valve operating positions for eight (8) load points over the engine's entire load range; valve position for other load points are determined by interpolation. If either of the pre-catalyst sensors fail, the control automatically defaults to the open loop mode using values from this table that were manually entered during initial control calibration.

2.2 Emissions Sampling System

The emissions sampling system at this site comprised the following arrangement:

1. Pre and post-catalyst sampling probes for Φ14" exhaust pipe, prepared using guidelines in EPA Method 1.
2. Filter (for particulates in the exhaust gas stream)
3. 3-way valve (to allow switching between pre and post–catalyst samples)
4. Heated sample line, maintained at 220°F, using a temperature controller
5. Heated head sample pump
6. Portable emissions analyzer

The above listed items are shown in Figure 14, Figure 15, Figure 16, Figure 17, and Figure 18. All the lines connecting sample probes to the filter were wrapped in exhaust header tape to minimize heat dissipation; these lines were also routed in close proximity to the catalyst housing, providing a localized elevated-temperature environment. Both these measures

prevented water condensation in the lines, thereby eliminating any reduction in output levels of emission species by way of aqueous phase absorption.

An alternate setup, shown in Figure 18 (right), was also used to draw exhaust into the analyzer. In this arrangement, the exhaust gas stream was drawn through the heated sample line directly into the analyzer using the analyzer's internal pump, bypassing the heated head pump. Utilization of this setup did not alter the flow rate of exhaust gas into the analyzer and was the preferred configuration for emissions sampling.

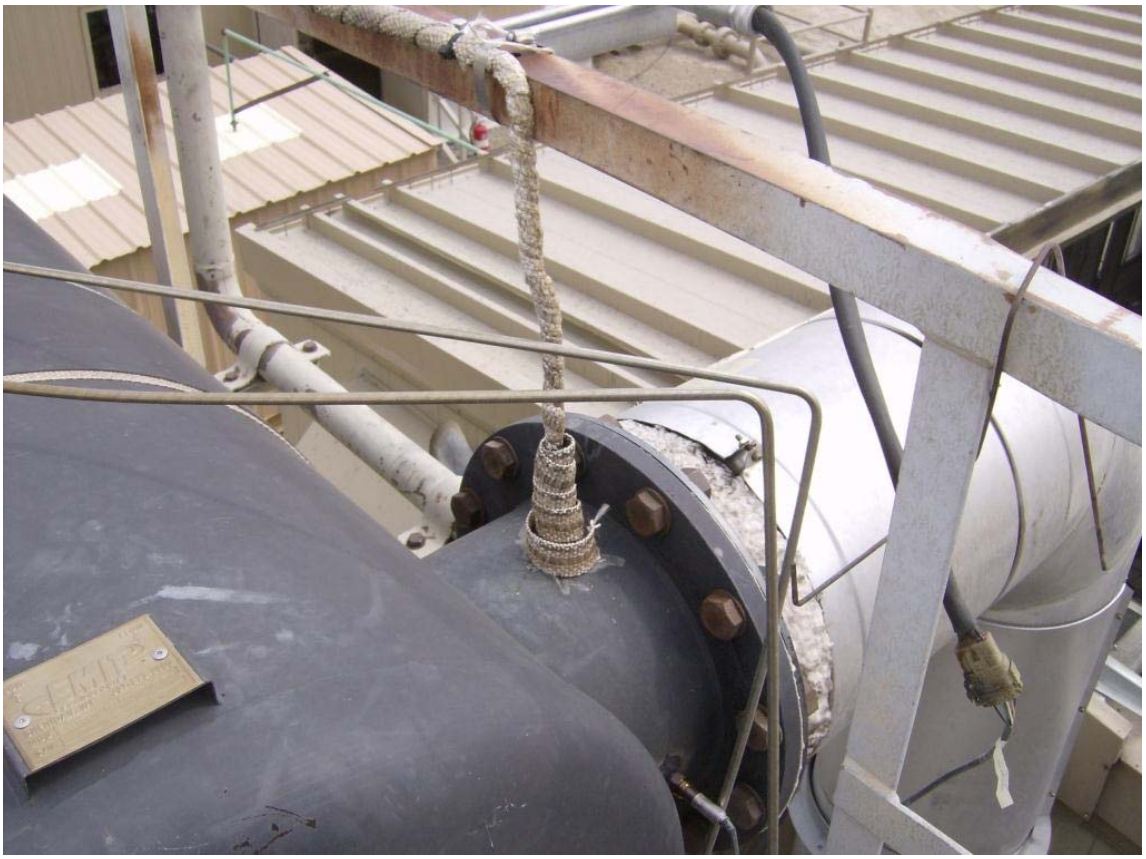

Figure 14: Pre-catalyst emissions sampling probe in exhaust manifold.

Figure 15: Post-catalyst emissions sampling probe in exhaust manifold.

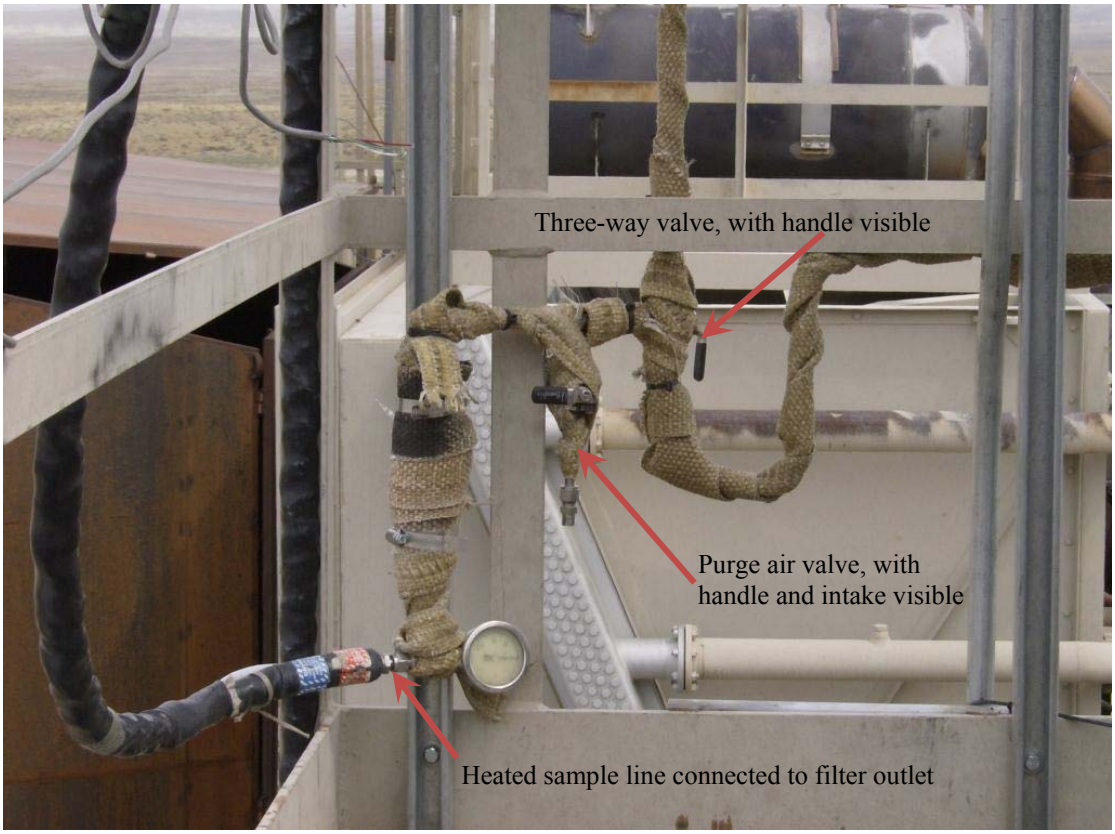

Figure 16: Heated sample line (bottom left) connected to filter outlet, shrouded in thermal wrap. Handle of three–way valve is on the far right, with handle of purge air valve visible in the middle.

Figure 17: Heated sample line is routed from the sampling port on the elevated catwalk (left), through a ground level window in the engine room (middle), to the inlet of the heated head pump (right).

Figure 18: (Left) Portable emissions analyzer setup inside the engine room. (Right) Alternate arrangement for exhaust sampling: heated sample line (hanging in foreground) ready for direct connection to the sampling port on the analyzer.

2.2.1 Portable Emissions Analyzer

The portable emissions analyzer used during field site visits was donated by ECOM America, model J2KN-IND. Among its many features, this model has an internal pump with bypass plumbing for fresh air purge, a thermo-electric gas cooler and moisture trap with automatic moisture dump, wireless handheld remote control with Bluetooth™ radio connectivity to a laptop or workstation, an on-board flowmeter, and automatic switch over between high and

low-range CO sensors. The unit used for the field test was fitted with sensors for measurement of CO (low range), CO (high range), NO, NO_2, and CH_4. Sensor resolution and measurement accuracies are shown in Table 2.

Table 2: Specifications of sensors fitted on ECOM J2KN portable emissions analyzer

Species	**Range**	**Resolution**	**Accuracy**	**Sensor Type**
O_2	0 – 21 %	0.1% vol.	± 2% measured	Electrochemical
CO (low)	0 – 4000 ppm	1 ppm	± 2% measured	Electrochemical
CO (high)	0 – 40,000 ppm	1 ppm	± 2% measured	Electrochemical
NO	0 – 4000 ppm	1 ppm	± 2% measured	Electrochemical
NO_2	0 – 500 ppm	1 ppm	± 2% measured	Electrochemical
CH_4	0 – 30,000 ppm	10 ppm	± 5% measured	Infra-Red
CO_2	0 – max. of fuel	N.A.	N.A.	Calculated

As the primary species of interest for this study were CO and NO, these were the calibration gases acquired for this field test. Prior to the start of emissions monitoring on each test day, the ECOM analyzer was calibrated using the gases listed in Table 3. At the end of the test day, a calibration check was conducted to quantify the sensor drift that occurred over the course of the day. For this field study, the established limit for sensor drift was ± 5% of the calibration standard. If, over the course of a test, the sensor temperature drifted beyond 10°F from the temperature at which initial calibration was performed, the analyzer was recalibrated at

the new sensor temperature. Details of calibrations conducted during each test day are provided in Appendix B.

Table 3: Calibration gases used for the portable emissions analyzer during field site visits

Species	Cal gas conc.	Grade/Accuracy	Expiration
O_2	Ambient (21%)	N.A.	N.A.
CO (low)	401 ppm	Certif. Master Class	28-Nov-2013
CO (high)	6891 ppm	± 2%	20-Aug-2013
NO	201 ppm	Certif. Master Class	28-Nov-2013

When using this portable analyzer in continuous mode, it was necessary to purge the cells with air between measurements to prevent cell poisoning and drift. A 50% duty cycle (15 minute measurement cycle; 15 minute purge cycle) was used to maintain measurement quality. During periods between site visits, engine operation was monitored remotely using SCADA data from existing compressor station instrumentation (Figure 19 and Figure 20). Emissions trends were similarly developed using SCADA information from CSU-installed pre and post-catalyst NOx sensors (Figure 21 and Figure 22). The output range of these NOx sensors is from 0 – 5V and the scale applied to the voltage output was as follows:

Pre-catalyst: 0V = 0 ppm ; 5V = 5000 ppm

Post-catalyst: 0V = -50 ppm ; 5V = 200 ppm

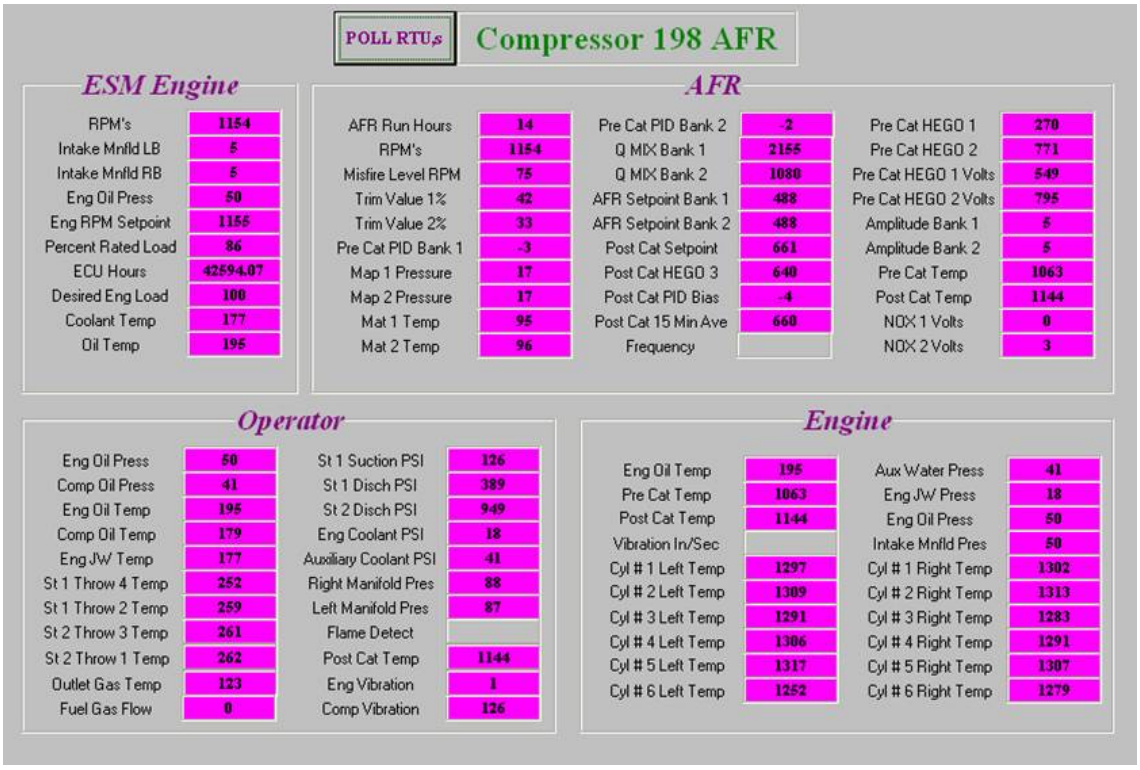

Figure 19: Screenshot of SCADA page for Engine Data

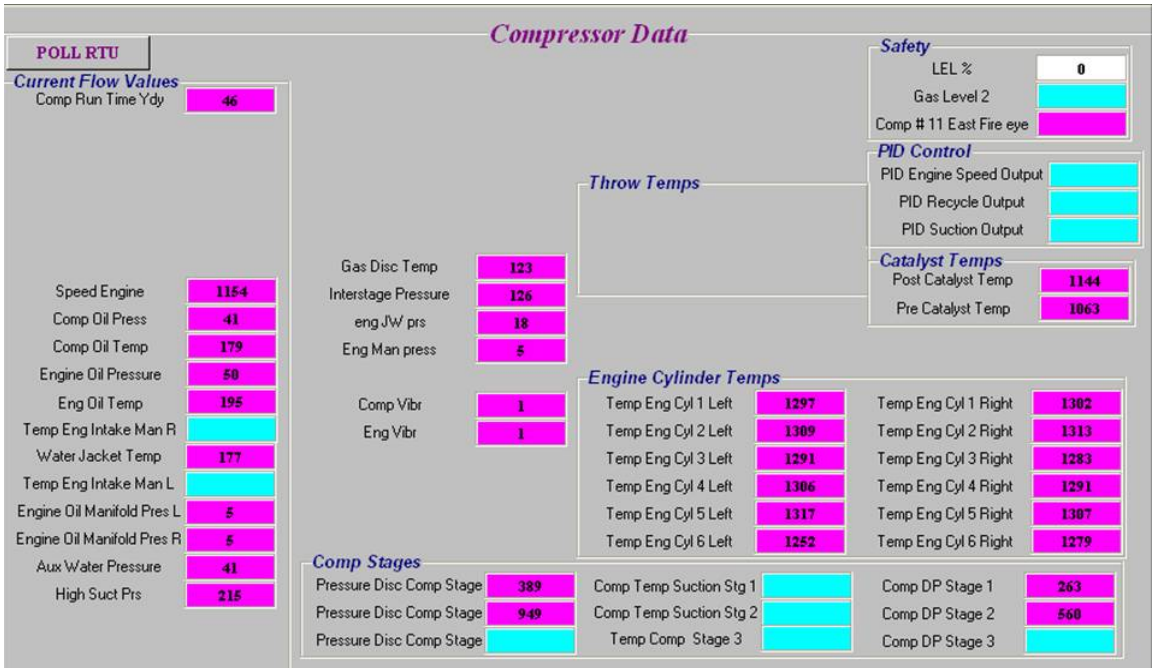

Figure 20: Screenshot of SCADA page for Compressor Data

Figure 21: (Left) Pre-catalyst NOx sensor. (Right) Post-catalyst NOx sensor.

Figure 22: NOx sensor control module installed inside sealed enclosure on elevated catwalk.

2.2.2 Portable Gas Chromatograph

A portable gas chromatograph (GC) was used to characterize fuel gas variations at the field site over a 24 hour period. The model used was the Varian CP–4900 Micro GC (Figure 23). This instrument has built-in Micro Electronic Gas Control regulators that can be adjusted to obtain constant or programmed pressure control, resulting in constant or programmed flow through the injector, column and detector. When a run is initiated, a gas sample is drawn through a sample loop inside the injector, using an onboard vacuum pump, and is then injected into the carrier gas stream. A typical injection time is 40 milliseconds (ms), which corresponds to an injection volume of 200 nL.

This model is also equipped with a Thermal Conductivity Detector (TCD) and a Differential Mobility Detector (DMD). The former responds to differences in thermal conductivity between the carrier gas and the gas sample constituents while the latter deploys an advanced form of Ion Mobility Spectroscopy (IMS).

CSU's GC is configured for use with Helium (He) as a carrier gas, having a minimum purity of 99.995% and limited to 80 ± 2 psi on the main gas supply.

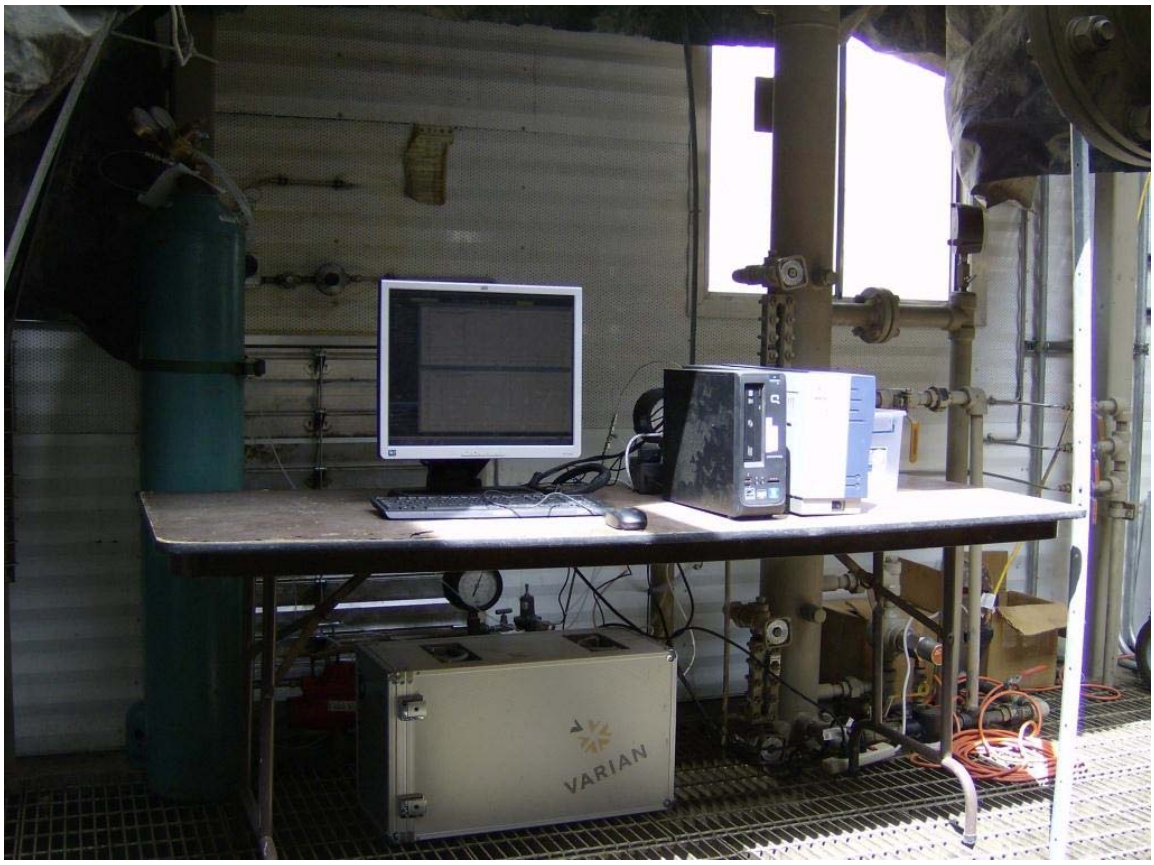

Figure 23: Portable fuel gas chromatograph station inside the engine room.

2.3 Project Timeline and Milestones

July 2011 – Site visit to Frenchie Draw (WY), hosted by Justin Lisowski (Encana). Visitors: Daniel Olsen, Chris Hagen (CSU) ; Chris DeFoor (Woodward) ; Earl Glover (Dresser-Rand Enginuity).

September 26, 2011: E3RB control box delivered to Encana office in Riverton, WY.

November 7 – 13, 2011: Installation of E3RB, followed by first commissioning attempt. Tuning could not be completed owing to wastegate malfunction therefore, commissioning was postponed. Engine hours on November 13 = 45,292.

January 2 – 4, 2012: Second commissioning attempt. Tuning could not be completed owing to exhaust leaks therefore, commissioning was postponed.

February 13 – 20, 2012: Third commissioning attempt. Single EmeraChem catalyst element deemed as insufficient for adequate NSCR exhaust after-treatment. Therefore, two (2) new Emit NSCR elements were installed in catalyst housing. Fuel pressure oscillations (120↔140 psig over 30 second intervals) were noticed in main supply line, owing to malfunctioning motor valve in liquids drop-out shed. This was corrected by over-pressurizing the fuel supply line to this engine, causing the pressure relief valve to remain open. In this way, a constant pressure of ~140 psig was maintained in the fuel supply line to this engine. All tuning was conducted at fuel pressure of ~140 psig.

February 20, 2012: Tuning and commissioning completed; handover to CSU for monitoring and performance evaluation. No further tuning was performed on the E3RB after system commissioning and handover. Engine hours = 47,434.

February 26 – 28, 2012: Monitoring visit # 1.

February 27, 2012: To overcome erratic engine behavior brought on by fuel pressure fluctuations, the fuel supply line was over-pressurized beyond the cracking pressure of the relief valve. This stabilized fuel pressure to the engine. All emissions data was collected at a constant fuel pressure of ~ 140 psig. Catalyst elements WERE NOT blown out with compressed air prior to evaluating controller performance and collecting emissions data.

March 11 – 13, 2012: Monitoring visit # 2.

March 13, 2012: Catalyst elements were blown out with compressed air prior to evaluating controller performance and collecting emissions data. Fuel pressure fluctuations were rectified – constant fuel pressure of ~140 psig has been restored to main fuel supply line.

April 1 – 3, 2012: Monitoring visit # 3.

April 2, 2012: Catalyst elements were blown out with compressed air prior to evaluating controller performance and collecting emissions data.

May 13 – 16, 2012: Monitoring visit # 4.

May 14, 2012: Catalyst elements were blown out with compressed air prior to evaluating controller performance and collecting emissions data.

May 16, 2012: New spark plugs installed in the engine.

May 30, 2012: Emit elements (2) removed from catalyst housing for washing. Interim NSCR exhaust after-treatment provided by EmeraChem single element.

June 24 – 27, 2012: Monitoring visit # 5.

June 25, 2012: Prior to emissions monitoring on this engine, the following maintenance was conducted: (a) Existing HEGO sensors on E3RB system were replaced with new HEGOs – the new sensors were identical models as those replaced. The old HEGOs, having ~5138 hours of run-time, were returned to Woodward for analysis. (b) The EmeraChem single catalyst element installed on May 30, 2012 was removed from the housing and two (2) freshly washed Emit catalyst elements were reinstalled.

July 18 – August 9, 2012: Engine offline owing to compressor main bearing failure.

August 19 – 24, 2012: Monitoring visit # 6.

August 20, 2012: Catalyst elements WERE NOT blown out with compressed air prior to evaluating controller performance and collecting emissions data. 6 month evaluation has been completed. Engine hours = 51,249.

August 21 – 24, 2012: E3RB tuning (HEGO setpoints, dither frequency/amplitude, PID bias) optimized for this engine based on results of equivalence ratio sweep conducted at high speed/high load condition.

The relevance of blowing out catalyst elements with compressed air prior to monitoring emissions will be discussed in the Results section of this thesis.

2.4 Test Matrix

Based on feedback from Encana field personnel, three distinct engine load conditions were defined, which represented the range of typical operation of the engine at this site; shown in Table 4 as High Speed/High Load (HS/HL), Mid Speed/Mid Load (MS/ML), and Low Speed/Low Load (LS/LL). The Inducted Charge Flow is an E3RB parameter, described in an earlier section as Qmix, which is used by the controller to indirectly ascertain engine load by calculating the volumetric flow rate of fuel/air charge in the intake manifold. It is useful to once again note that Qmix is a calculated parameter that incorporates both engine speed and load in a single metric.

The emissions monitoring protocol consisted of recording post-catalyst engine emissions at all points in the test matrix, followed by a pre-catalyst measurement at the very last point, allowing for evaluation of catalyst performance at that operating condition. During transitions between each load point, E3RB response was monitored and recorded by way of trends

generated through Woodward's Control Assistant software, which interfaced with the E3RB controller via a laptop USB connection.

Table 4: Engine speed/load test matrix used for emissions monitoring and evaluation of E3RB performance

Operating Condition	**Speed (RPM)**	**Inducted Charge Flow (scfm)**
High Speed/High Load (HS/HL)	1150	2100
Load Step: Monitor E3RB transient response		
Mid Speed/Mid Load (MS/ML)	1000	1700
Load Step: Monitor E3RB transient response		
Low Speed/Low Load (LS/LL)	850	1400
Load Step: Monitor E3RB transient response		
High Speed/High Load (HS/HL)	1150	2100

2.4.1 Performance Evaluation Protocol

The following steps were performed during each site visit, as part of the monitoring protocol. It should be noted that the emissions analyzer was configured to operate at 50% duty cycle (15 minutes emission sampling ; 15 minutes fresh air purge).

1. If it is not already running, start and load the engine per standard procedures. Operate the unit under load for several hours until the system achieves equilibrium.
2. Set the unit to HS/HL condition and allow 20 minute equilibration period.

a. Record two 15 minute data sets of post-catalyst emissions and all relevant engine and catalyst operating parameters.
b. Review the data for repeatability and record additional data sets as required.

3. Set the unit to MS/ML condition and allow 20 minute equilibration period.
    a. During this load step, record 15 minutes of E3RB controller data.
    b. Record two 15 minute data sets of post-catalyst emissions and all relevant engine and catalyst operating parameters.
    c. Review the data for repeatability and record additional data sets as required.
4. Set the unit to LS/LL condition and allow 20 minute equilibration period.
    a. During this load step, record 15 minutes of E3RB controller data.
    b. Record two 15 minute data sets of post-catalyst emissions and all relevant engine and catalyst operating parameters.
    c. Review the data for repeatability and record additional data sets as required.
5. Return the unit to HS/HL condition and allow 20 minute equilibration period.
    a. During this load step, record 15 minutes of E3RB controller data.
    b. Record two 15 minute data sets of post-catalyst emissions and all relevant engine and catalyst operating parameters.
    c. Review the data for repeatability compared to step 2 above. Investigate any aberrations.
    d. Record one 15 minute data set of pre-catalyst emissions and all relevant engine and catalyst operating parameters.

2.4.2 Evaluation of Engine Power Output

Emissions species were measured as raw concentrations in parts per million dry (ppmd). In order to normalize this raw data to brake specific values, engine power output was required to be known. Direct measurement of engine power was not available at this site and neither was fuel flow, owing to a malfunctioning orifice meter. So, instead three alternate approaches, outlined below, were devised to determine engine horsepower and by extension brake specific emissions. A side-by-side comparison of the engine power output obtained using each method is presented in Figure 24.

Method 1 (Calculated)

Shaft power is calculated using known values of total inducted charge (Qmix), and fuel gas composition, as well as OEM engine specifications for brake specific fuel consumption at various engine speeds.

Method 2 (ESM Load)

The ESM (Engine System Manager) is Waukesha's engine management system, which integrates spark timing control, speed governance, detonation detection, start-stop control, diagnostic tools, fault logging, and engine safeties. At this site, the ESM load rating displayed on the PLC for each operating condition was converted to a proportionate power output, based on the engine speed at that particular load rating.

Method 3 (Ariel Model)

Using recorded values of engine speed, suction and discharge pressures/temperatures for a given loading condition, the engine output was calculated using Ariel Corporation's proprietary

compressor sizing program. A parasitic loss of 5% was assumed for auxiliary loads such as cooling fans.

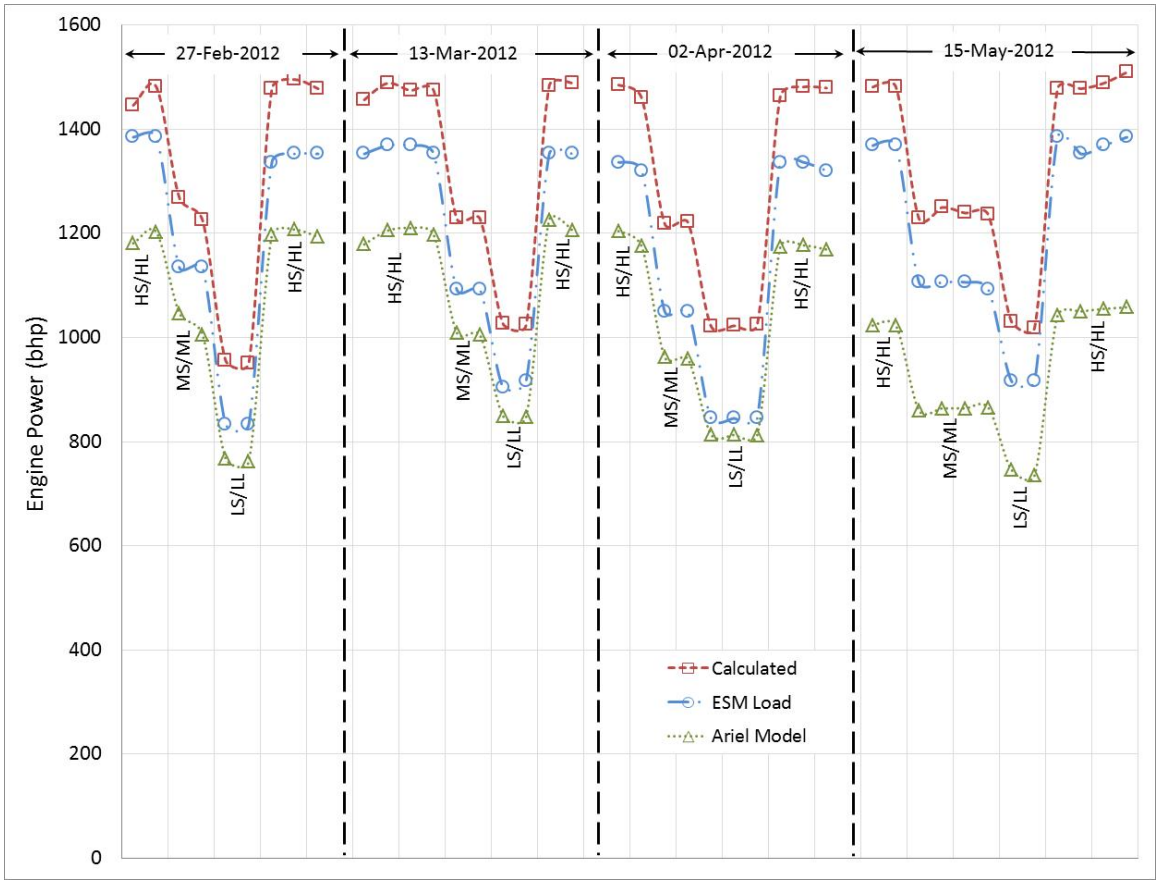

Figure 24: Comparison of engine power output obtained using three different methods.

From Figure 24, it can be seen that variation between the three methods is significant. Torque measurements for compressor and auxiliary shafts would need to have been made in order to reliably measure engine power output and use it to identify the most accurate of the three methods. However, since resources were not at hand to measure shaft torque, for the purposes of reporting brake specific emissions, it was decided to calculate engine power using Method 1.

3. Results

3.1 Engine Tuning

The E3RB was tuned by Woodward across the entire range of site operating conditions anticipated by Encana field personnel. Figure 25 shows the post-catalyst emissions levels of CO and NOx obtained at various engine load points on February 20, 2012. Taking into consideration the sharp rise in NOx emissions if an engine operates outside of the lean-limit of the NSCR control window as compared to the gradual increase in CO emissions for an engine operating beyond the rich-limit, conventional wisdom suggests that the target post-catalyst CO:NOx ratio for optimal NSCR performance be ~2:1 [9].

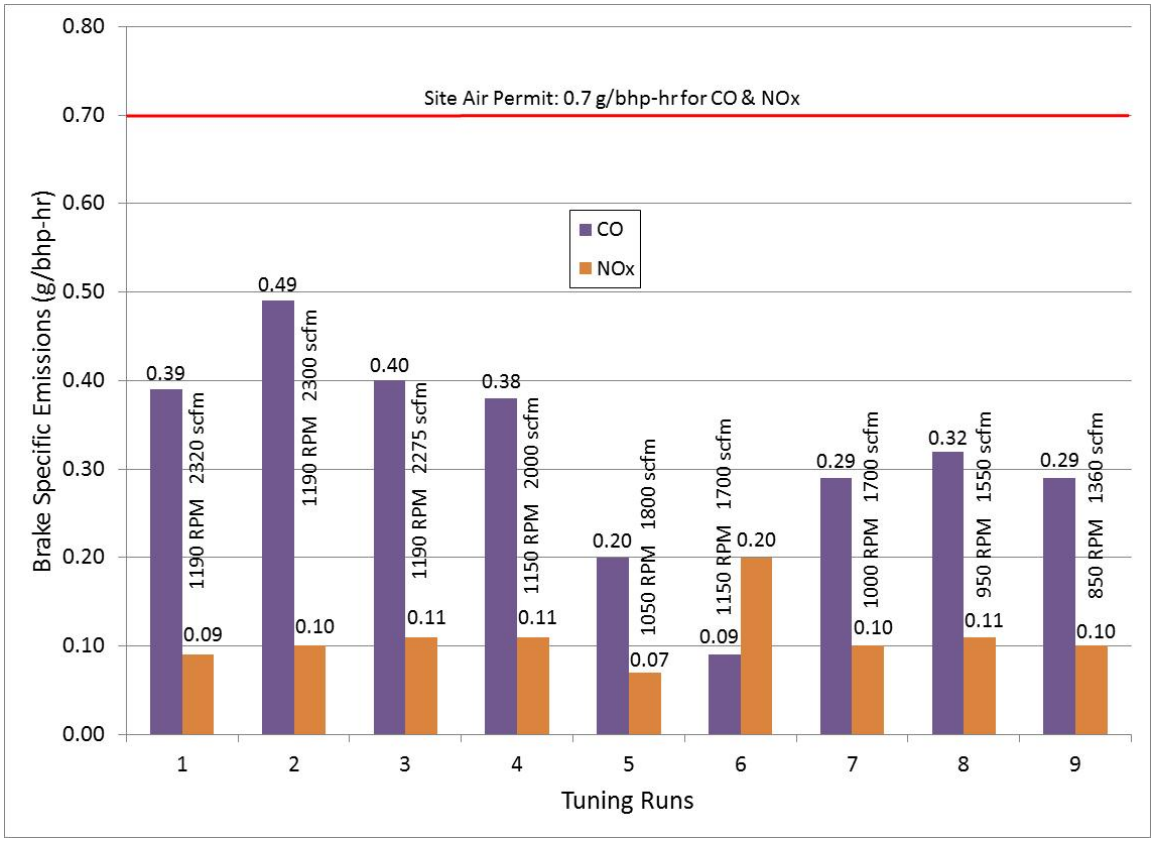

Figure 25: Tuned emissions level across the engine operating load range.

In this case, CO:NOx at high load conditions is ~4:1, tapering off to ~3:1 at mid and low loads, with an inversion at Run 6, where CO:NOx is ~1:2. High levels of engine-out CO emissions were observed (> 20 g/bhp-hr); the prime suspect behind this is most likely poor engine health, which is discussed in a following section. It is assumed that appropriate tuning adjustments would have been made to the AFR control, if this issue was discovered during pre-commissioning activities.

3.2 Alarms/Faults

The following system fault/alarm settings were demonstrated to showcase the features of this controller:

1. Misfire
2. System lean/rich
3. Post-catalyst HEGO sensor failure
4. Post-catalyst high temperature
5. Pre-catalyst high/low temperature
6. Bank 1 and 2 HEGO sensor (pre-catalyst) failure

E3RB response trends for each of these alarms can be viewed in Appendix C.

3.3 Engine Health

During the initial screening conducted to identify a suitable unit for this field evaluation, the primary criteria used were low engine hours and reduced catalyst age, with no attention given to other attributes of engine health such as consumption rates of engine fluids (oil and coolant). This oversight in assessment of overall engine health proved to be a costly mistake as it was later

discovered that this particular engine used copious amounts – averaging 10 gallons per day (gpd) – of engine oil, which is an order of magnitude greater than that of adjacent engines (similarly configured Waukesha 7044GSI models), having oil consumption rates of around 0.5 gpd. Poor engine condition and the related high oil consumption can be considered a significant factor influencing:

(i) engine-out CO:NOx ratio

(ii) degradation of HEGO sensors due to ash-masking of the sensor element

(iii) partial combustion of oil, resulting in additional CO emissions, which are independent of AFR control

(iv) catalyst poisoning of reactive/oxygen storage sites by Calcium, Phosphorus, Zinc, and Magnesium, which are all commonly used additives in engine oil

(v) catalyst degradation due to ash-masking which in effect reduces catalyst surface area

Catalyst elements were blown out at the beginning of every monitoring visit, with the exception of first and last visits, in order to clear the ash built-up on the catalyst elements (Figure 26).

Samples of ash collected from the catalyst elements were analyzed using X-ray Photoelectron Spectroscopy (at CSU's CIF in the Department of Chemistry) to understand the elemental composition of the powder. The results of this elemental analysis can be seen in Table 5 and Figure 27. The measured quantities of Calcium, Phosphorus, and Zinc – which are all additives in the engine oil used at this site – was further evidence that the high rate of oil consumption by this engine is responsible for the accelerated rate of catalyst degradation that

was observed. It is assumed that the oil consumption occurs by way of oil ingress into the combustion chamber, owing to poor sealing by the piston rings. However, an opportunity to verify this assumption did not present itself during the field test. The brand of oil used in this engine is Conoco El Mar Low Ash 40, manufactured by ConocoPhillips.

Figure 26: Catalyst elements being blown out with compressed air to clear ash-masking.

Table 5: Elemental composition of catalyst ash

Element	Oxygen	Calcium	Carbon	Phosphorus	Sulphur	Zinc
Weight (%)	37.09	31.68	15.97	5.64	2.36	1.15

Element	Copper	Iron	Aluminum	Silicon	Magnesium
Weight (%)	0.74	0.39	0.08	0.08	0.06

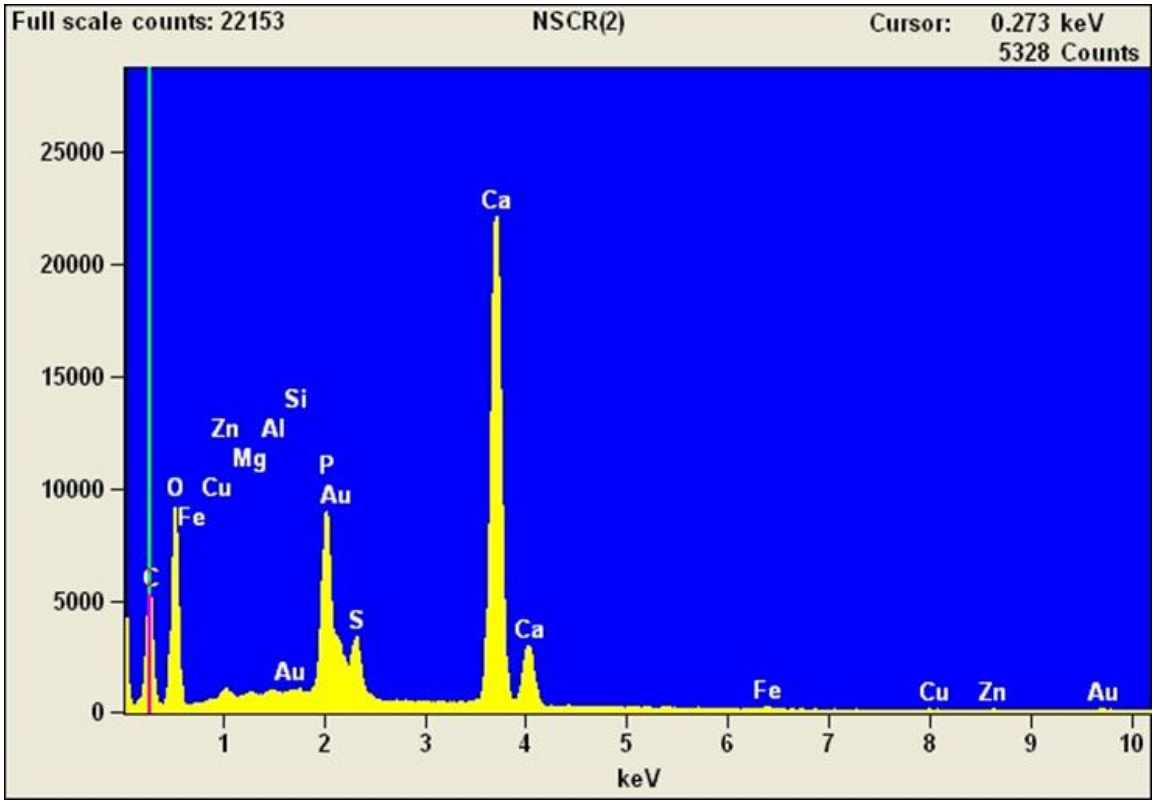

Figure 27: Spectrogram of elemental composition of catalyst ash.

The extent of ash-masking on the catalyst was characterized by correlating it to the pressure differential measured across catalyst elements, using pressure taps affixed to the catalyst housing (Figure 28).

Figure 28: Pre (right) and post (left) catalyst pressure taps affixed atop the catalyst housing.

During the first evaluation visit, conducted on February 27, one week after the E3RB's commissioning on February 20, the catalyst elements were not cleared with compressed air owing to a lack of awareness of the oil consumption issue and therefore, masking not yet being a point of concern. The rationale for foregoing compressed air cleaning of catalyst elements during the last evaluation visit, conducted on August 20, is two-fold:

(a) During prior update meetings (conference calls) with the project team, the method of employing compressed air to blow out catalyst elements was strongly criticized as a poor practice, having more detriments than benefits, when examined over the life of the catalyst.

(b) From the catalyst pressure differential trend in Figure 29, it can be seen that at the HS/HL operating condition, the rise in pressure between the penultimate data point on June 25 and the following one on August 20 was 0.6" of water. Also noting that between June 25 and August 20, the unit was offline for a period of ~3 weeks, from July 18 to August 9, it was decided that the amount of masking resulting in the observed pressure rise would likely not be sufficient to disrupt catalyst function and by extension, an increase in levels of post-catalyst emissions.

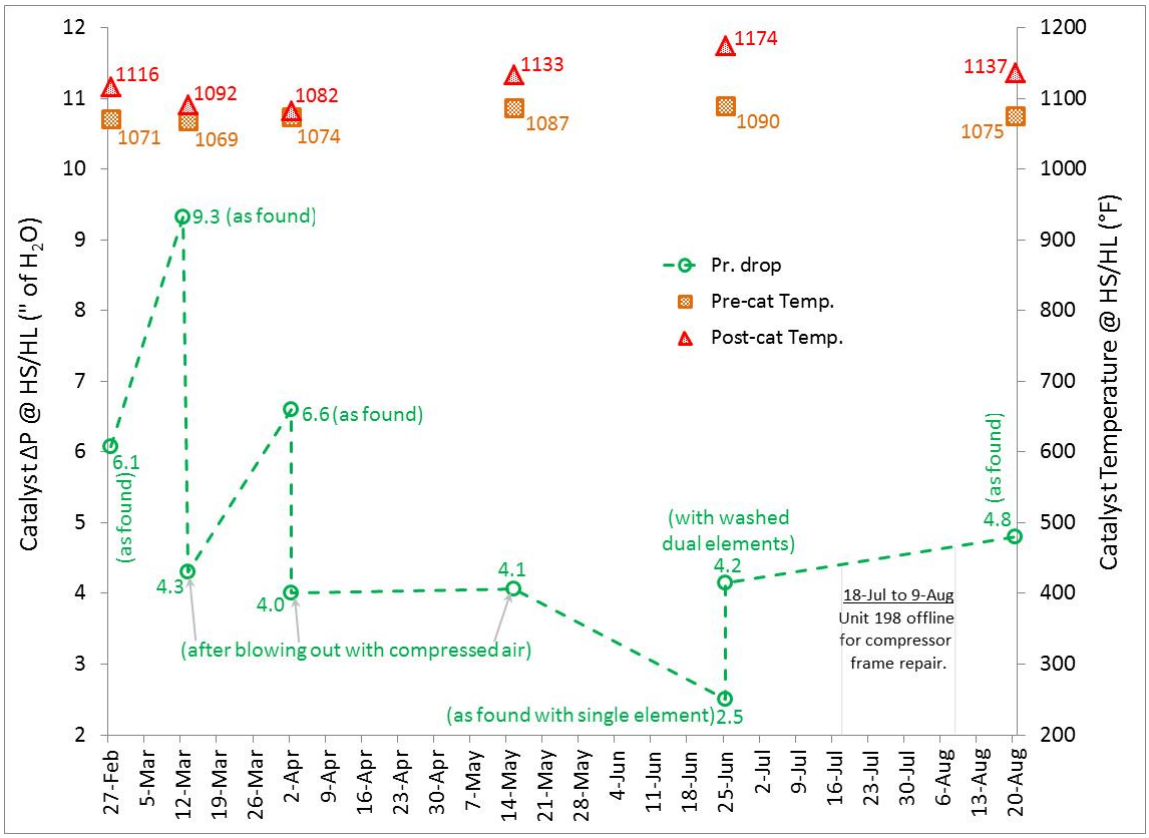

Figure 29: Trend of pressure drop and temperature across catalyst elements at HS/HL operation.

Therefore, the emissions test on August 20 was viewed as an opportunity to examine catalyst performance and emissions levels resulting from not blowing out the catalyst elements with compressed air.

3.4 Steady-State Performance

3.4.1 Engine Condition: High Speed/High Load (HS/HL)

Two key indicators used in this study to qualify the degree of AFR control exerted by the E3RB at the HS/HL condition are the pre and post-catalyst ratios of CO:NOx. In an ideal AFR control scenario, the first recorded pre and post-catalyst CO:NOx ratios serve as benchmarks from which subsequent ratios should exhibit minimal deviation. Therefore, any observed increase in post-catalyst emissions can be attributed to catalyst degradation and aging of sensor elements.

Referring to the lower trend in Figure 30 and using the pre-catalyst CO:NOx ratio of 1.56 from the first site visit on February 27 as a benchmark, during the two subsequent site visits (March 13, April 2), this ratio deviates -10% from the benchmark, which implies AFR has drifted toward lean operation. Beyond that, for the remaining duration of the test, the AFR drifts toward rich operation. A noticeable increase occurs after new HEGO sensors were installed on June 25. The upper trend in the same figure shows a ~24% increase in engine-out emissions of CO after the new HEGO sensors were installed. Comparing the post-catalyst CO:NOx in Figure 31 to the pre-catalyst CO:NOx in Figure 30, it is noticed that with the exception of the data point from August 20, the post-catalyst CO:NOx trend moves opposite to pre-catalyst CO:NOx. While this is contrary to expectations, a proposed explanation is provided later in this section. From the post-catalyst emissions trend in Figure 31, it can be seen that both CO and NOx emissions were within air permit limits for this site, during the first three site visits. CO emissions were found to exceed site air permit limits during the monitoring visit on May 15. This can be attributed to two factors, namely:

(i) poor engine condition that contributed to excessive oil consumption

(ii) excessive NOx margin used during initial tuning

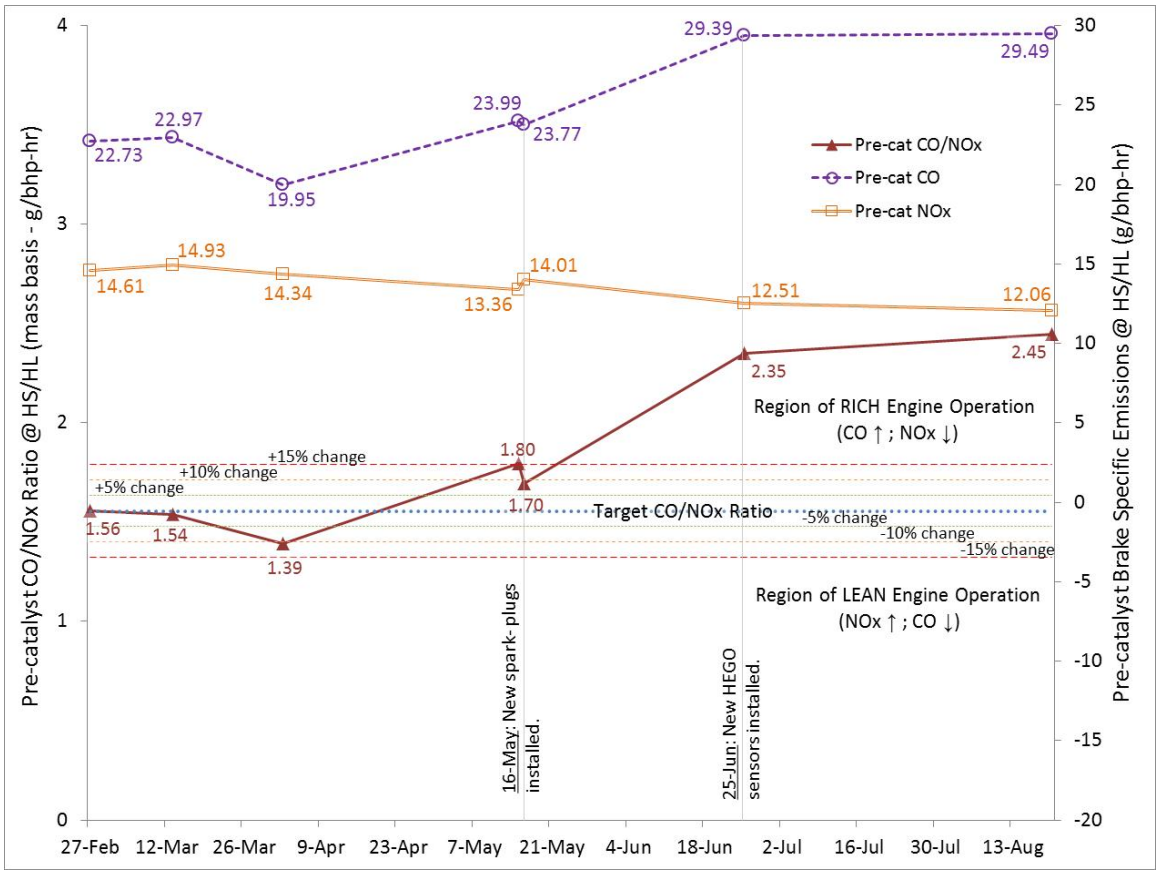

Figure 30: Trends of pre-catalyst emissions and CO:NOx @ HS/HL operation.

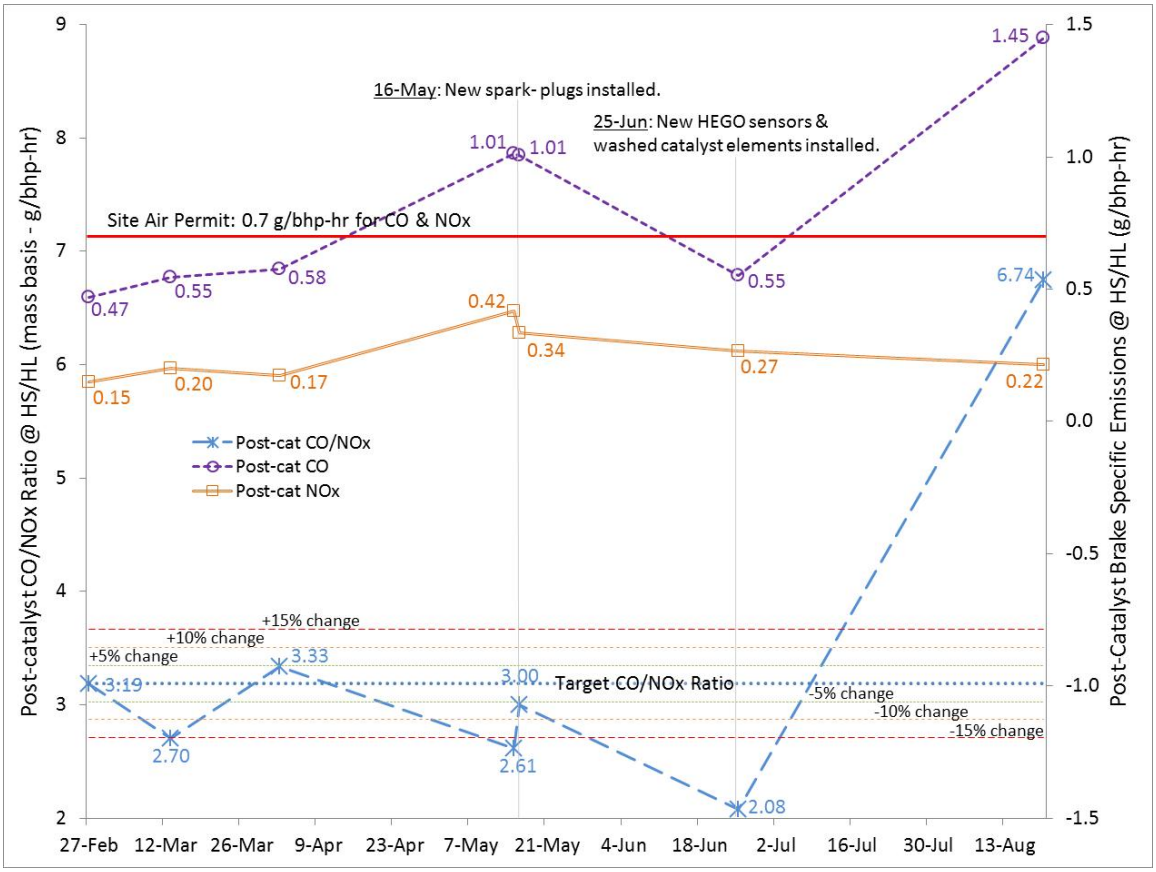

Figure 31: Trends of post-catalyst emissions and CO:NOx at HS/HL operation.

In order to eliminate low ignition energy and incomplete combustion as root causes for the rise in CO, new spark plugs were installed in the engine. After this was completed on May 16, another test was conducted to examine the effect of this change on emissions. Figure 31 shows a noticeable drop in NOx with CO unchanged. This is contrary to expectations because new spark plugs would create higher in-cylinder temperatures resulting from improved combustion. From combustion kinetic considerations, this would be expected to increase engine-out NOx while lowering CO. However, from Figure 32, it can be seen that installation of new spark plugs generated lower in-cylinder temperatures during engine operation (temperatures for cylinders 10-12 were not recorded by the SCADA system). This trend provides a rationale for

the observed increase in NOx emissions (ie. lower in-cylinder temperatures). However, the root cause behind it is still not understood. The old spark plugs removed from the engine did not exhibit any traces of fouling and spark plug gaps were not recorded.

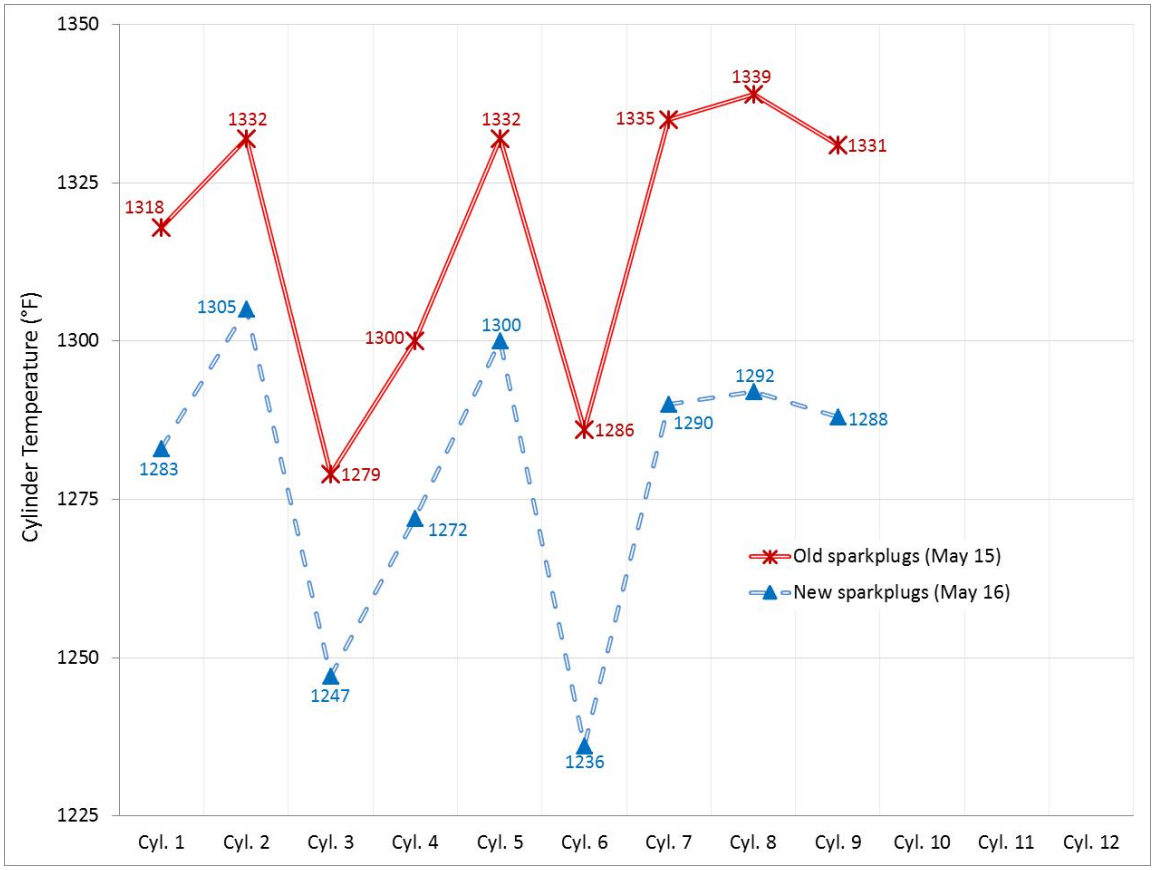

Figure 32: Comparison of in-cylinder temperatures before/after spark plug change.

Since new spark plugs did not resolve the high CO emissions, it was surmised that ash-masking of sensor elements on the HEGOs was feeding improper input signals to the AFR controller. Therefore, on the next monitoring visit, new HEGO sensors were installed on the E3RB. The combination of new HEGO sensors and freshly washed catalyst elements resulted in bringing CO emissions back in compliance during the monitoring visit on June 25.

During the last monitoring visit on August 20, CO emissions were found to be out of compliance, despite a reduction in the NOx emissions level. The resulting post-catalyst CO:NOx represented a 112% increase from the benchmark of 3.19, established on February 27.

The catalyst efficiency trends for reduction of CO and NOx are shown in Figure 33. The trend for CO reduction efficiency is unremarkable until May 16. The decline in CO reduction efficiency during the period between June 25 and August 20 is steeper than during the period from February 27 to May 16. Keeping in mind that (i) ash on the catalyst elements was not cleared with compressed air on February 27 and August 20 (ii) the compressor station was offline for a period of 3 weeks, starting July 18 and ending August 9, the drastic reduction in CO conversion efficiency cannot be explained with the data at hand. For the monitoring visit in May, analyzing the efficiency of NOx reduction in conjunction with pre and post-catalyst NOx trends from Figure 30 and Figure 31 (respectively) shows that after the new spark plugs were installed, there was a very apparent increase in pre-catalyst NOx emissions and mild decrease in CO emissions. Accompanying this increase in engine-out NOx was a corresponding increase in NOx reduction efficiency, while that of CO remained almost constant. This increase in catalyst efficiency for NOx reduction is explained in the discussion linked to Table 6.

Another interesting catalyst efficiency behavior occurs when NOx reduction efficiency increases during the periods of March 13 – April 2 and June 25 – August 20 while CO reduction efficiency declines over the same period. This observation is explained in the context of dominant NSCR reactions that occur in the catalyst.

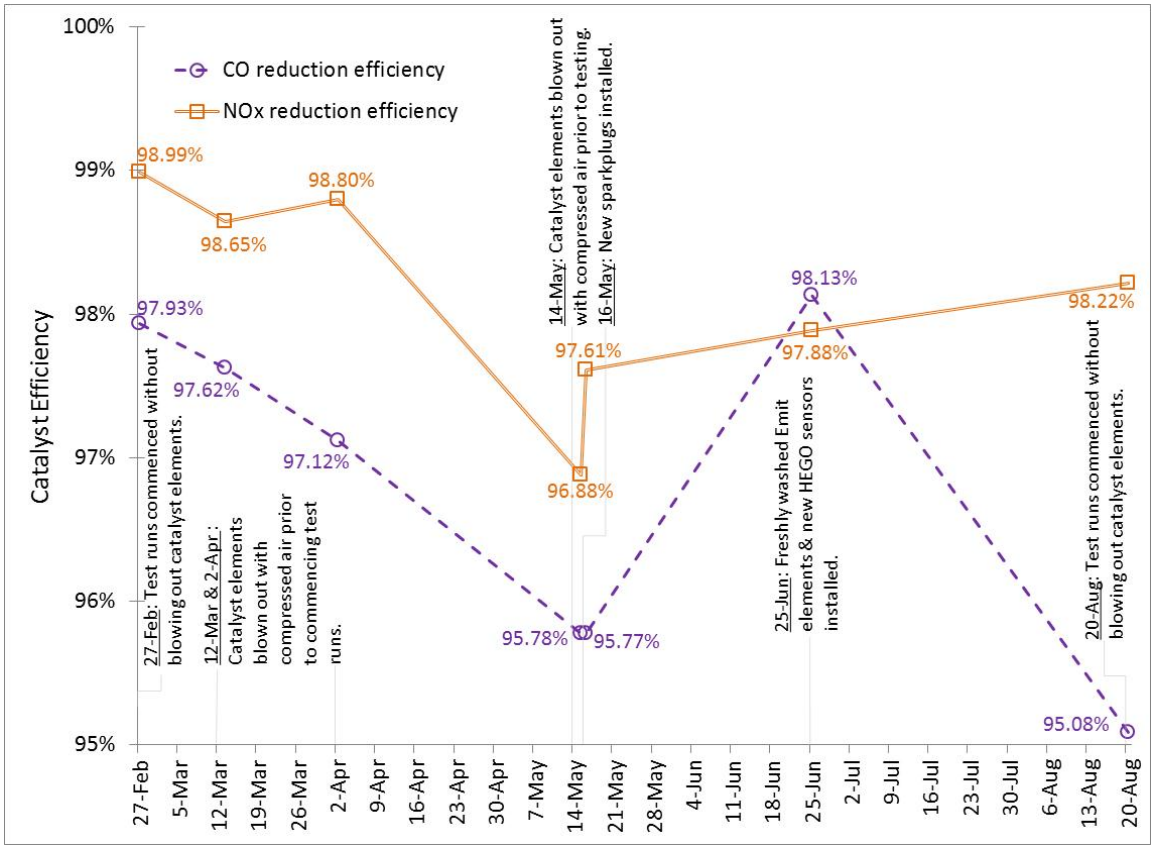

Figure 33: Catalyst efficiency @ HS/HL operation.

Table 6 summarizes the observed trends in various parameters, over the duration of the study; the direction of the arrows indicates the relative movement of a particular trend with respect to the prior recorded value. $(CO:NOx)_{pre}$ and $(CO:NOx)_{post}$ respectively represent the relative motions of pre and post-catalyst CO:NOx ratios; η_{CO} and η_{NOx} respectively represent the relative motion of catalyst reduction efficiencies for CO and NOx. Equations (a) and (b) are two key reactions that occur in an NSCR catalyst for CO oxidation and NO reduction, respectively. The values tabulated in the last column, titled 'NSCR Rxn.', are hypotheses as to which of the two NSCR reactions dominated during the monitoring run under consideration.

$$CO + \tfrac{1}{2} O_2 \rightarrow CO_2 \qquad \ldots\ldots. (a)$$

$$NO + CO \rightarrow \tfrac{1}{2} N_2 + CO_2 \qquad \ldots\ldots \text{(b)}$$

Of particular interest are the behaviors from April 2, May 16, and August 20, each of which exhibit increases in NOx reduction efficiency, running counter to the expected degradation trend, similar to that displayed by CO reduction efficiency. A possible explanation for this observation is provided below.

Table 6: Summary of emissions trends @ HS/HL operation

	$(CO:NOx)_{pre}$	$(CO:NOx)_{post}$	η_{CO}	η_{NOx}	NSCR Rxn.
Feb 27	Baseline				----
Mar 13	↔	↓	↓	↓	(a) / (b)
Apr 2	↓	↑	↓	↑	(b)
May 15	↑	↓	↓	↓	(a) / (b)
May 16	↓	↑	↓	↑	(b)
Jun 25	↑	↓	↑	↑	(a) / (b)
Aug 20	↑	↑	↓	↑	(b)

On April 2, $(CO:NOx)_{pre}$ decreases, owing to a drop in engine-out CO, whereas $(CO:NOx)_{post}$ rises; also η_{CO} decreases while η_{NOx} increases. The drop in η_{CO} can be attributed to minimal stored oxygen in the catalyst (brought about by ash-masking of oxidation storage sites) whereas the increase in η_{NOx} is assumed to be due to the dominance of NSCR reaction (b), which takes advantage of the excess CO in the exhaust gas stream that was not oxidized. A similar

trend is noticed on May 16 and the hypothesis extended is the same as that proposed for April 2. On August 20, with the exception of a reversal in $(CO:NOx)_{pre}$, the trends are identical to those on April 2 and May 16.

An examination of four E3RB parameters, namely PID Bias and pre-catalyst HEGO signals for each bank (Figure 34), reveals noticeable changes in both PID bias and HEGO setpoints upon installation of the new HEGO sensors on June 25. An abrupt increase in engine-out CO emissions (AFR control shifting rich) is observed once the new setpoints and biases take effect and can likely be correlated to the richer engine operation that commences on June 25. An increase in engine oil consumption did not occur during this time period so, it can be ruled out as a cause for higher CO emissions.

This case demonstrates that if the HEGO sensors are replaced after system commissioning, the E3RB will require retuning in order to continue maintaining optimal AFR control; this is particularly relevant at sites where emission limit margins are tight. Retuning may not be necessary at sites where margins are looser.

It is worth noting that during the period between February 27 and May 15, engine-out CO emissions trend similar to the left bank PID bias, while the right bank PID bias remains stable. There are no conclusions to be drawn from this observed similarity.

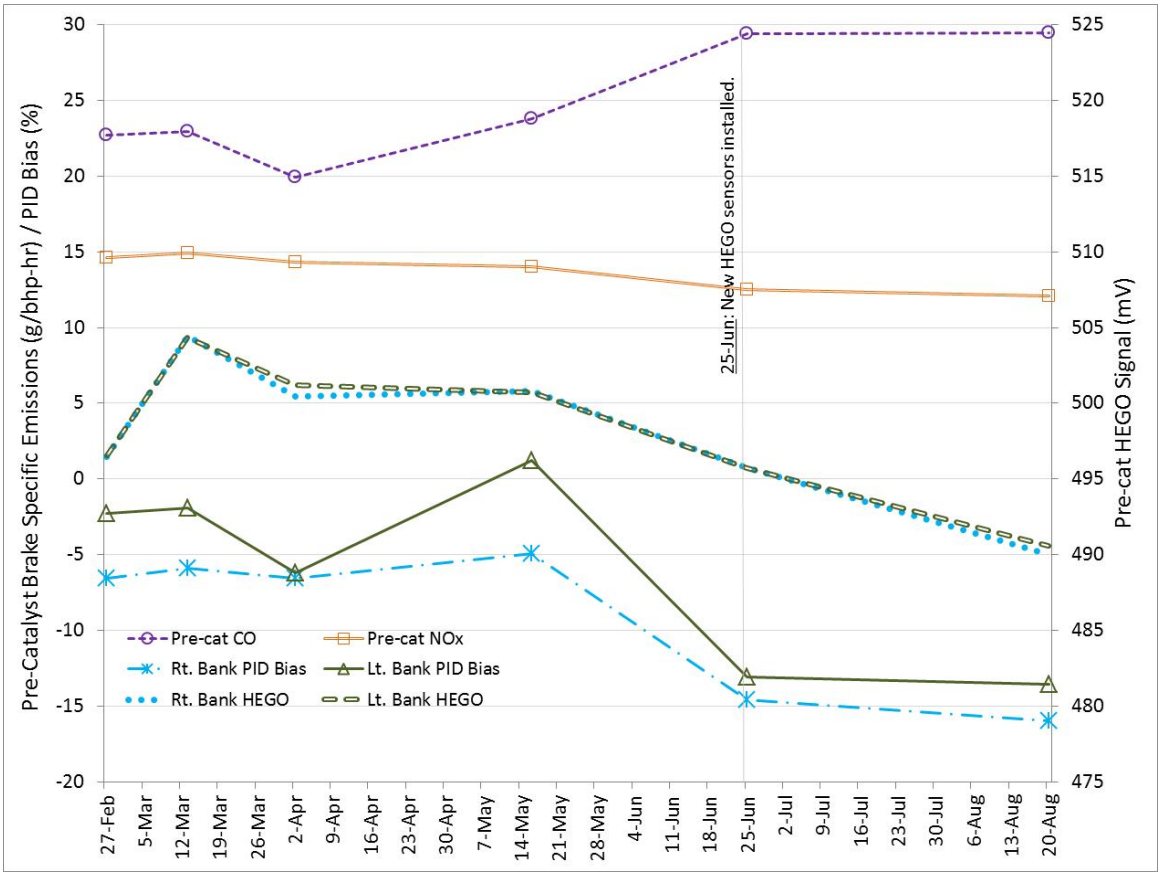

Figure 34: Trends of E3RB parameters and pre-catalyst emissions @ HS/HL operation.

An alternate method to depict the change in AFR operation is with a NOx-CO crossplot, with NOx on the x-axis and CO on the y-axis. When analyzed in conjunction with a CO:NOx trend, these crossplots can be used to characterize the relative contributions of CO and NOx in an exhaust mixture that is either rich or lean.

Figure 35 shows the variation in pre-catalyst CO and NOx at HS/HL operation. From this crossplot, it can be noted that starting from the first data point on February 27, the AFR control initially trended slightly lean in March and April, followed by successively richer operation in May, June and August. Similarly, Figure 36 shows the variation in post-catalyst CO and NOx at HS/HL operation, with an alternating pattern of rich-lean post-catalyst conditions, starting from

February and settling in a rich region at the final data point in August. Other parameters recorded during engine operation at HS/HL are shown in Figure 37. As expected, it can be seen that manifold air temperatures and throttle position follow the ambient air temperature trace. Throttle position data for May 15 and August 20 was unavailable owing to a sensor fault in the PLC. With the exception of April 2, manifold air pressures maintain at 5 psig ± 0.3psig.

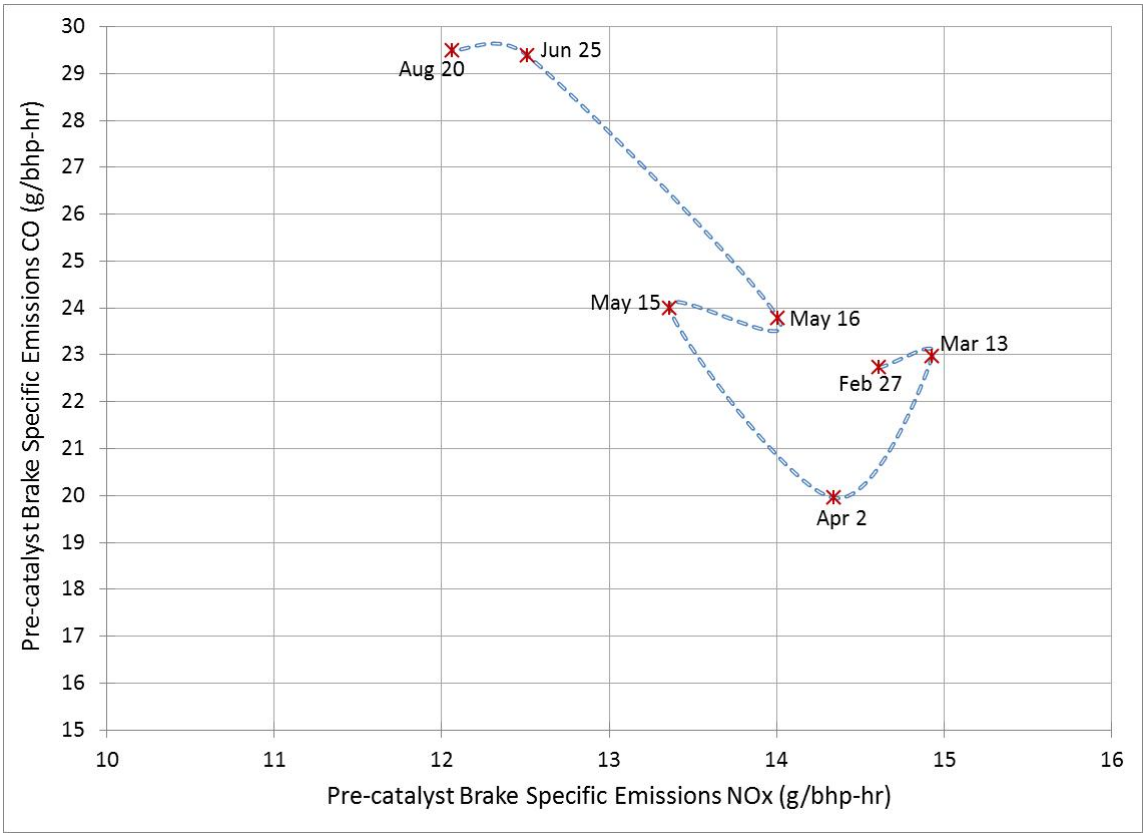

Figure 35: Pre-catalyst NOx-CO crossplot @ HS/HL operation.

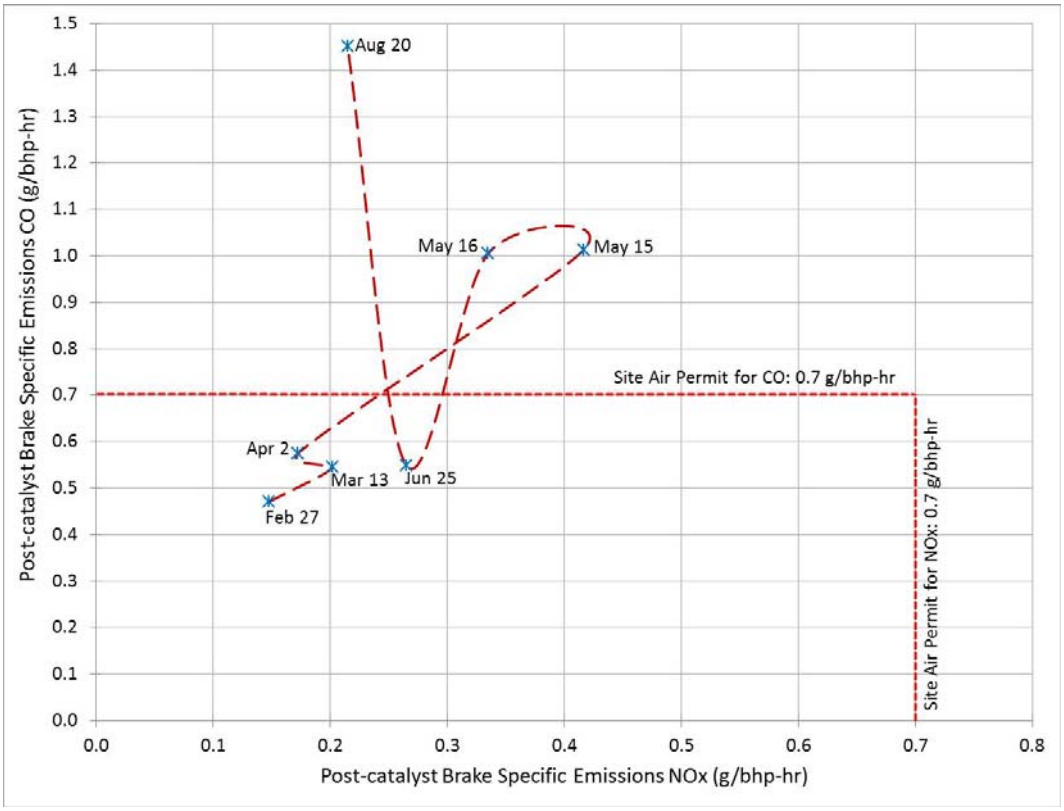

Figure 36: Post-catalyst NOx-CO crossplot @ HS/HL operation.

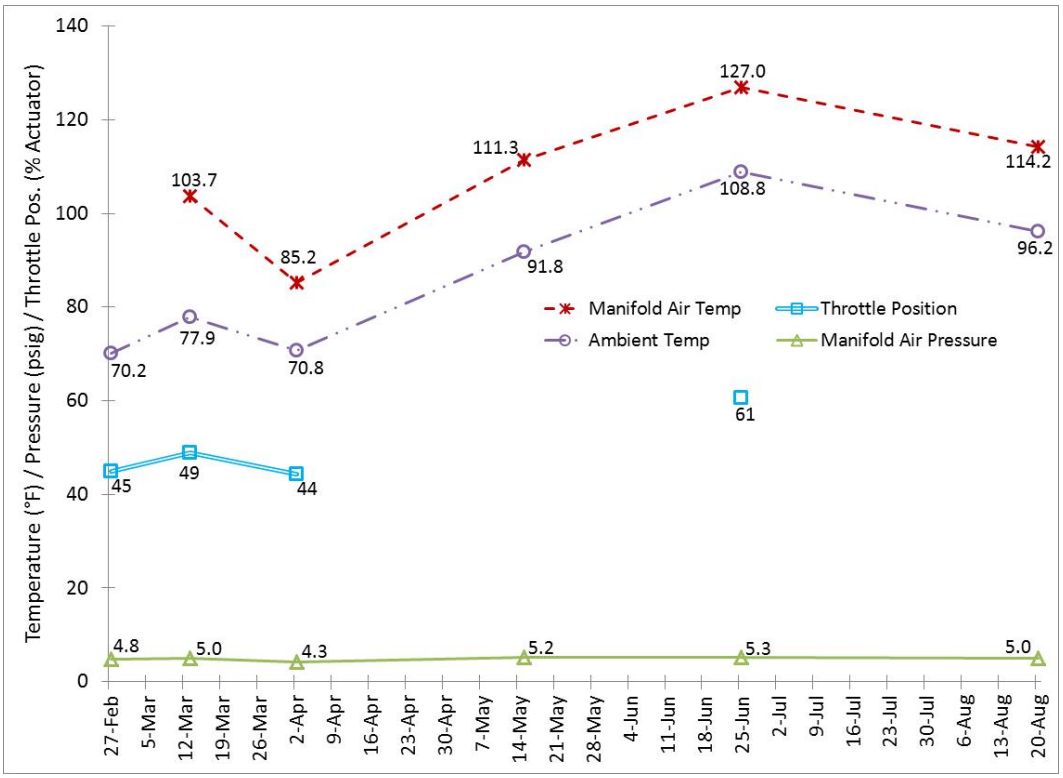

Figure 37: Trends of other engine parameters and ambient temperature @ HS/HL operation.

3.4.2 Engine Condition: Medium Speed/Medium Load (MS/ML)

This section discusses trends in emissions and AFR control at MS/ML operation (Speed: 1000 RPM, Qmix: 1700 scfm). The trend for pressure drop across catalyst elements can be seen in Figure 38. It should be noted that since the ash on catalyst elements was not blown out on February 27 and August 20, the pressure drop recorded on those days is noticeably higher than during the remainder of the monitoring visits.

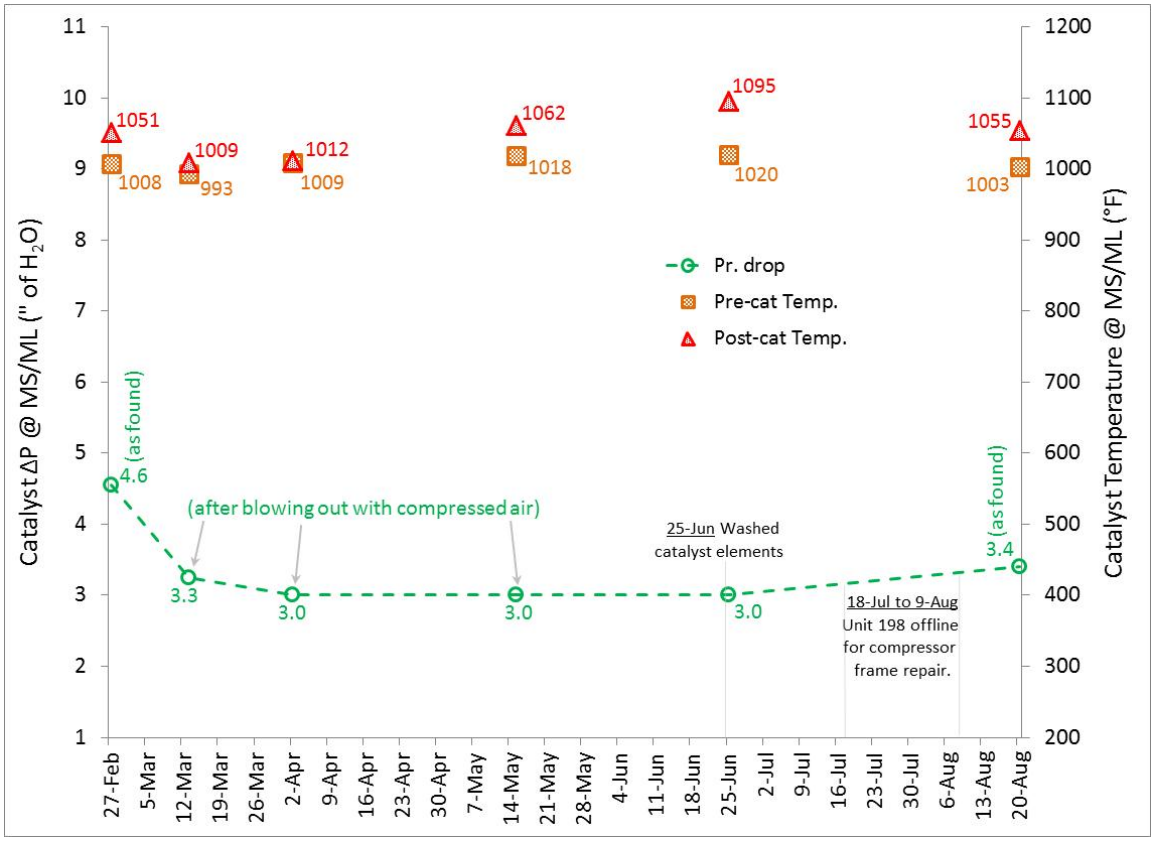

Figure 38: Trend of pressure drop and temperature across catalyst elements at MS/ML operation.

During MS/ML operation, only post-catalyst emissions data was recorded. Therefore, movement of CO:NOx on the post-catalyst side cannot be correlated to engine-out CO:NOx. However, from examining Figure 39 and Figure 40, the following observations can be made:

(a) During the first four site visits (February 27 – May 15), the engine emissions were within site air quality limits. It should be recalled that the nominal operating condition, defined for purposes of regulatory emissions compliance, is HS/HL.

(b) The benchmark post-catalyst CO:NOx ratio of 2.16, recorded on February 27, is in line with expectations. CO:NOx trend recorded during the three subsequent visits is also within acceptable limits, showing a good CO margin.

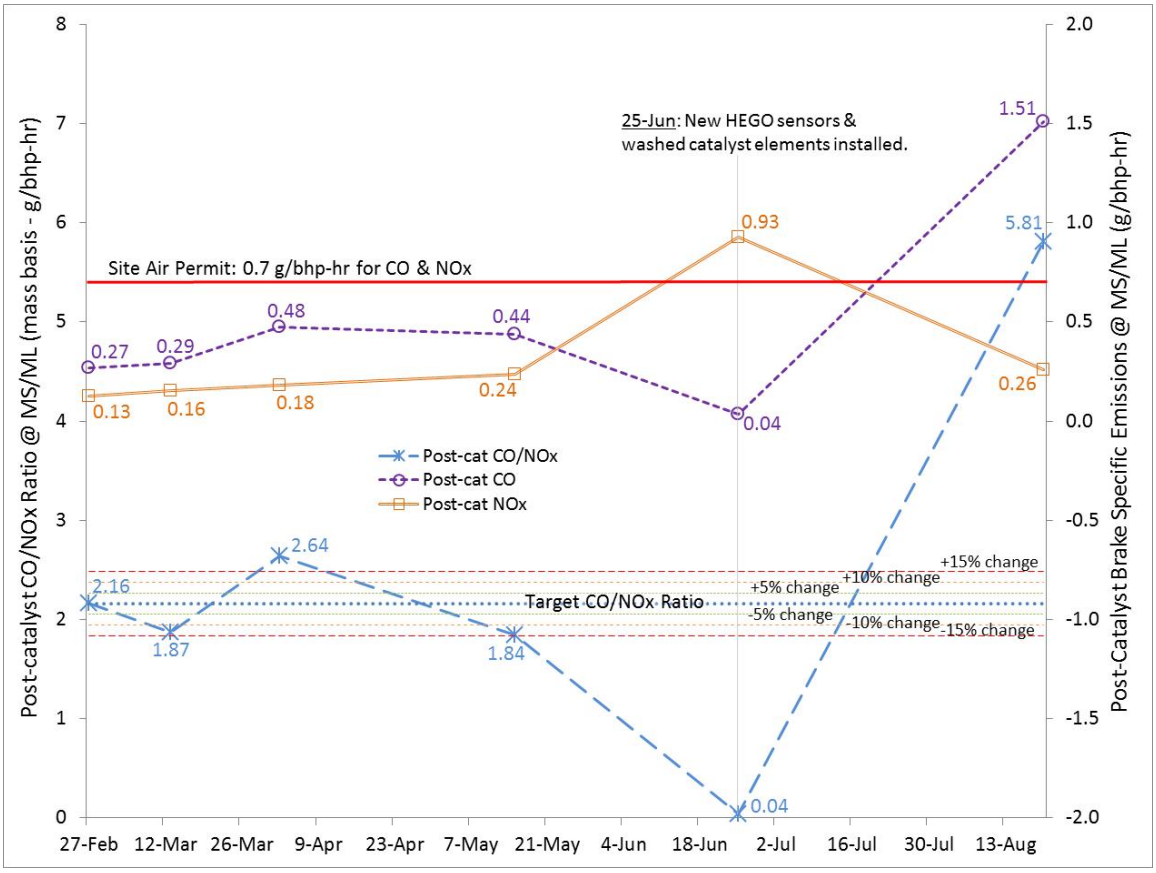

Figure 39: Trends of post-catalyst emissions and CO:NOx at MS/ML operation.

(c) On June 25, after new HEGO sensors were installed, a cross-over occurs between CO and NOx emissions. Assuming that a similar reversal occurred with pre-catalyst engine-out emissions, it would imply that the engine AFR moved toward stoichiometry, causing the

spike in NOx and drop in CO. This change in AFR can be attributed to E3RB control, as evidenced by the sharp declines in both PID bias and HEGO values.

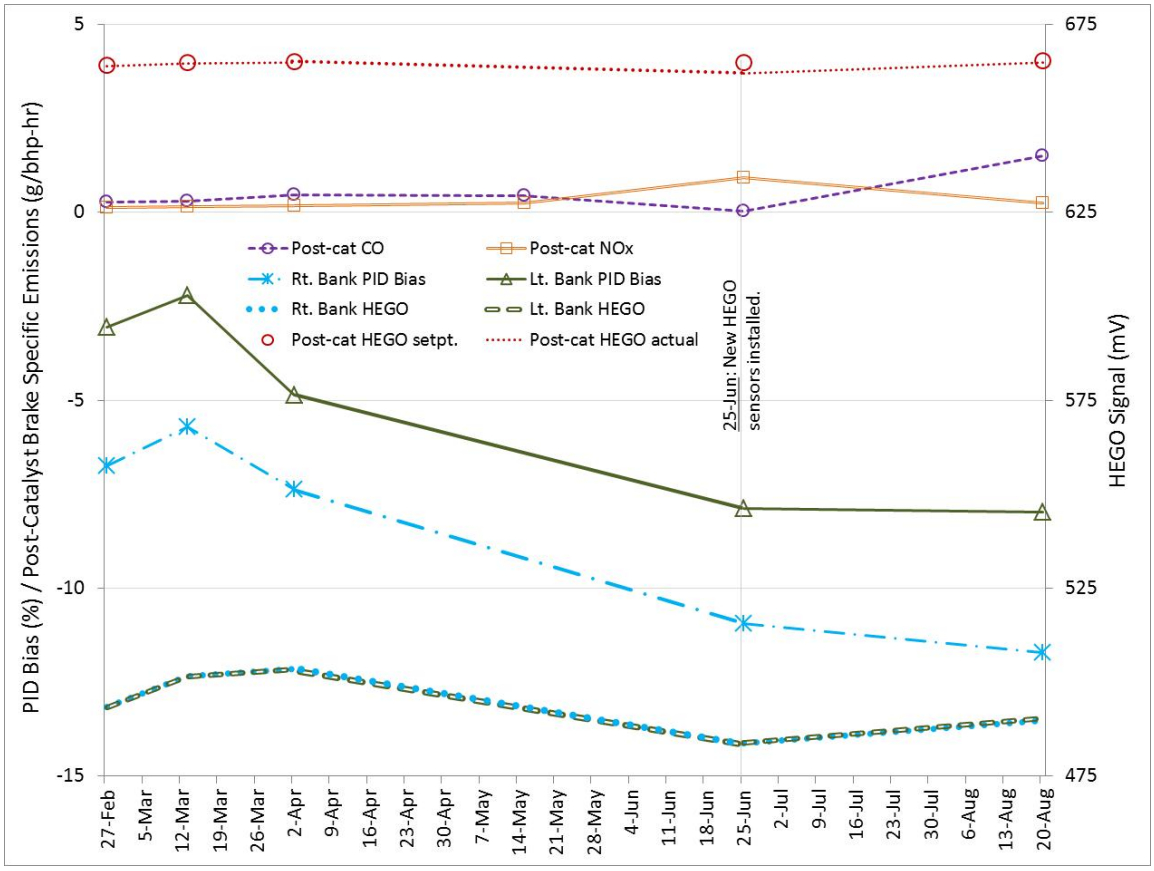

Figure 40: Trends of E3RB parameters and post-catalyst emissions @ MS/ML operation.

(d) On August 20, another emissions cross-over occurs, this time with a rise in CO and dip in NOx, indicating that the AFR has migrated to a rich region. This migration is likely related to the rise in recorded values of the HEGO signal for each bank. The role of catalyst degradation, while undocumented, should not be discounted as a contributing factor in poor CO reduction.

The NOx–CO crossplot in Figure 41 provides further insight about the AFR control deviation that occurred after the HEGO sensor change on June 25. On August 20, the control is

operating in a region that creates NOx emissions in the same neighborhood as on May 15 but with CO emissions several times higher. During the period from February 27 to May 15, the controller maintains good AFR control, as evidenced by the tight grouping of data points from this period.

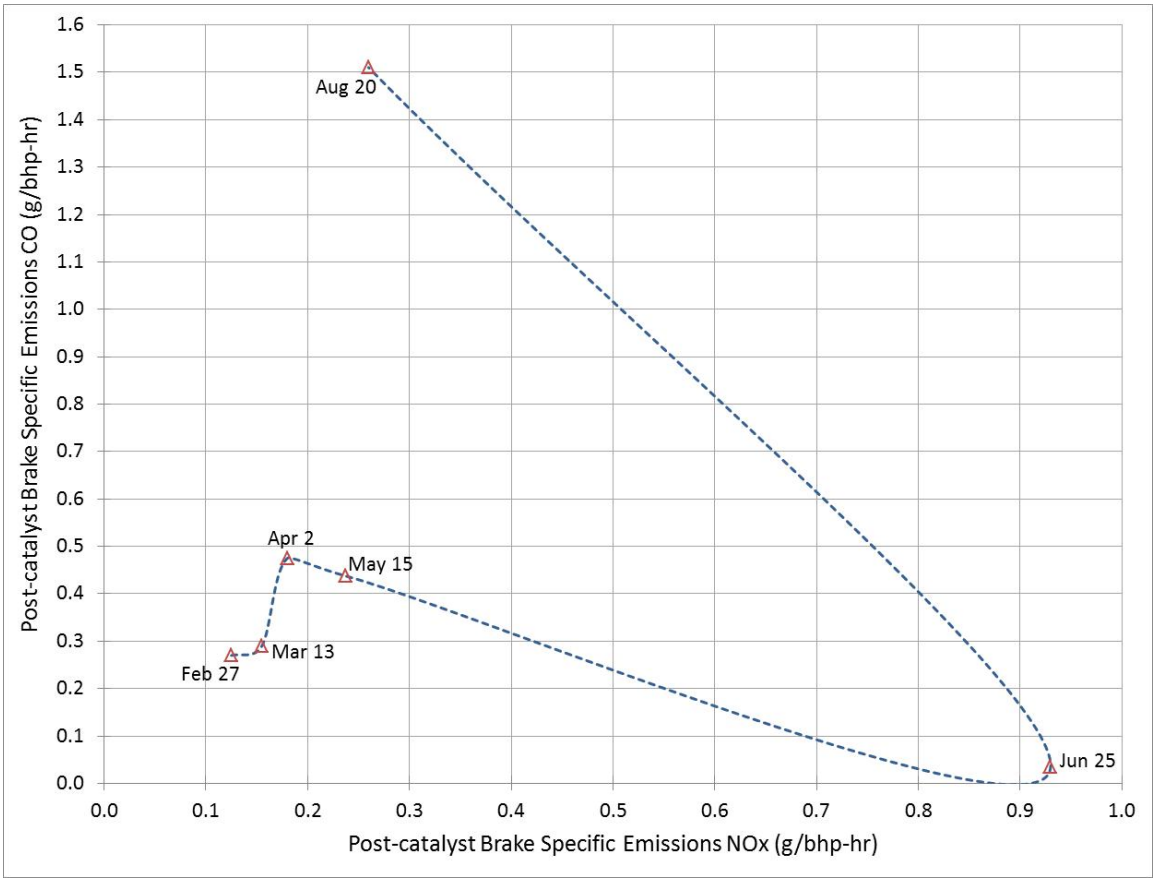

Figure 41: Post-catalyst NOx-CO crossplot @ MS/ML operation.

3.4.3 Engine Condition: Low Speed/Low Load (LS/LL)

This section discusses trends in emissions and AFR control at LS/LL operation (Speed: 850 RPM, Qmix: 1400 scfm). The trend for pressure drop across catalyst elements can be seen in Figure 42. It should be noted that since the ash on catalyst elements was not blown out on

February 27 and August 20, the pressure differential recorded on those days is noticeably higher than during the remainder of the monitoring visits.

During LS/LL operation, only post-catalyst emissions data was recorded. Therefore, movement of CO:NOx on the post-catalyst side cannot be correlated to engine-out CO:NOx. However, from examining Figure 43 and Figure 44, the following observations can be noted:

(a) During the first three site visits (February 27 – April 2), the engine emissions were within site air quality limits. It should be recalled that the nominal operating condition, defined for purposes of regulatory emissions compliance, is HS/HL.

(b) The benchmark post-catalyst CO:NOx ratio of 2.09, recorded on February 27, is in keeping with the recommended value of 2:1. CO:NOx trend during the two subsequent visits is also within acceptable limits.

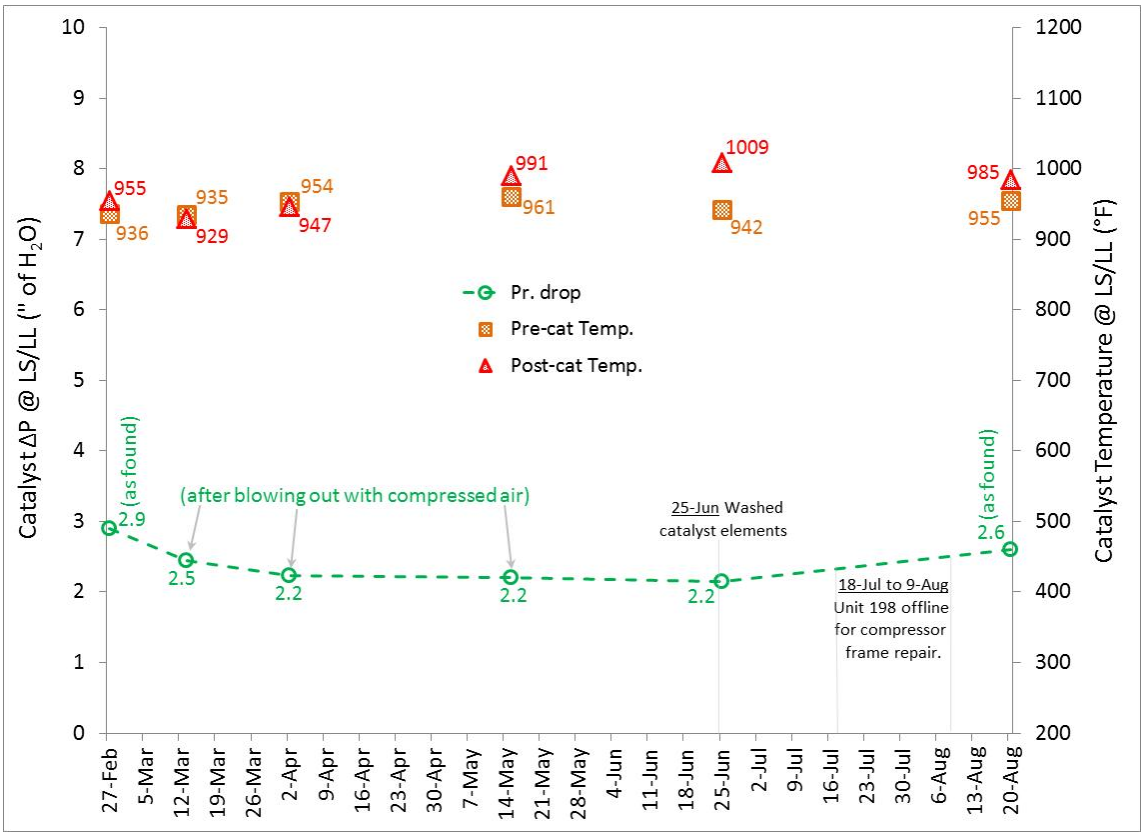

Figure 42: Trend of pressure drop and temperature across catalyst elements at LS/LL operation.

(c) On May 15, CO emissions increase beyond the site's air permit limit.

(d) On June 25, after new HEGO sensors were installed, a drastic spike in both CO and NOx emissions is observed, with levels of both species showing non-compliance with the existing air permit. Correlating this to the change in post-catalyst HEGO value, which is a significant drop from the post-catalyst HEGO setpoint, it indicates that the engine AFR migrated very rich, causing the observed increases in both CO and NOx.

(e) On August 20, the emissions are found to have decreased; however, CO is still above the air permit limit while NOx is now within the acceptable range. At this time, the engine AFR likely moved leaner than where it was on June 25, settling in what would be considered an AFR rich region. The post-catalyst HEGO value is seen to rejoin the setpoint to which it is controlled.

The NOx–CO crossplot in Figure 45 provides further insight about the AFR control behavior (migration to a very rich region) that occurred after the HEGO sensors were changed on June 25. Compared with this, on August 20, the control is seen to operate in a leaner region. During the period from February 27 to May 15, the controller maintains good AFR control, as evidenced by the tight grouping of data points from this period.

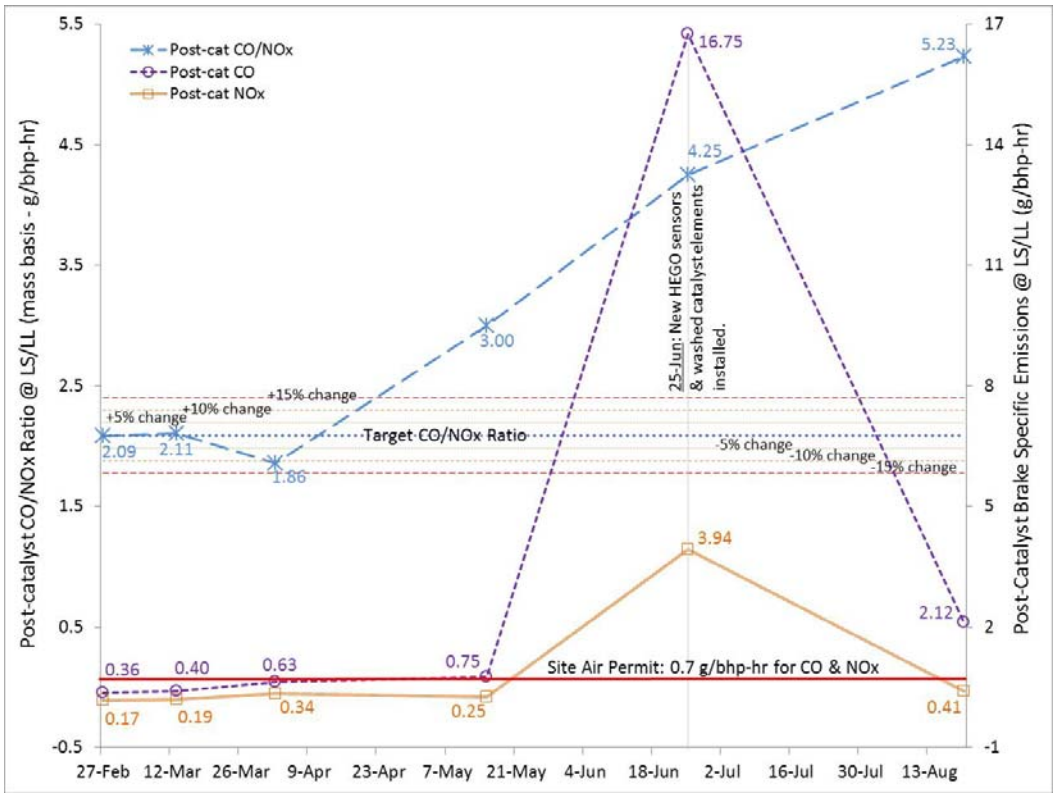

Figure 43: Trends of post-catalyst emissions and CO:NOx at LS/LL operation.

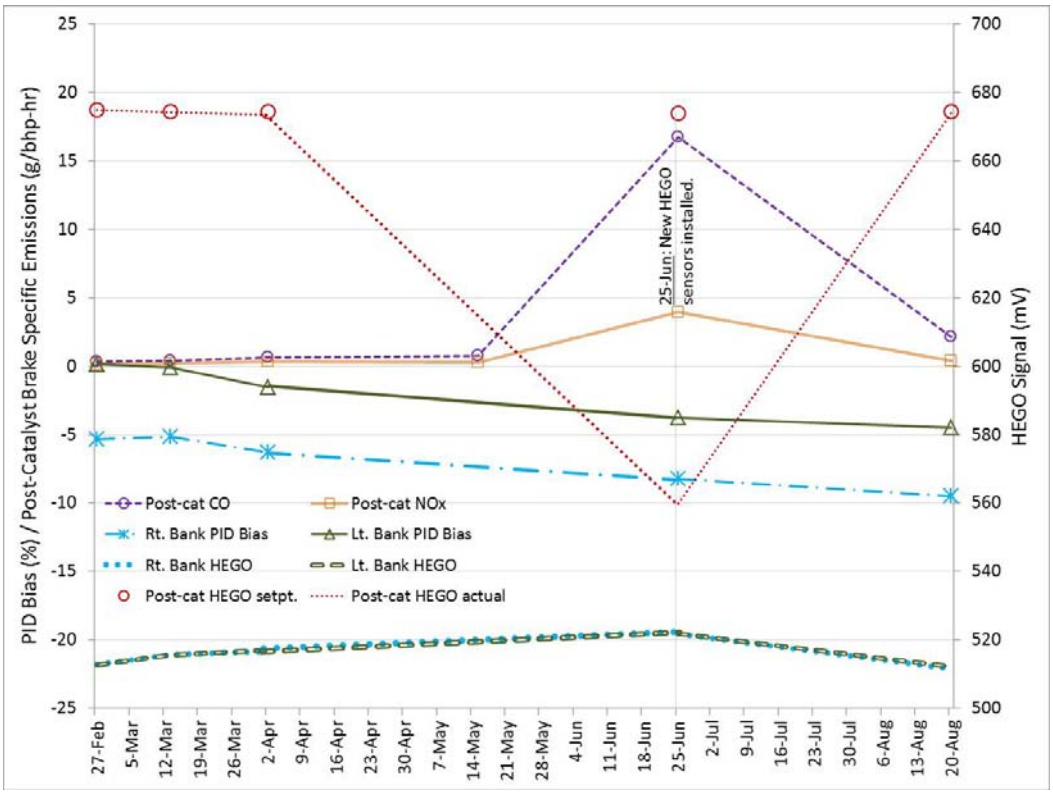

Figure 44: Trends of E3RB parameters and post-catalyst emissions @ LS/LL operation.

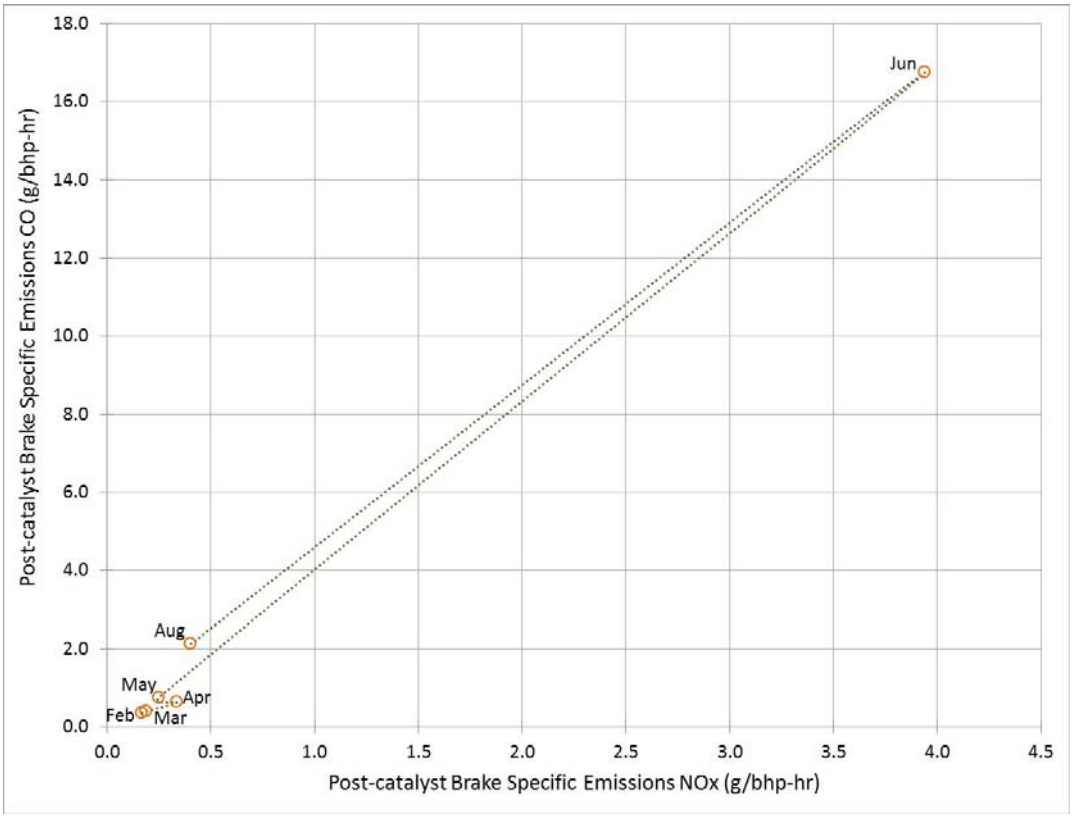

Figure 45: Post-catalyst NOx-CO crossplot @ LS/LL operation.

3.5 Retuned Performance

Upon completion of the 6 month evaluation test, the E3RB was retuned using data from an equivalence ratio (ϕ) sweep that was conducted to determine optimal settings for the post-catalyst setpoint @ HS/HL operation. The results of this ϕ sweep are shown in Figure 46, Figure 47, Figure 48, and Figure 49. A change in ϕ was simulated by altering the post-catalyst HEGO sensor setpoint; this accounts for the independent axis on all the above-mentioned figures being labeled as Post-catalyst HEGO setpoint. Based on the air quality permit limits assigned for this site, the NSCR control window at HS/HL operation was determined to lie between 618 mV for NOx (lower limit) and 646 mV for CO (upper limit).

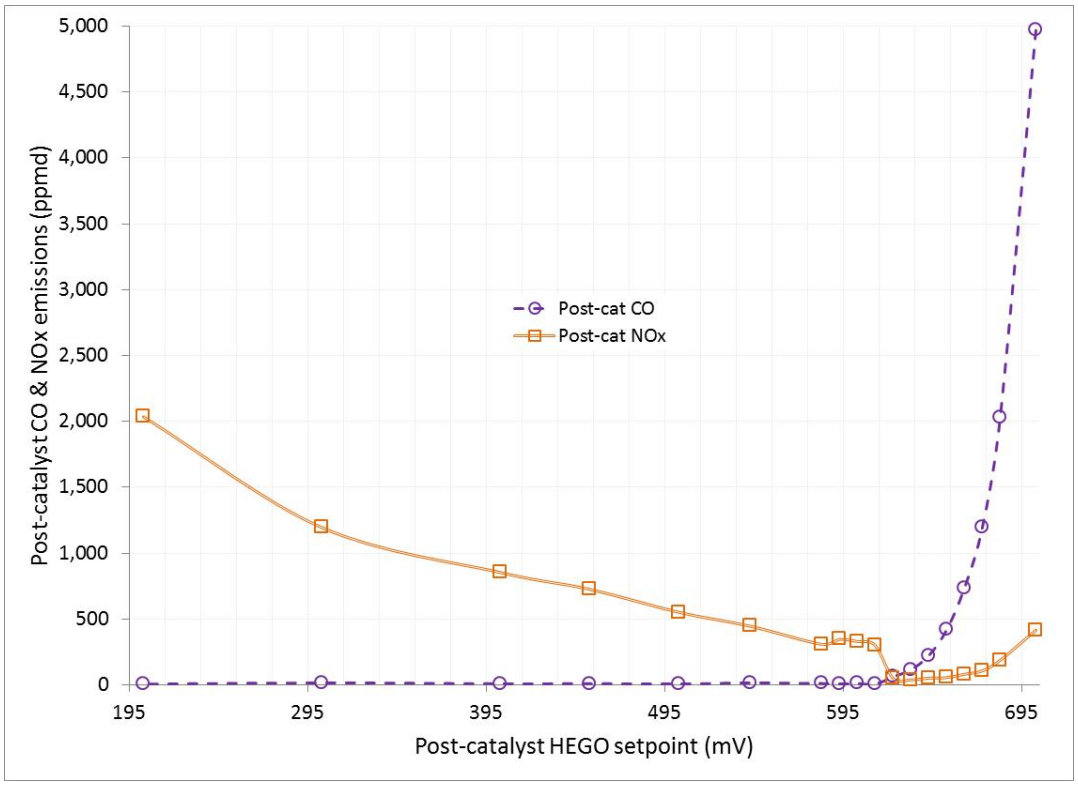

Figure 46: (Coarse scale) Simulated ϕ sweep vs. post-catalyst emissions.

Therefore, the nominal value for the setpoint was readjusted to be 633 mV, which is the midpoint between the upper and lower limits. When operating between these setpoint limits at HS/HL, the corresponding range of expected catalyst efficiencies are 95% ↔ 99% for NOx and 97.6% ↔ 99.7% for CO.

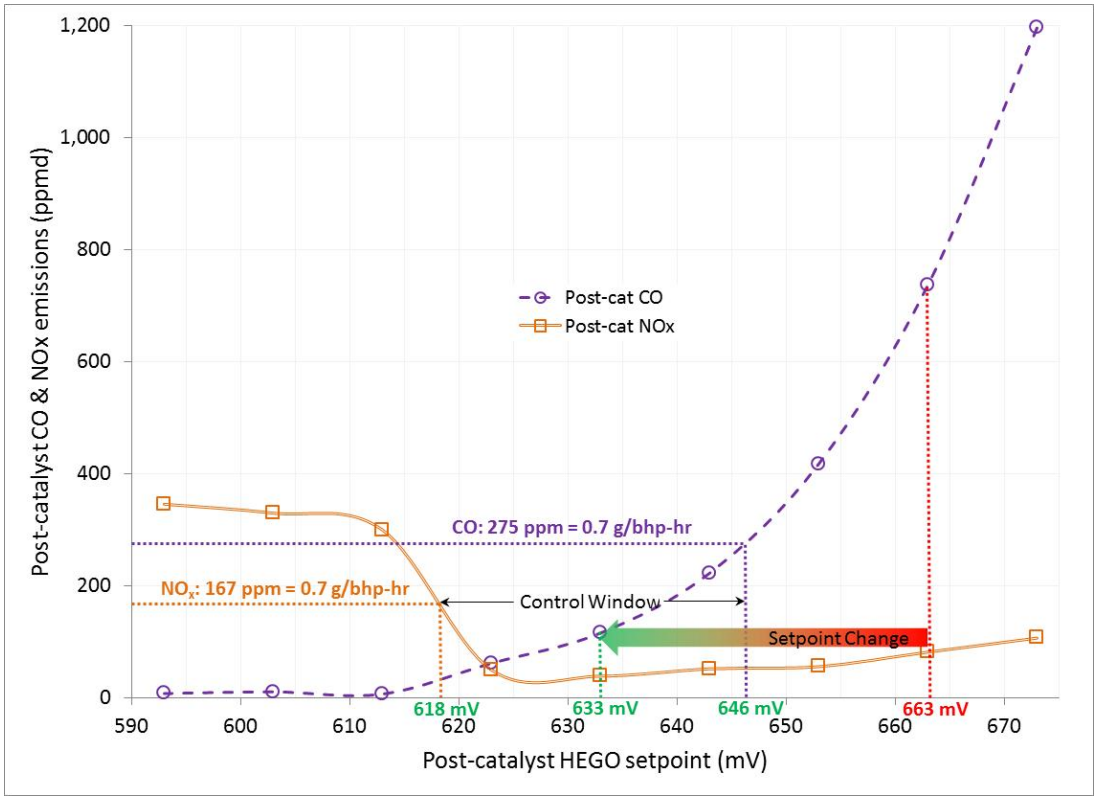

Figure 47: (Fine scale) Simulated ϕ sweep vs. post-catalyst emissions.

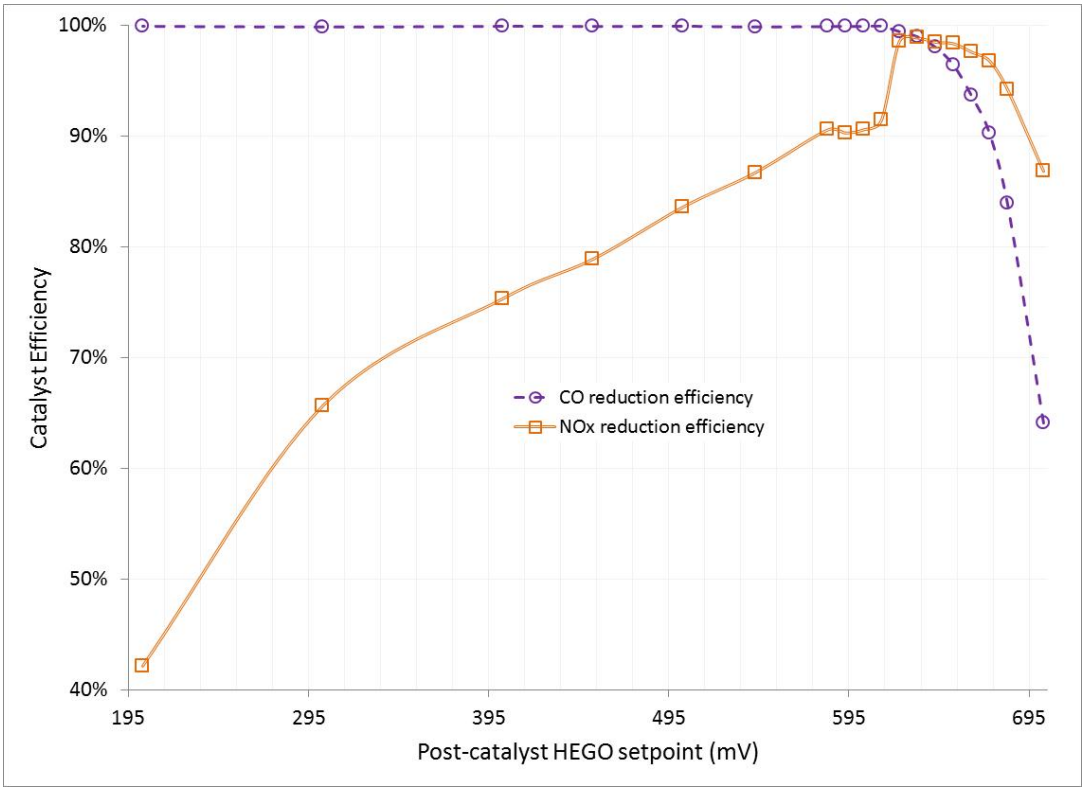

Figure 48: (Coarse scale) Simulated ϕ sweep versus catalyst efficiency.

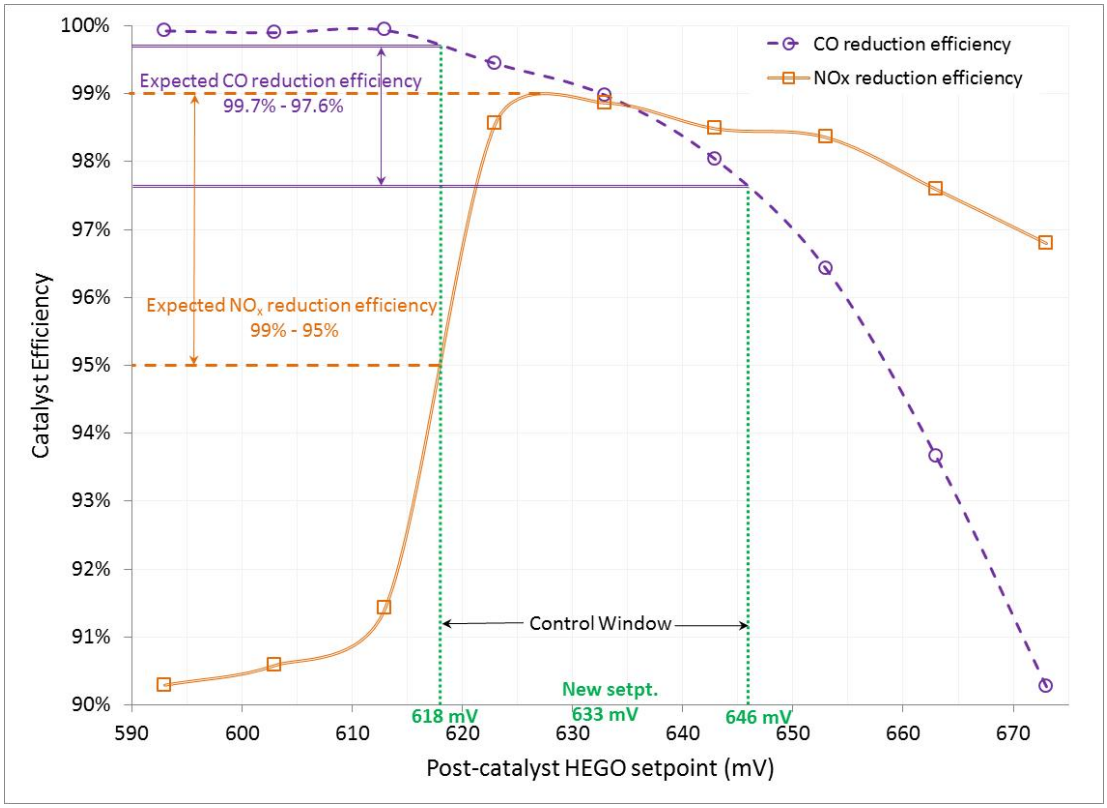

Figure 49: (Fine scale) Simulated ϕ sweep vs. catalyst efficiency.

Using a comparable percentage reduction, post-catalyst HEGO setpoints at MS/ML and LS/LL operation were similarly adjusted. Further fine-tuning was conducted at the HS/HL condition to determine optimal settings for dither frequency/amplitude as well as AFR setpoints (pre-catalyst HEGO setpoints). Upon completion of tuning, emission measurements were recorded at each engine operating condition so as to document any emissions performance enhancements created by this new E3RB settings.

An unexpected plateau in post-catalyst NOx emissions and corresponding reduction efficiency is noticed during the ϕ sweep, occurring between post-catalyst HEGO setpoints between 585 mV and 615 mV. When examining the pre-catalyst emissions trend during the ϕ sweep (Figure 50), it can be seen that between 195 mV & 545 mV, the engine moves toward

richer operation, which is expected as the post-catalyst signal transitions from low mV to high mV. Beginning at 545 mV and lasting until 595 mV, it is observed that the engine unexpectedly begins a lean excursion, as evidenced by the spike in NOx and dip in CO emissions; increasing this signal beyond 595 mV, the engine backtracks to rich operation. When contrasting this engine-out emissions trace against the corresponding post-catalyst emissions, the lean excursion that occurs between 545 mV - 595 mV does not appear to register on the post-catalyst trace. However, when analyzing catalyst efficiency for this same range of post-catalyst HEGO setpoint, the plateau in the NOx trend can be attributed to the lean excursion, which clearly disrupts the expected smooth increase in catalyst efficiency between 545 mV & 645 mV.

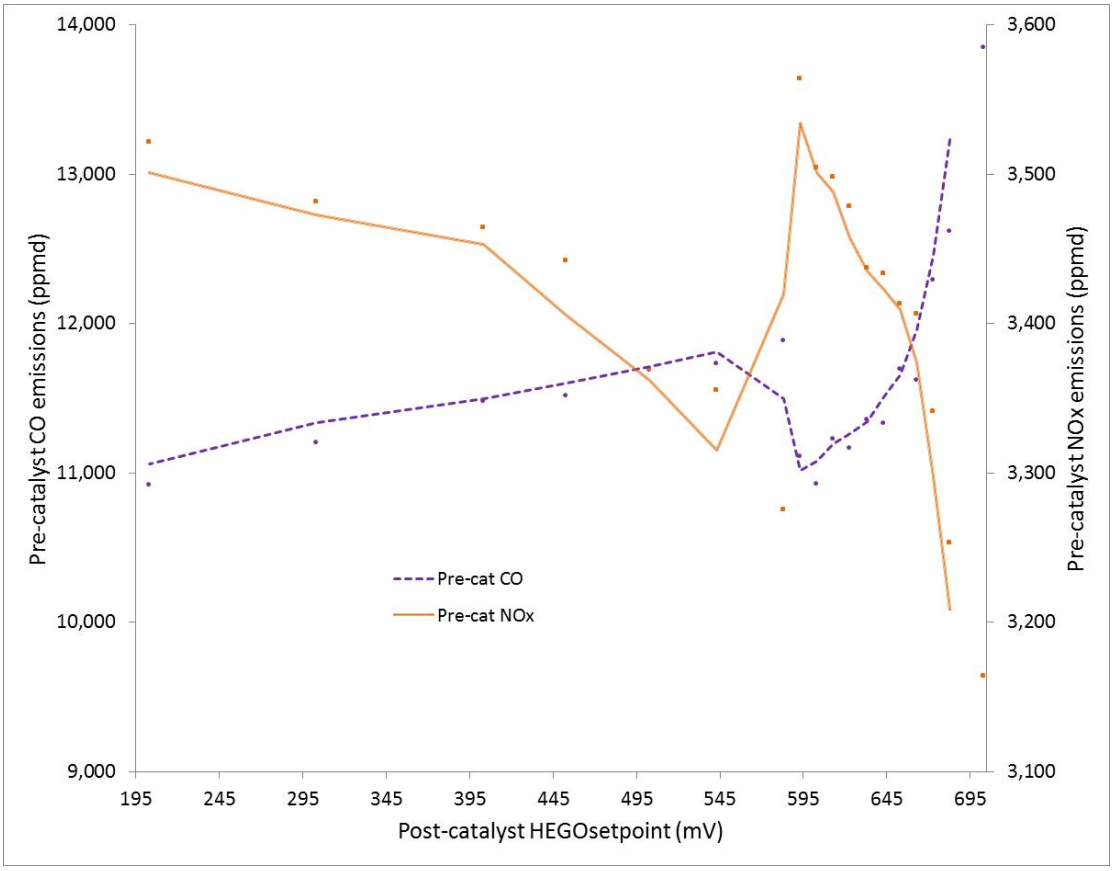

Figure 50: Simulated ϕ sweep vs. pre-catalyst emissions.

A possible explanation for this unexpected behavior is offered as follows:

Since the data was not recorded simultaneously (only one analyzer was used), an anomaly might have occurred during the pre-catalyst data segment that was not observed during the corresponding post-catalyst segment. An example of such an anomaly would be a temporary increase in oil leakage into the combustion chamber: since the O_2 sensors used to assess ϕ have varied responses to different fuels owing to the change in H/C and O/C ratios, and given that oil is a very different fuel than natural gas, during excessive oil leakage, the engine-out emissions will change but the O_2 sensor response will not reflect the appropriate ϕ value.

The emissions trend after retuning at HS/HL operation is seen in Figure 51. The post-catalyst CO:NOx ratio was readjusted to an acceptable value of 2.5, having respective CO and NOx contributions of 0.38 g/bhp-hr and 0.13 g/bhp-hr.

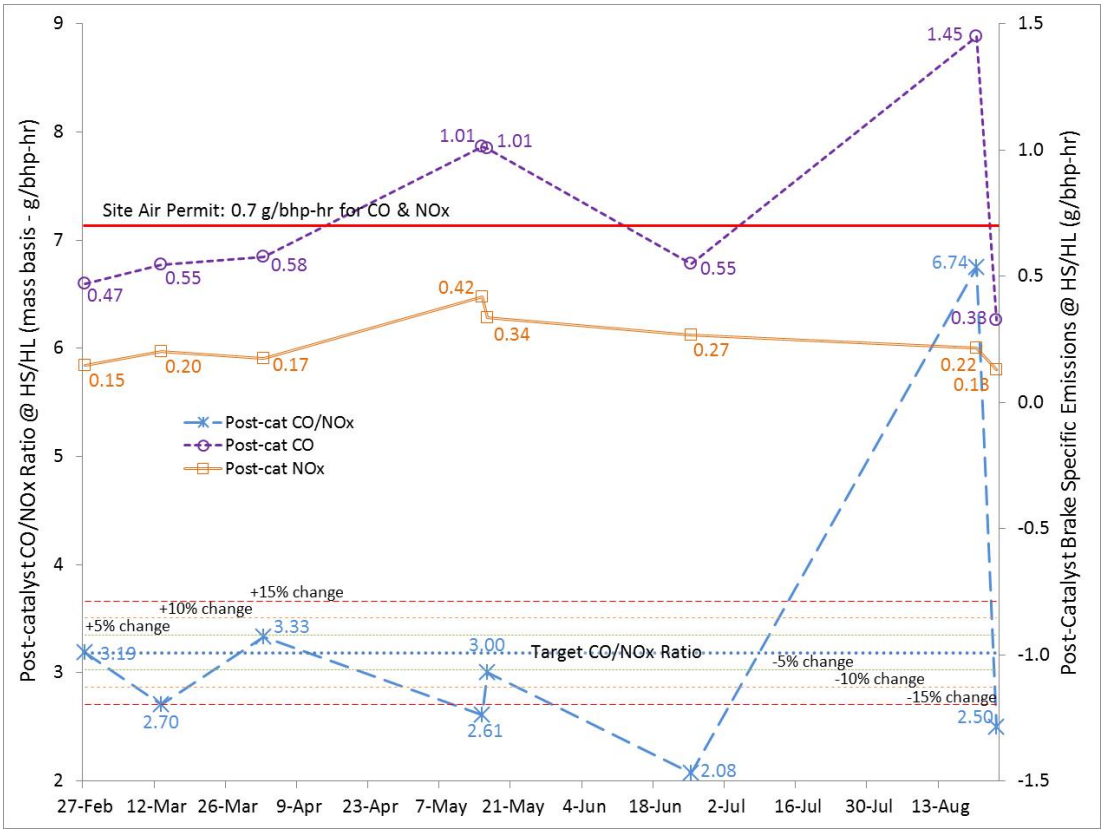

Figure 51: (New tuning) Trends of post-catalyst emissions and CO:NOx at HS/HL operation.

The emissions trend after retuning at MS/ML operation is shown in Figure 52. The post-catalyst CO:NOx ratio was readjusted to a value of 3.33, having respective CO and NOx contributions of 0.40 g/bhp-hr and 0.12 g/bhp-hr. While this is not an optimal CO:NOx ratio, it should be noted that time constraints prevented a ϕ sweep from being conducted to determine optimal controller settings at this operating condition. However, since emissions were within air permit limits for the site, performance was ascribed as satisfactory.

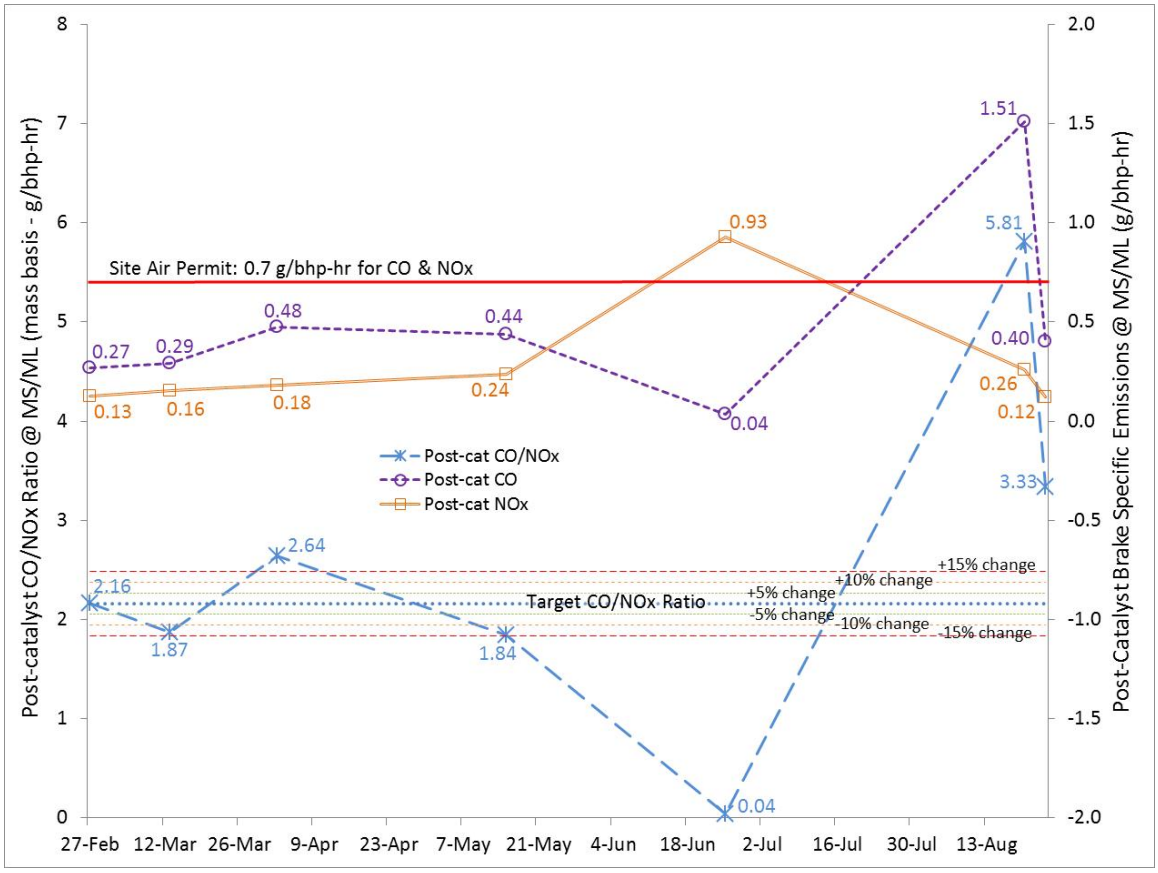

Figure 52: (New tuning) Trends of post-catalyst emissions and CO:NOx at MS/ML operation.

At the LS/LL condition, a cross-over occurred between CO and NOx emissions, indicating an AFR migration toward stoichiometry. This can also be deduced from the CO:NOx, in Figure 53, which plummeted to a value of 0.01, indicating an excess of NOx in the post-

catalyst exhaust gas stream. Despite the overage in NOx emissions (1.32 g/bhp-hr), E3RB settings were not optimized because it was concluded that the engine would likely never be used at this load point over the course of regular operations. A few attempts at minor adjustments in setpoints and PID biases showed the controller to be very sensitive at this load point; in one instance a change in post-catalyst HEGO setpoint of 1 mV created a cross-over scenario in which CO was over the limit and NOx, under.

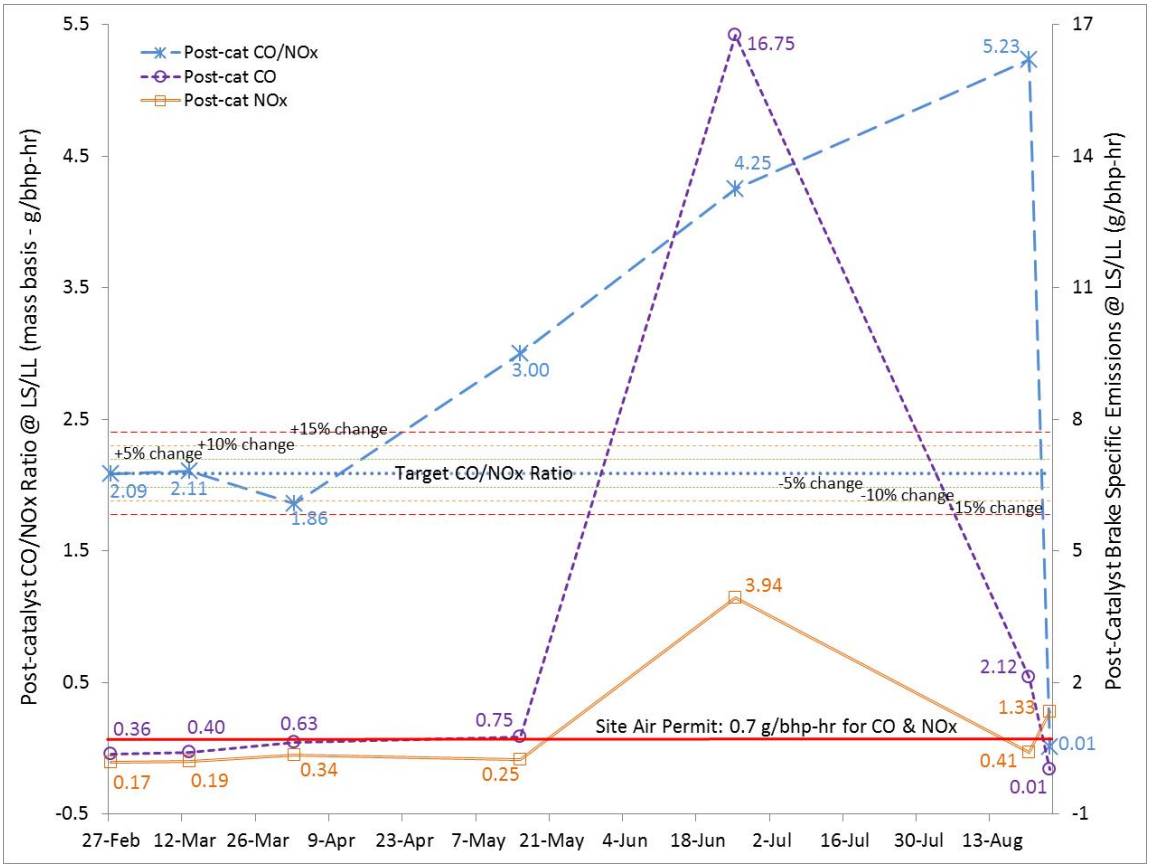

Figure 53: (New tuning) Trends of post-catalyst emissions and CO:NOx at LS/LL operation.

3.6 Fuel Gas Composition

In order to investigate the effect of variation in fuel gas composition on engine performance and related emissions output, a portable gas chromatograph was deployed at the site

from May 15 to May 16, during which time fuel gas composition was monitored for a period of 16 hours; Figure 54 shows the fuel gas composition recorded over a 12-hour subset of this same period. Methane composition in the fuel is seen to be stable, varying between 82 – 85 mole %, while CO_2 and Propane vary between 3.5 – 4% and 2.5 – 3 mole%, respectively. Ethane was not identified in the chromatogram owing to a peak-shift. The post-catalyst NOx emissions for the same time period, recorded via SCADA as 15-minute averages, can be seen to fluctuate from 15 – 85 ppm. NOx data for hours 1.5 – 5.5 were recorded as negative values and are not plotted in the figure.

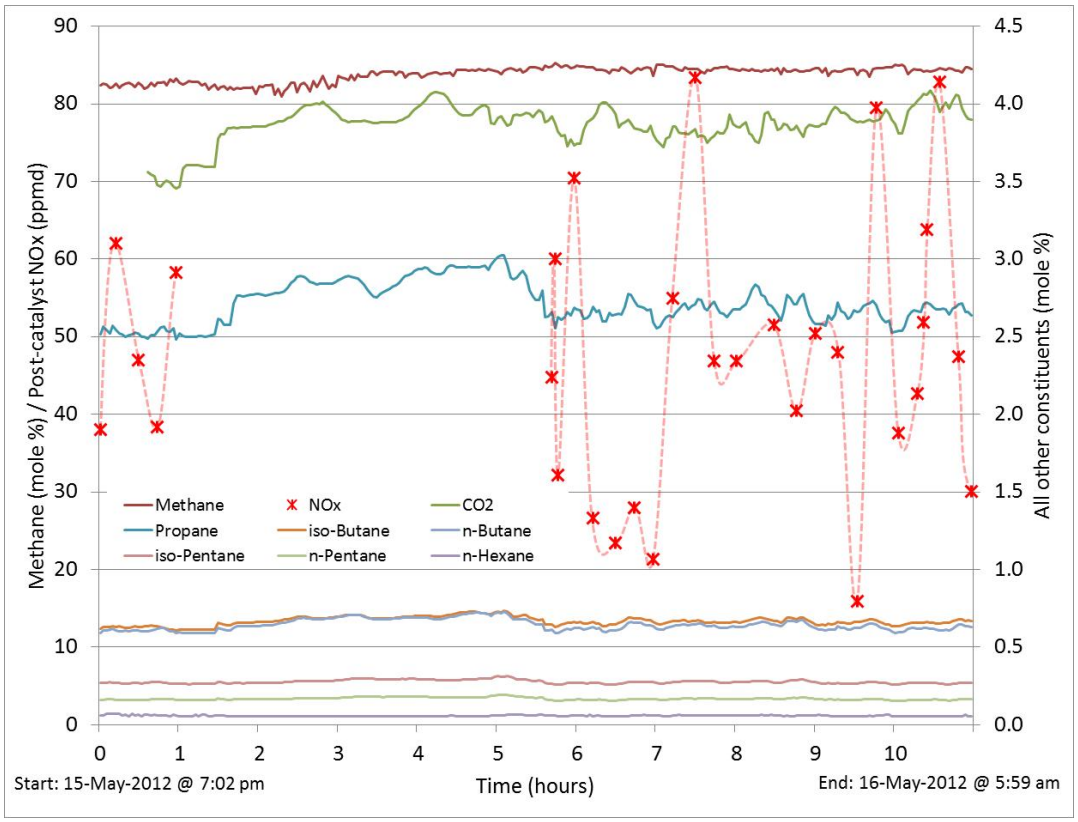

Figure 54: 12-hour trend of fuel gas composition and NOx emissions.

Based on the trends in Figure 54, the following conclusions can be made:

(i) Fuel gas composition at this site was stable during the monitoring period.

(ii) Variations in NOx emissions that occurred during this period are unrelated to fuel gas composition.

3.7 Diurnal Cycle

A 24-hour evaluation of E3RB operation was conducted from June 26th to 27th, encompassing one full diurnal cycle. During this time, engine emissions were monitored at speed/load settings determined by field operators; average engine speed was 1140 RPM and average load (as represented by the total inducted charge into the engine) was 2150 scfm. From an earlier section, it can be recalled that the 'Total Inducted Charge' is a parameter used by the E3RB controller (referred as Qmix) to ascertain the operational load point of an engine. From Figure 55, NOx emissions are seen to vary between 0.22 – 0.34 g/bhp-hr over the period of interest, while CO emissions range between 0.54 – 0.79 g/bhp-hr. From the CO:NOx trend, it can be seen that the E3RB controls AFR within a narrow band of operation from Hour 2 – 12, beyond which there is a gradual richening of AFR until hour 17. At hour 18, there is a noticeable drop in CO:NOx, indicating AFR migration to leaner conditions, followed by a gradual migration back to a richer region, comparable to operation during hours 3 – 7. In summary, although CO slightly exceeded the limit, there was sufficient compliance margin for NOx that would allow the controller to be leaned out.

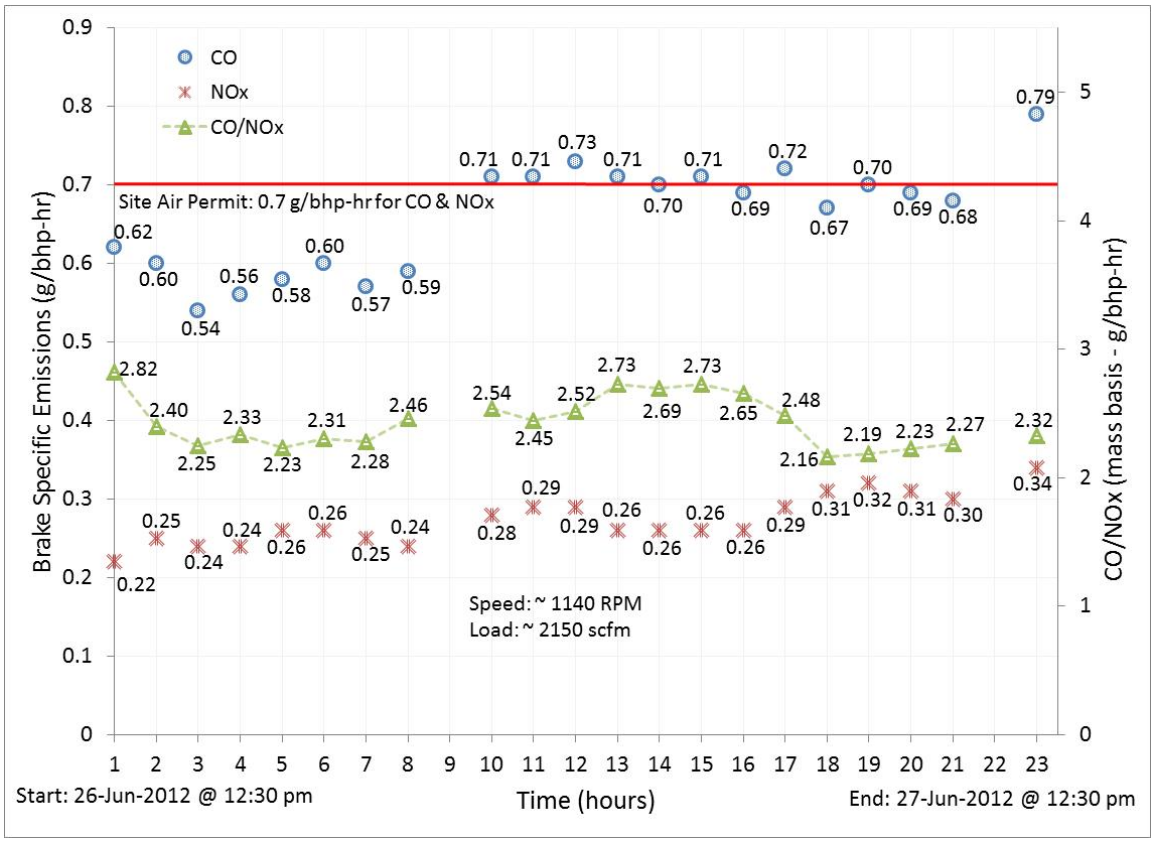

Figure 55: 24-hour evaluation of E3RB performance.

3.8 Remote Monitoring

During intervals between site visits, emissions were remotely monitored using NOx sensor output to SCADA. The accuracy of the post-catalyst NOx sensor was ± 30 ppm while that of the pre-catalyst sensor was ± 3% of the measured reading. An analysis of the operating conditions (engine speed and load) showed that the engine was operating at or near the HS/HL point for over 95% of the time, during the period from April 4 to August 20. From the daily-average post-catalyst NOx trend in Figure 56, it can be seen that NOx emissions at HS/HL exceeded site air permit limits on April 24 (168 ppm), May 27 (173 ppm), May 28 (184 ppm), May 29 (184 ppm), and August 16 (204 ppm). It should be noted that given the low accuracy of

the post-catalyst sensor, only the recorded daily average of 204 ppm (on August 16) is of particular concern, with regards to exceeding the site air permit. It is not clear as to the reason for this emissions behavior on August 16. Between E3RB commissioning on February 20 and April 4, the post-catalyst NOx sensor was not functioning properly therefore, the data for this period has been omitted from the NOx trend.

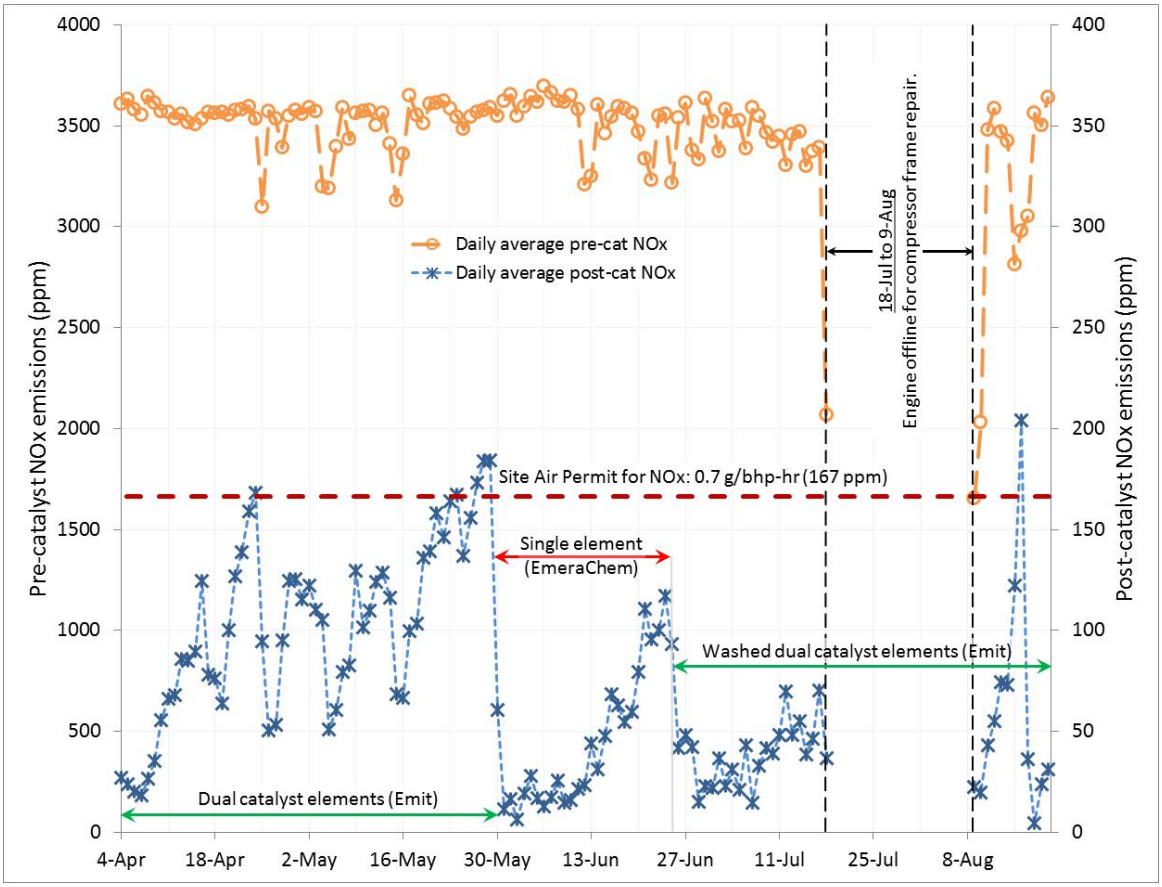

Figure 56: Daily average NOx trends obtained from SCADA.

3.9 Transient Performance

3.9.1 Load Steps

The E3RB's transient response was monitored during load steps between each operating condition, as previously outlined in Table 4. An example of this transient response monitoring is provided in Figure 57, during a load change from HS/HL to MS/ML. The E3RB's dithering strategy can be observed in the trends for right and left bank HEGO actual. It can be seen that engine speed and load stabilize within the first 3 minutes and that E3RB HEGO signals (setpoints and actual) stabilize shortly thereafter (ie. within the following 2 – 3 minutes). This can be considered a good response to changes in engine operating condition. As can be expected, there is a slight decrease in both manifold air pressure (MAP) and temperature (MAT) in each bank, when transitioning to a lower speed/load point. However, this is hard to distinguish owing to the coarse scale used on the secondary y-axis. Similar trends for E3RB transient responses for each load changes during every site visit can be viewed in Appendix D.

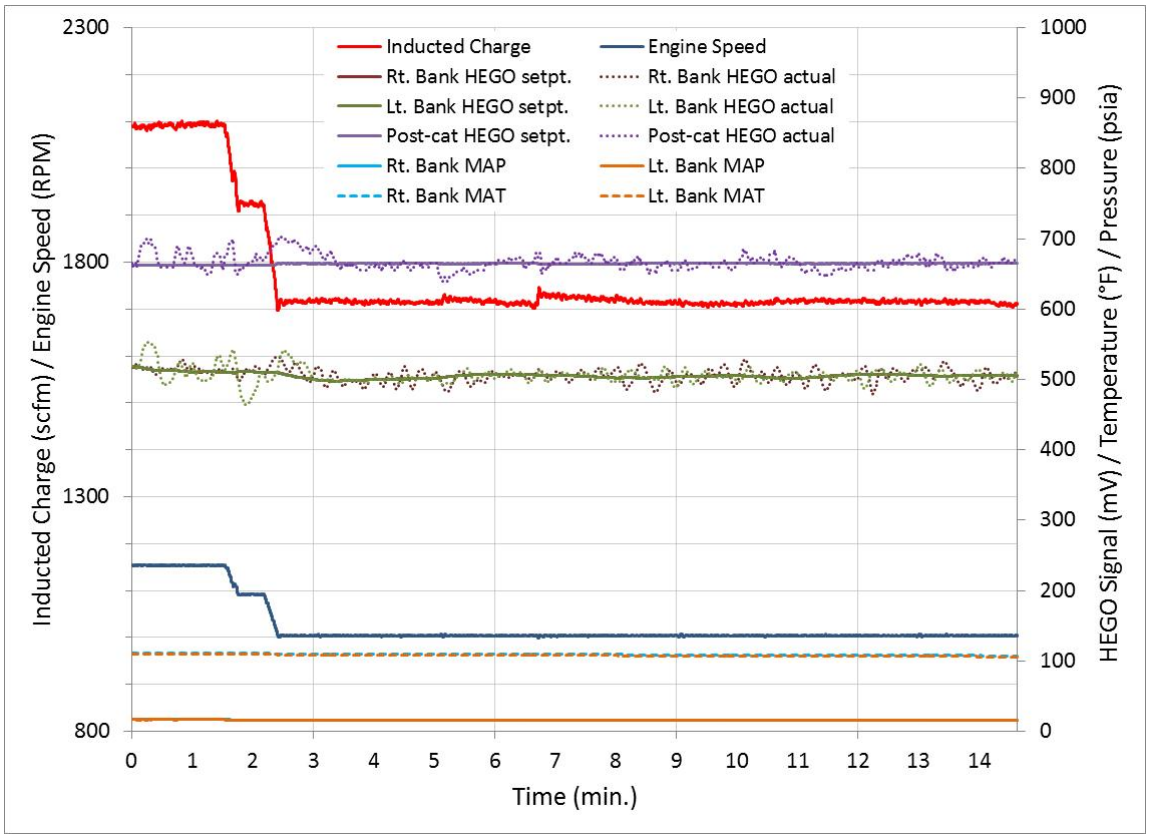

Figure 57: Transient response of E3RB parameters during load step from HS/HL to MS/ML.

3.9.2 Shutdown

E3RB response during an engine shutdown event on March 12 is shown in Figure 58. Of particular interest is the control behavior once the load drops below the threshold of 1000 scfm; from this time forward until shutdown, the actual HEGO signals diverge significantly from their respective setpoints, indicating a transition from closed-loop to open-loop setpoint tables.

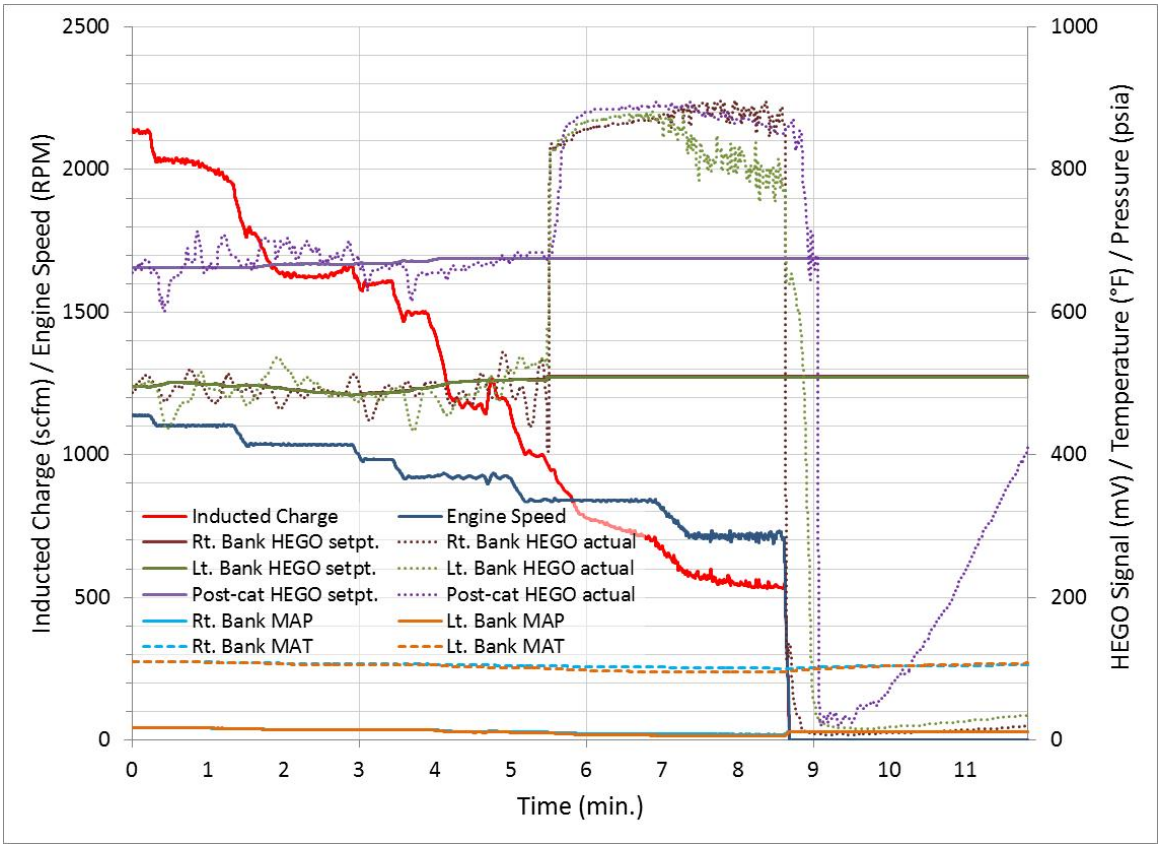

Figure 58: Transient response of E3RB parameters during engine shutdown on March 12.

3.9.3 Startup

Similarly, E3RB response was also recorded during an engine startup event on March 12. From Figure 59, it can be seen that the engine attains stable speed and load settings from minute 6, the pre-catalyst HEGO signals stabilize by minute 9, and the actual post-catalyst HEGO signal stabilizes by around minute 21. From an emissions perspective, the duration of the latter signal's instability roughly correlates with the period that NOx emissions exceed the air permit (Figure 60). On the other hand, CO emissions are very reasonable until minute 20, after which time, it begins to exhibit spikes that exceed the air quality limit (Figure 61). The crossover in CO and

NOx emissions that occur during this time period is indicative of AFR migration from stoichiometry to rich operation.

It should be noted that while concentrations of NOx and CO, in certain instances, do exceed the limit, it does not represent an out-of-compliance condition since regulatory bodies allow a period of between 30 and 60 minutes following startup during which engine emissions are exempt from the air quality permit requirements issued for a given site.

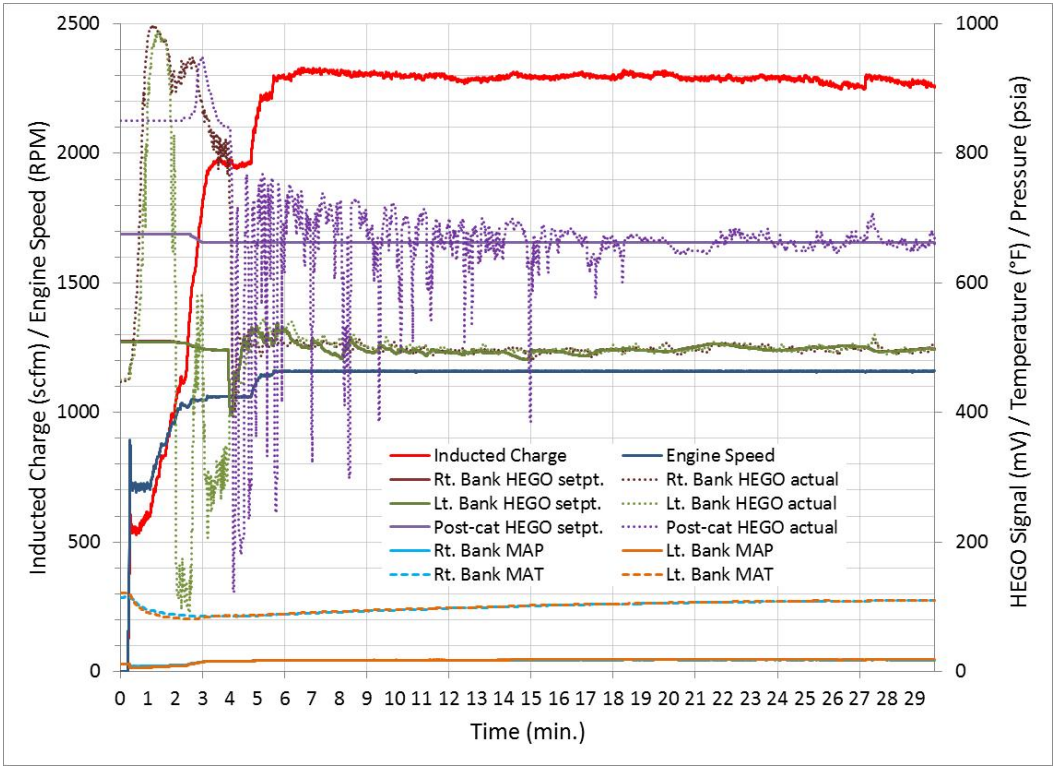

Figure 59: Transient response of E3RB parameters during engine startup on March 12.

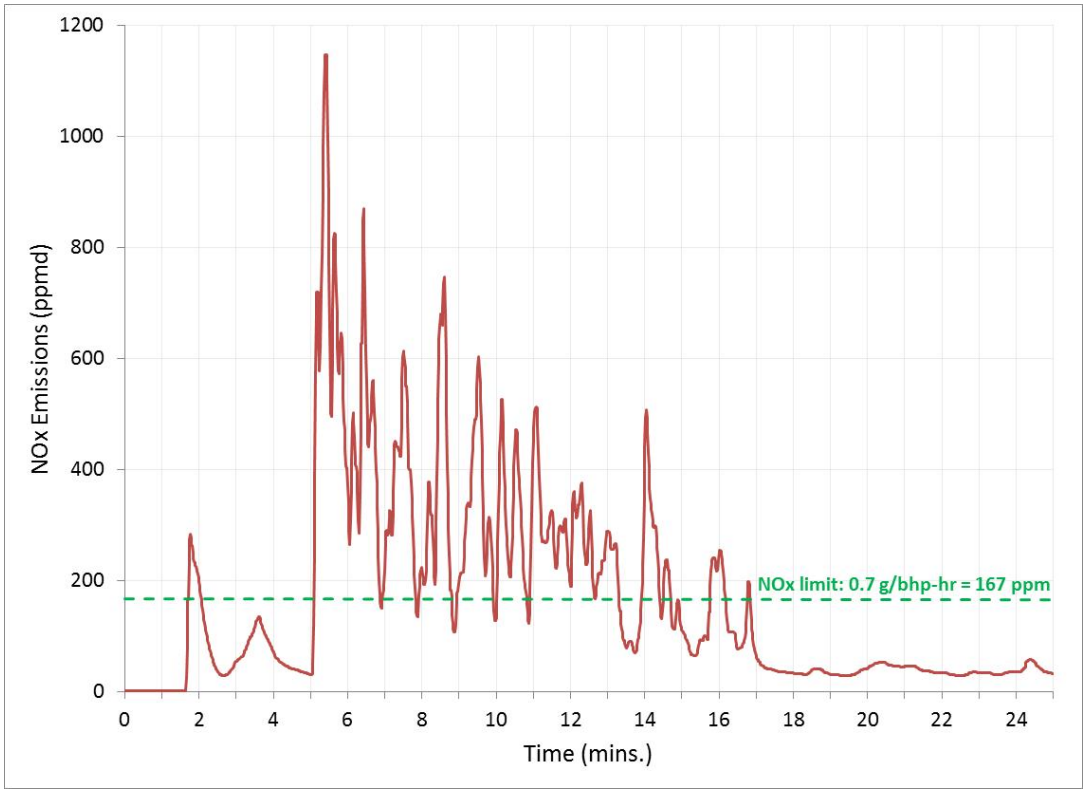

Figure 60: NOx emissions during engine startup on March 12.

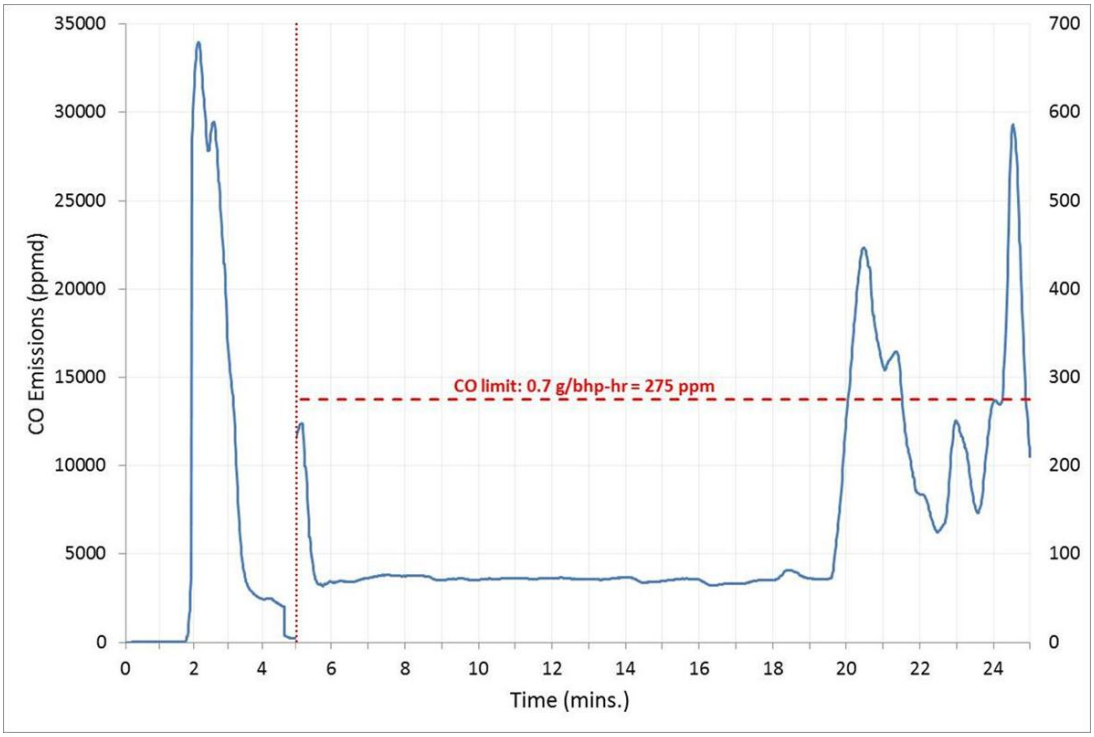

Figure 61: CO emissions during engine startup on March 12.

4. Conclusions and Recommendations

Performance of the E3RB AFR controller was evaluated for 6 months, starting February 20 and ending August 20. During this time, emissions monitoring site visits were conducted to assess controller performance. Based on the results presented in the previous section, the following conclusions and recommendations are made:

1. For the initial three month period (February 17 to May 15), the controller showed excellent AFR control of engine outlet emissions despite high lubrication oil consumption which could have caused degradation of the HEGO sensors. This demonstrated the robust capabilities of the E3RB in its ability to handle extraneous variables relating to engine health and assuring sustained sensor health.
2. For at least a 2-½ month period, as-found tests demonstrated compliance with emission limits, after the ash had been blown out of the catalyst. However, emissions taken May 15, June 25, and August 20 showed erratic behavior. Attempts to correct the problems included replacement of sparkplugs, replacement of HEGO sensors, and installation of a washed dual-element catalyst. Ash from high oil consumption had compromised the ability to verify E3RB performance.
3. Upon completion of the 6 month evaluation test, the engine was easily brought back into compliance by retuning the E3RB controller (changing the post-catalyst HEGO set point). Some of the problems encountered after May 15 may have been corrected by adjusting the controller.
4. As evidenced during the first three months of operation and subsequent diurnal tests, the E3RB's performance as a multi-point AFR control system was consistent, demonstrating

appropriate AFR adjustments to variation in engine operation, over a wide range of ambient conditions.

5. Due to the high levels of lubrication oil consumption, transient testing results were inconclusive.
6. The evaluation demonstrated proper operation of several alarms including misfire, system rich/lean, sensor failure, post-catalyst high temperature, pre-catalyst high temperature, and pre-catalyst low temperature.

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Appendix A: Engine Specifications

DRESSER Waukesha

L7044GSI

VHP® Series Four® Gas Engine
1120 - 1680 BHP (835 - 1253 kWb)

Specifications

Image may not be an accurate representation of this model

Cylinders: V12
Piston Displacement: 7040 cu. in. (115 L)
Bore & Stroke: 9.375" x 8.5" (238 x 216 mm)
Compression Ratio: 8:1
Jacket Water System Capacity: 100 gal. (379 L)
Lube Oil Capacity: 190 gal. (719 L)
Starting System: 125 - 150 psi air/gas 24V electric
Dry Weight: 21,000 lb. (9,525 kg)

Standard Equipment

AIR CLEANER – Two, 3" dry type filter with hinged rain shield and service indicator.

AIR FUEL RATIO CONTROL (AFR) – Integrated ESM® - AFR catalyst rich-burn control, main fuel gas regulator actuators, exhaust O2 sensor(s), and post turbocharger exhaust thermocouple. Factory mounted and tested. AFR maintains emissions through load and speed changes. The ESM AFR meets Canadian Standards Association Class 1, Division 2, Group A, B, C & D (Canada & US) hazardous location requirements. Note: For dual fuel applications, ESM AFR system will control the primary fuel source only.

BARRING DEVICE – Manual.

BATTERY BOX – Ship loose battery box designed to accommodate two series 31 12 VDC batteries. Includes power disconnect switch and 20 foot (6.1 m) cable for connection to ESM Power Distribution Box.

BEARINGS – Heavy duty, replaceable, precision type.

BREATHER – Self regulating, closed system.

CONNECTING RODS – Drop forged steel, rifle drilled.

CONTROL SYSTEM – Waukesha Engine System Manager (ESM) integrates spark timing control, speed governing, detonation detection, start-stop control, diagnostic tools, fault logging and engine safeties. Engine Control Unit (ECU) is central brain of the control system and main customer interface. Interface with ESM is through 25 foot (7.6 m) harness to local panel, through MODBUS RTU slave connection RS-485 multidrop hardware, and through the Electronic Service Program (ESP). Customer connections are only required to the local panel, fuel valve, and 24V DC power supply. Compatible with Woodward load sharing module. ESM meets Canadian Standards Association Class I, Division 2, Group A, B, C & D (Canada & US) hazardous location requirements.

CRANKCASE – Integral crankcase and cylinder frame. Main bearing caps drilled and tapped for temperature sensors. Does not include sensors.

CRANKSHAFT – Forged steel, seven main bearings, counterweighted and dynamically balanced.

CYLINDERS – Removable wet bainitic cast iron type cylinder liners, chrome plated on outer diameter.

CYLINDER HEADS – Twelve interchangeable. Four valves per cylinder, with water cooled exhaust valve seats. Roller valve lifters and hydraulic push rods. Flange mounted ignition coils.

ELECTRONIC SERVICE PROGRAM (ESP) – Microsoft® Windows-based program provided on CD-ROM for programming and interface to ESM. Includes E-Help for troubleshooting any ESM faults. Serial harness is provided for connection of a customer supplied laptop to the ECU RS-232 port.

ENGINE MONITORING DEVICES – Factory mounted and wired sensors for lube oil pressure and temperature; intake manifold temperature and pressure; overspeed; and jacket water temperature; all accessible through ESM®. ESM continually monitors combustion performance through accelerometers to provide detonation protection. Dual magnetic pick-ups are used for accurate engine speed monitoring. ESM provides predictive spark plug diagnostics as well as advanced diagnostics of engine and all ESM sensors and logs any faults into non-volatile flash memory. Sensors meet Canadian Standards Association Class 1, Division 2, Group A, B, C, & D (Canada & US) hazardous location requirements.

ENGINE ROTATION – Counterclockwise when facing flywheel.

EXHAUST OUTLET – Single vertical at rear. Flexible stainless steel connection with 8" (203 mm) pipe flange.

FLYWHEEL – Approx. WR^2 = 155000 lb-in²; with ring gear (208 teeth), machined to accept two drive adapters: 31.88" (810 mm) pilot bore, 30.25" (768 mm) bolt circle, (12) 0.75" - 10 tapped holes; or 28.88" (734 mm) pilot bore, 27.25" (692 mm) bolt circle, (12) 0.625"-11 tapped holes and (12) 0.75"-10 tapped holes.

FLYWHEEL HOUSING – No. 00 SAE.

FUEL SYSTEM – Single 3" ANSI flange fuel inlet connection. Two natural gas, 4" (102 mm) updraft carburetors and two mounted Fisher 99, 2" (51 mm) gas regulators, 30-60 psi (207-414 kPa) fuel inlet pressure required. 10 foot (3 m) harness provided for ESM control of customer supplied fuel shutoff valve

GOVERNOR – Electric throttle actuator controlled by ESM with throttle position feedback. Governor tuning is performed using ESP. ESM includes option of a load-coming feature to improve engine response to step loads.

IGNITION SYSTEM – Ignition Power Module (IPM) controlled by ESM, with spark timing optimized for any speed-load condition. Dual voltage energy levels automatically controlled by ESM to maximize spark plug life. Shielded ignition components meet Canadian Standard Association Class 1, Division 2, Group A, B, C & D (Canada & US) hazardous location requirements.

INTERCOOLER – Air-to-water.

LEVELING BOLTS

LIFTING EYES – Requires 9.5 ton Working Load Limit (W.L.L.) anchor shackles.

LUBRICATION – Full pressure, gear type pump. Engine mounted full flow lube oil micro-fiberglass filters with mounted differential pressure gauge. MICROSPIN® bypass filter, engine mounted. Air/gas motor driven prelube pump, requires final piping.

MANIFOLDS – Exhaust, (2) water cooled.

OIL COOLER – Shell and tube type, with thermostatic temperature controller and pressure regulating valve. Factory mounted.

OIL PAN – Deep sump type. 190 gallon (719 L) capacity, including filter and cooler.

PAINT – Oilfield orange primer.

PISTONS – Aluminum with floating pin. Oil cooled. 8:1 compression ratio.

SHIPPING SKID – For domestic truck or rail.

TURBOCHARGERS – (2) with water-cooled bearing housing and adjustable wastegates.

VIBRATION DAMPER – Viscous type.

WATER CIRCULATING SYSTEM, AUXILIARY CIRCUIT – Belt driven water circulating high capacity pump for intercooler and lube oil cooler. See S6543-36 performance curve for use with standard 10" diameter crankshaft pulley.

WATER CIRCULATING SYSTEM, ENGINE JACKET – Belt driven water circulating pump. Cluster type thermostatic temperature regulating valve, full flow bypass type with 165° - 170° F (74° - 77° C) start to open thermostats. Flange connections and mating flanges for (2) 4" (102 mm) inlets and (1) 5" (127 mm) outlet.

POWER RATINGS: L7044GSI VHP Series Four Gas Engines

Model	C.R.	Bore & Stroke in. (mm)	Displ. cu. in. (litres)	Brake Horsepower (kWb Output) 130°F (54°C) I.C. Water Temperature							
				1200 RPM		1000 RPM		900 RPM		800 RPM	
				C	I	C	I	C	I	C	I
L7044GSI	8:1	9.375" x 8.5" (238 x 216)	7040 (115)	1680	1680	1400	1400	1260	1260	1120	1120
				(1253)	(1253)	(1044)	(1044)	(940)	(940)	(835)	(835)

		1200 rpm	1000 rpm
	Power bhp (kWb)	1680 (1253)	1400 (1044)
	BSFC (LHV) Btu/bhp-hr (kJ/kWh)	7744 (10955)	7559 (10693)
	Fuel Consumption Btu/hr x 1000 (kW)	13010 (3813)	10583 (3101)
Emissions	NOx g/bhp-hr (mg/nm³ @ 5% O_2)	13.30 (4922)	12.90 (4782)
Emissions	CO g/bhp-hr (mg/nm³ @ 5% O_2)	11.20 (4140)	9.40 (3477)
Emissions	THC g/bhp-hr (mg/nm³ @ 5% O_2)	2.40 (873)	2.30 (844)
Emissions	NMHC g/bhp-hr (mg/nm³ @ 5% O_2)	0.35 (131)	0.34 (127)
Heat Balance	Heat to Jacket Water Btu/hr x 1000 (kW)	3849 (1128)	3227 (946)
Heat Balance	Heat to Lube Oil Btu/hr x 1000 (kW)	567 (166)	462 (135)
Heat Balance	Heat to Intercooler Btu/hr x 1000 (kW)	179 (53)	122 (36)
Heat Balance	Heat to Radiation Btu/hr x 1000 (kW)	724 (212)	642 (188)
Heat Balance	Total Exhaust Heat Btu/hr x 1000 (kW)	3900 (1143)	2962 (868)
Intake/ Exhaust System	Induction Air Flow scfm (Nm³/hr)	2424 (3651)	1972 (2970)
Intake/ Exhaust System	Exhaust Flow lb/hr (kg/hr)	11273 (5113)	9171 (4160)
Intake/ Exhaust System	Exhaust Temperature °F (°C)	1179 (637)	1112 (600)

Typical heat data is shown, however no guarantee is expressed or implied. Consult your Dresser Waukesha Application Engineering Department for system application assistance.

All natural gas engine ratings are based on a fuel of 900 Btu/ft³ (35.3 MJ/nm³) SLHV, with a 91 WKI®. For conditions or fuels other than standard, consult the Dresser Waukesha Application Engineering Department.

Data based on standard conditions of 77°F (25°C) ambient temperature, 29.53 inches Hg (100kPa) barometric pressure, 30% relative humidity (0.3 inches HG / 1 kPa water vapor pressure).

Fuel consumption based on ISO3046/1-1995 with a tolerance of +5% for commercial quality natural gas having a 900 BTU/ft³ (35.3 MJ/nm³) SLHV.

Heat data based on fuel consumption +2%.

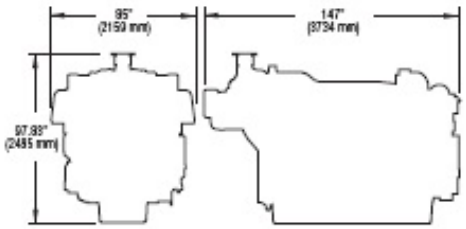
Heat rejection based on cooling exhaust temperature to 77°F (25°C).

Rating Standard: All models - Ratings are based on ISO 3046/1-1986 with mechanical efficiency of 90% and Tcra (clause 10.1) as specified above limited to ± 10° F (5° C). Ratings are also valid for SAE J1349, BS5514, DIN6271 and AP17B-11C standard atmospheric conditions.

C = ISO Standard Power/Continuous Power Rating: The highest load and speed which can be applied 24 hours per day, seven days per week, 365 days per year except for normal maintenance. It is permissible to operate the engine at up to 10% overload, or a maximum load indicated by the intermittent rating, whichever is lower, for two hours in every 24 hour period.

I = Intermittent Service Rating: The highest load and speed that can be applied in variable speed mechanical system application only. Operation at this rating is limited to a maximum of 3500 hours per year.

Consult your local Waukesha representative for system application assistance. The manufacturer reserves the right to change or modify without notice, the design or equipment specifications as herein set forth without incurring any obligation either with respect to equipment previously sold or in the process of construction except where otherwise specifically guaranteed by the manufacturer.



Appendix B: Emissions Analyzer Calibration Log

Table 7: Calibration gas concentrations used during field test

Calibration gas concentration (ppm)		**Lower Limit (- 5%)**	**Upper Limit (+ 5%)**
NOx	202	192	212
CO – low	401	381	421
CO – high	6891	6547	7236

Table 8: Calibration log for portable emissions analyzer

Date	Sensor temperature (°F)		Post-test calibration check			Result (Pass/Fail)
	Initial	Final	NOx (ppm)	CO – low (ppm)	CO – high (ppm)	
February 27	69.5	70.1	203	395	- - -	Pass
March 13	79.7	80.4	202	391	6855	Pass
April 2	71.4	73.0	203	386	6885	Pass
May 15	80.9	84.0	200	384	6885	Pass
June 25	100.7	110.0	206	391	6740	Pass
June 26	109.5	86.5	Pass	Fail	- - -	- - -
June 27	90.3	94.0	203	404	- - -	Pass
August 20	91.2	99.5	199	397	6680	Pass

Appendix C: Alarm/Fault Checks

Misfire

This alarm (designated as AL370) was demonstrated on August 23, 2012, by disconnecting the ignition cable between the primary coil and the candle. The resulting fault was recorded in the fault log as well as realtime via Woodward's ToolKit trend (Figure 62).

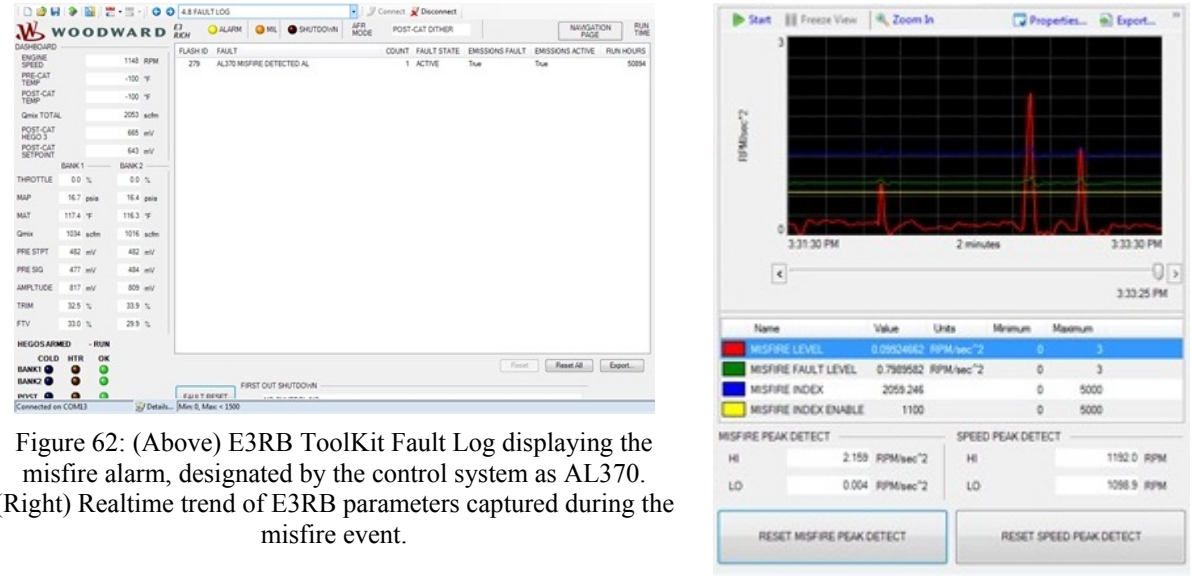


Figure 62: (Above) E3RB ToolKit Fault Log displaying the misfire alarm, designated by the control system as AL370. (Right) Realtime trend of E3RB parameters captured during the misfire event.

System Lean/Rich

These alarms (designated as AL10 for System Rich and AL15 for System Lean) were demonstrated on November 13, 2011, by manually adjusting the fuel trim valve so as to prevent the E3RB from obtaining the necessary fuel-air mixture. The faults were monitored in real-time using Woodward ToolKit trends (Figure 63).

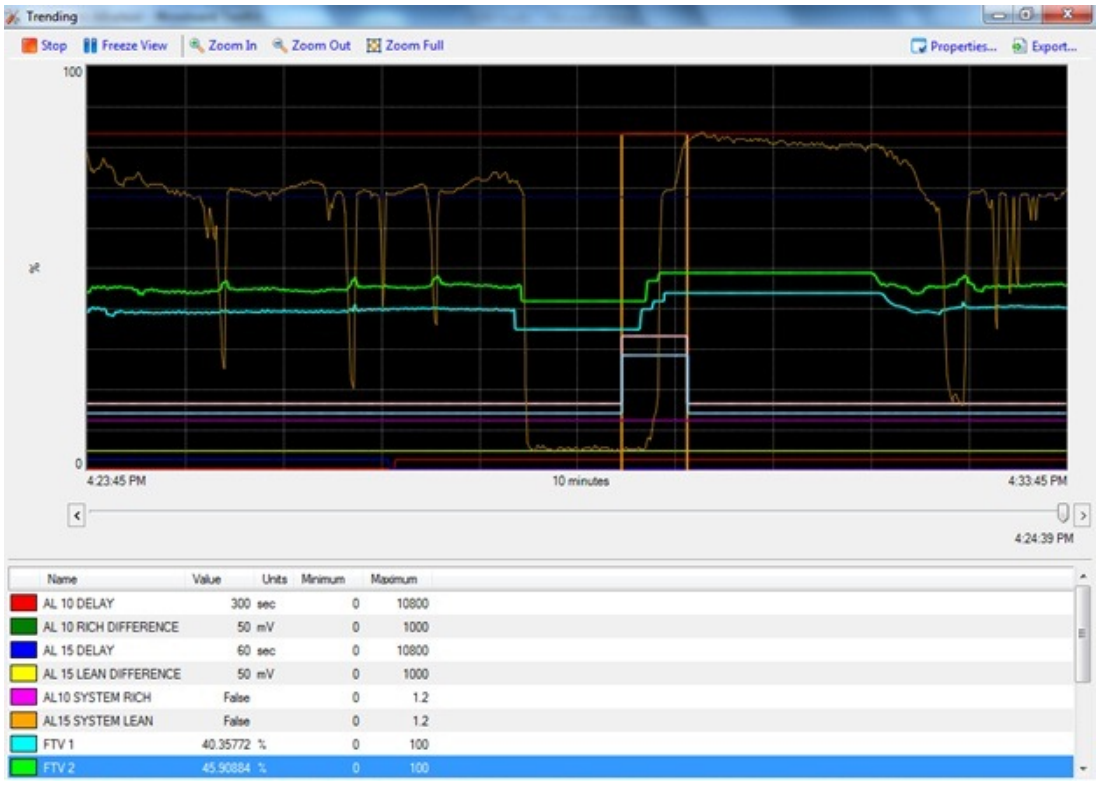
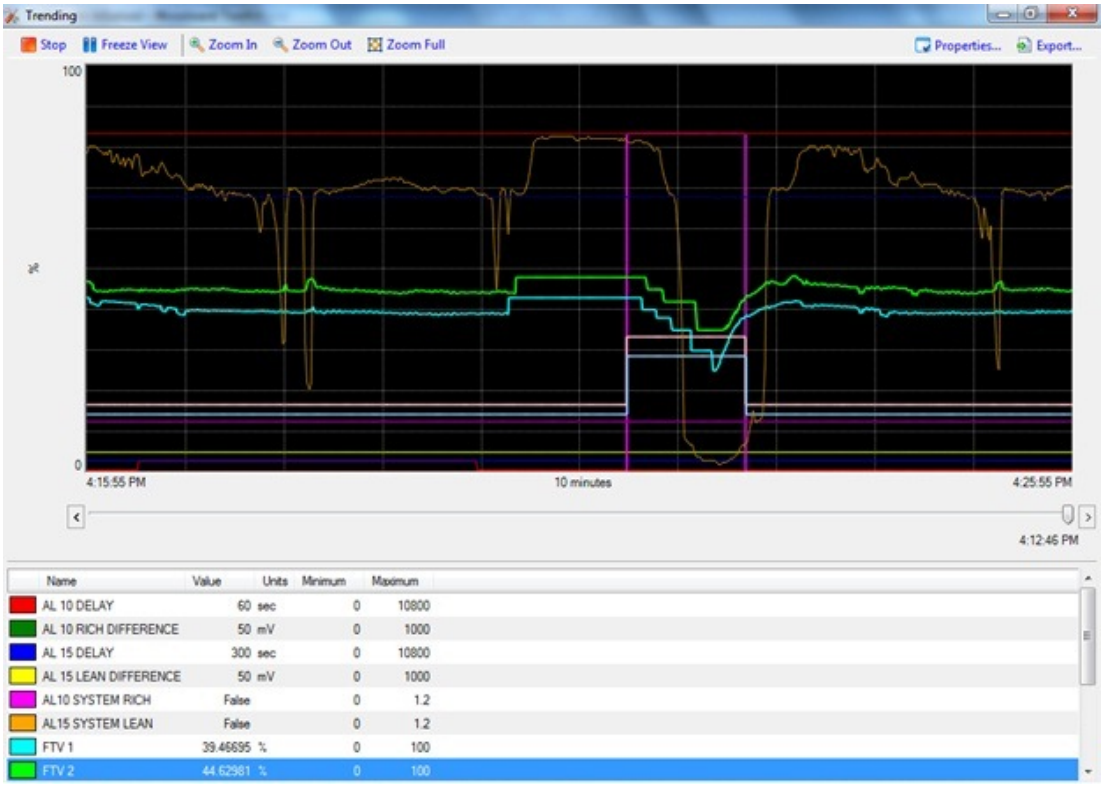


Figure 63: E3RB ToolKit trends displaying alarms for System Lean (orange trend - above) and System Rich (magenta trend - below) conditions.



Post-catalyst HEGO sensor

Alarms for post-catalyst HEGO sensor failure (designated as AL576 for HEGO 3 Heater Open Circuit and AL590 for HEGO 3 Sensor Failed) were demonstrated on November 13, 2011, by disconnecting the post-catalyst HEGO sensor from the E3RB system. The faults were monitored in real-time using a Woodward ToolKit trend (Figure 64).

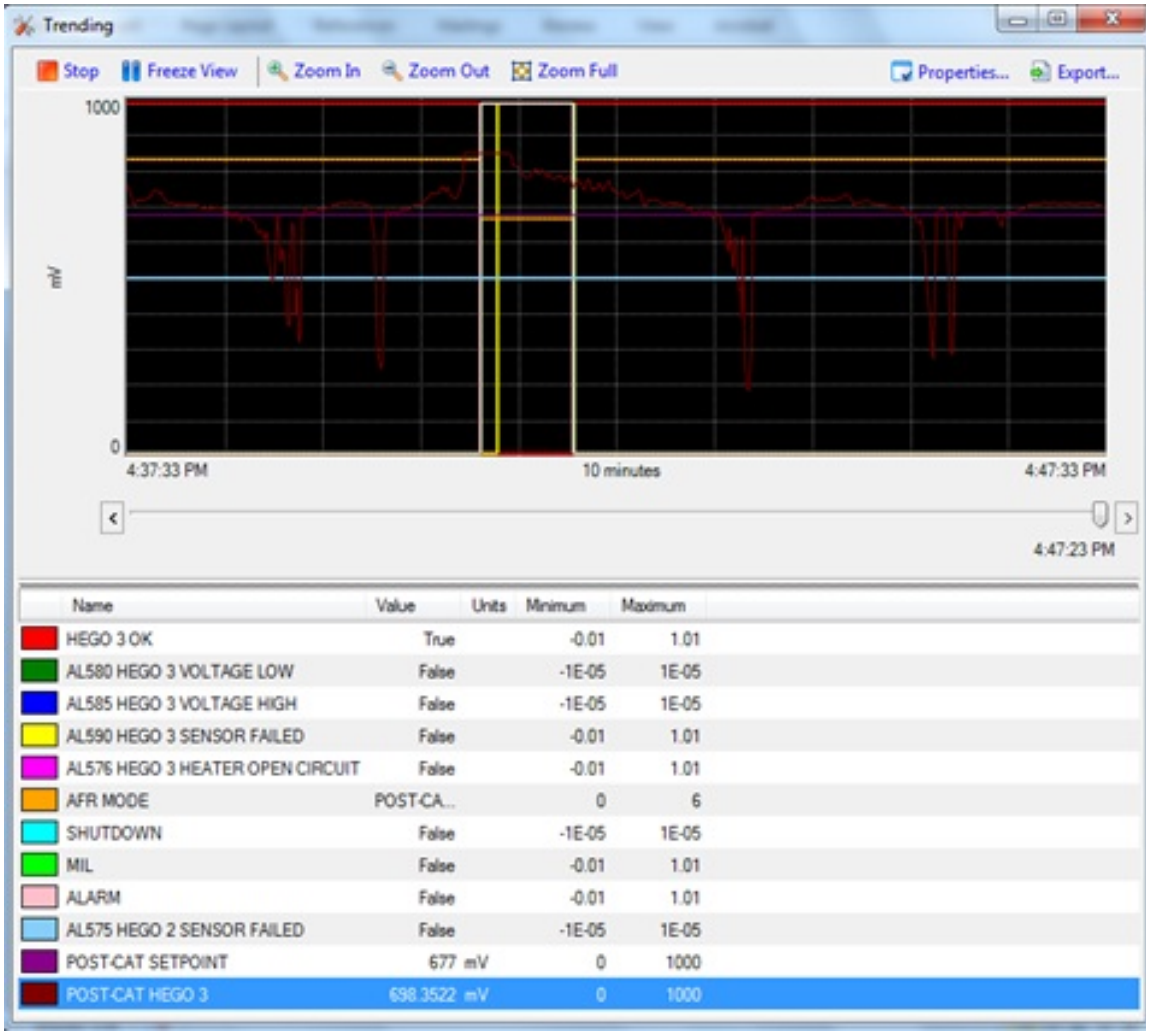


Figure 64: E3RB ToolKit trend displaying an alarm during simulated failure of the post-catalyst HEGO sensor (identified as HEGO 3).

Post-catalyst High Temperature

The post-catalyst high temperature alarm (designated as AL453) was demonstrated on February 18, 2012, by simulating an appropriate voltage signal to AN19 on the controller. The faults were monitored in real-time using a Woodward ToolKit trend (Figure 65). A simulation was required to showcase this feature on the E3RB as post-catalyst temperature thresholds at this site were monitored only by the PLC.

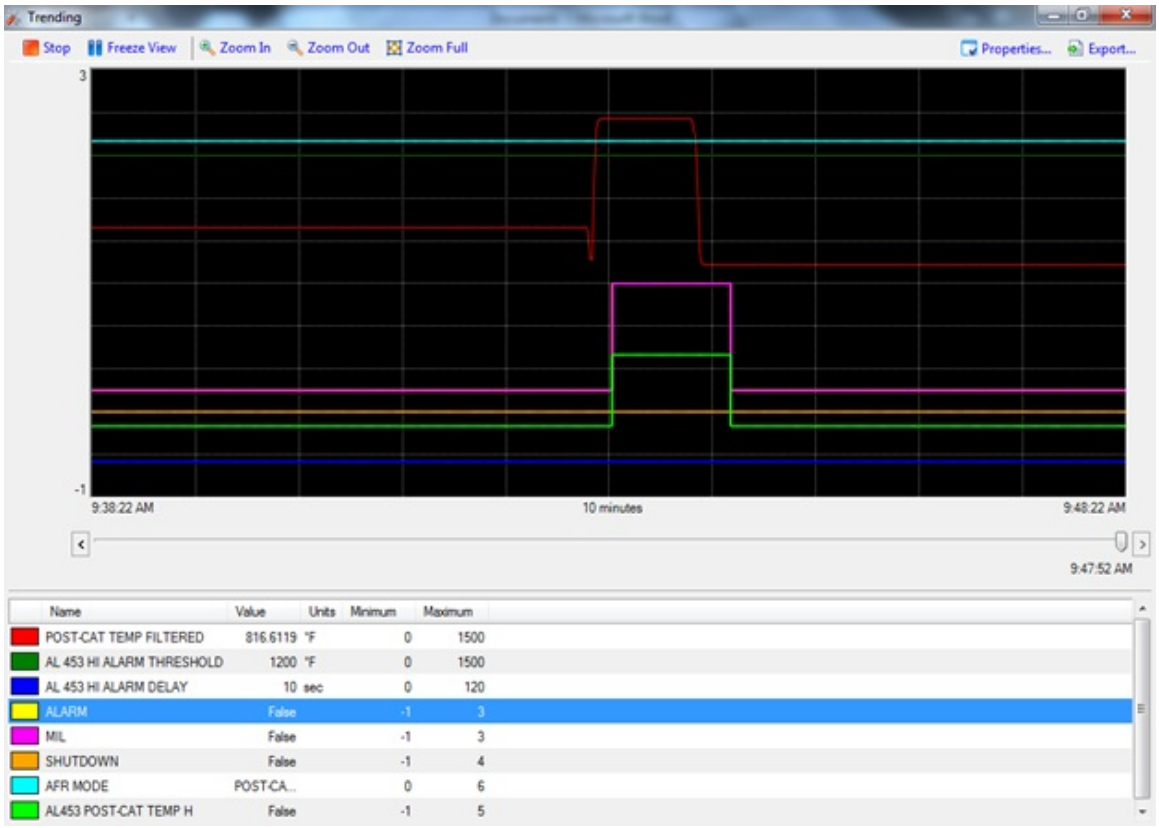


Figure 65: E3RB ToolKit trend displaying an alarm during a simulated exceedance of the high temperature limit recorded by the post-catalyst temperature sensor (not installed).

Pre-catalyst High/Low Temperature

The pre-catalyst high/low temperature alarms (designated as AL451 for High and AL470 for Low) were demonstrated on February 18, 2012, by simulating appropriate voltage signals to AN18 on the controller. The faults were monitored in real-time using Woodward ToolKit trends (Figure 66 and Figure 67). A simulation was required to showcase this feature on the E3RB as catalyst temperature thresholds were monitored only by the PLC at this site.

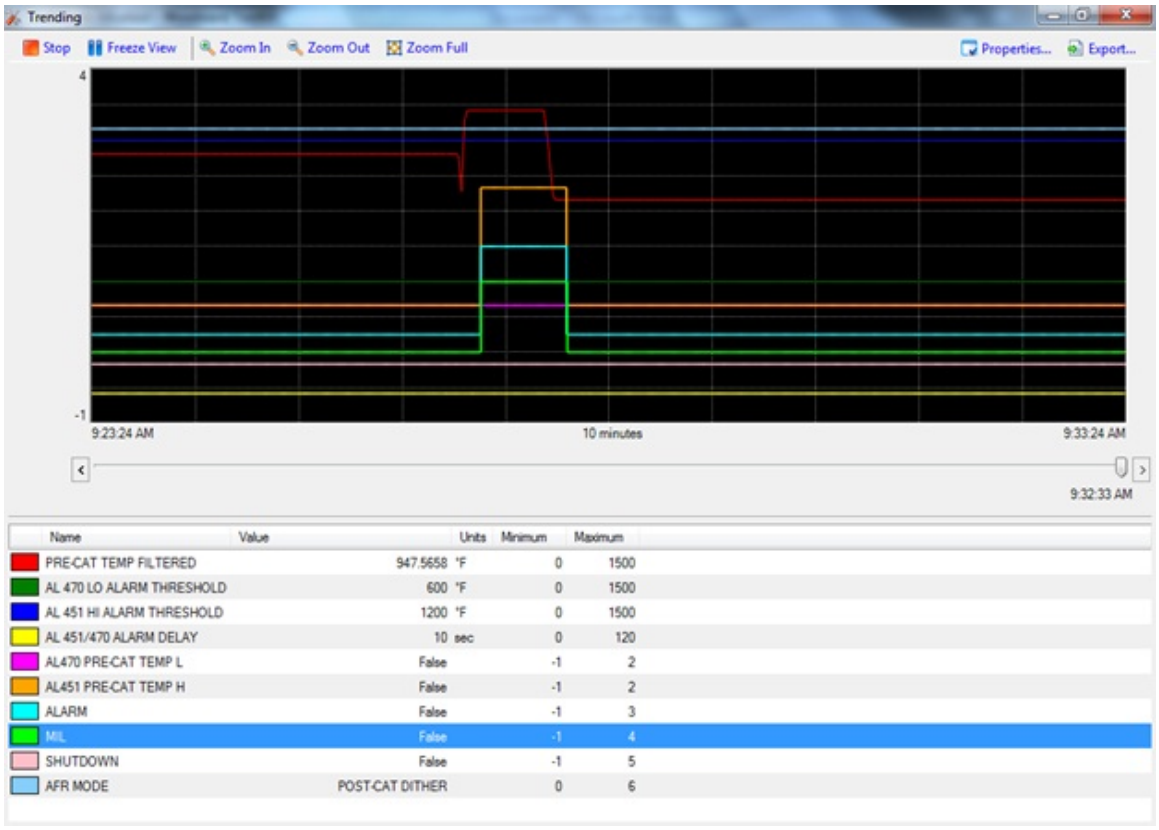


Figure 66: E3RB ToolKit trend displaying an alarm during a simulated exceedance of the high temperature limit recorded by the pre-catalyst temperature sensor (not installed).

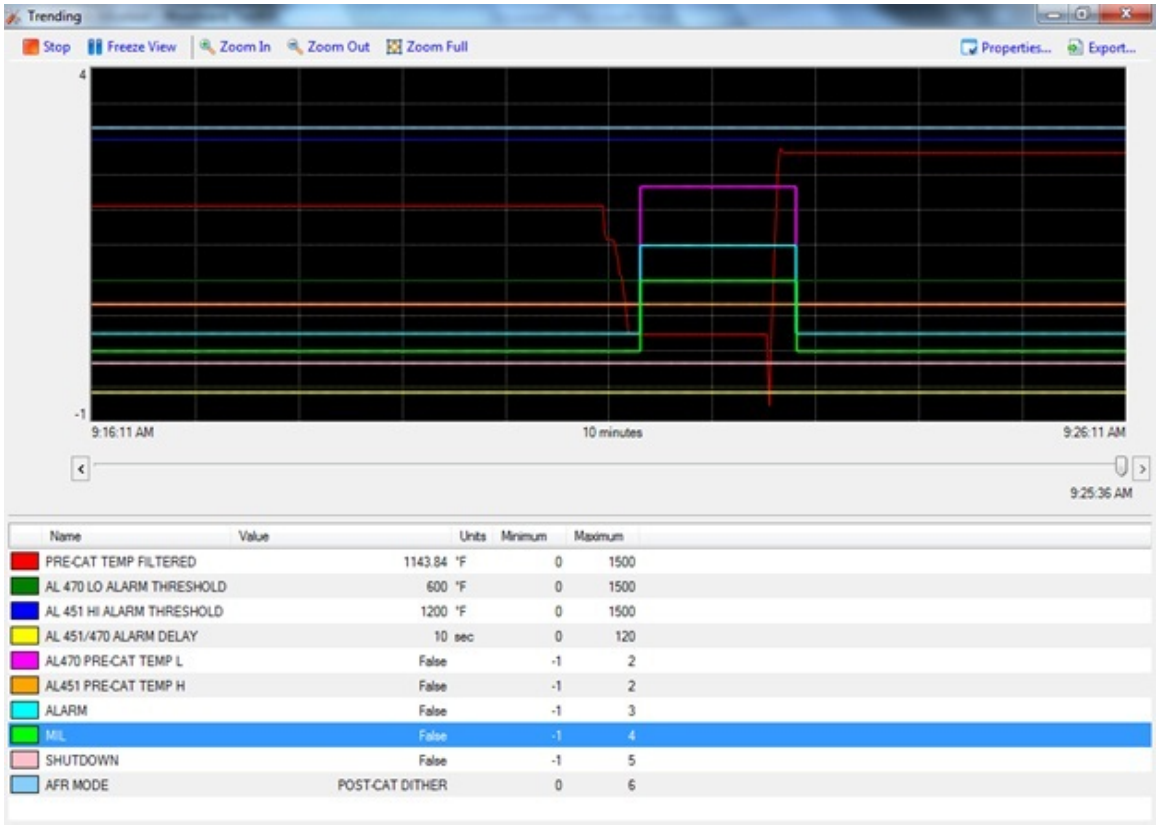


Figure 67: E3RB ToolKit trend displaying an alarm during a simulated exceedance of the low temperature limit recorded by the pre-catalyst temperature sensor (not installed).

Pre-catalyst HEGO sensors

Alarms for pre-catalyst HEGO sensor failures (designated as AL560 for Bank 1 [Right] and AL575 for Bank 2 [Left]) were demonstrated on February 19, 2012, by disconnecting the pre-catalyst HEGO sensors from the E3RB system and the resulting faults monitored in real-time using Woodward ToolKit trends (Figure 68).

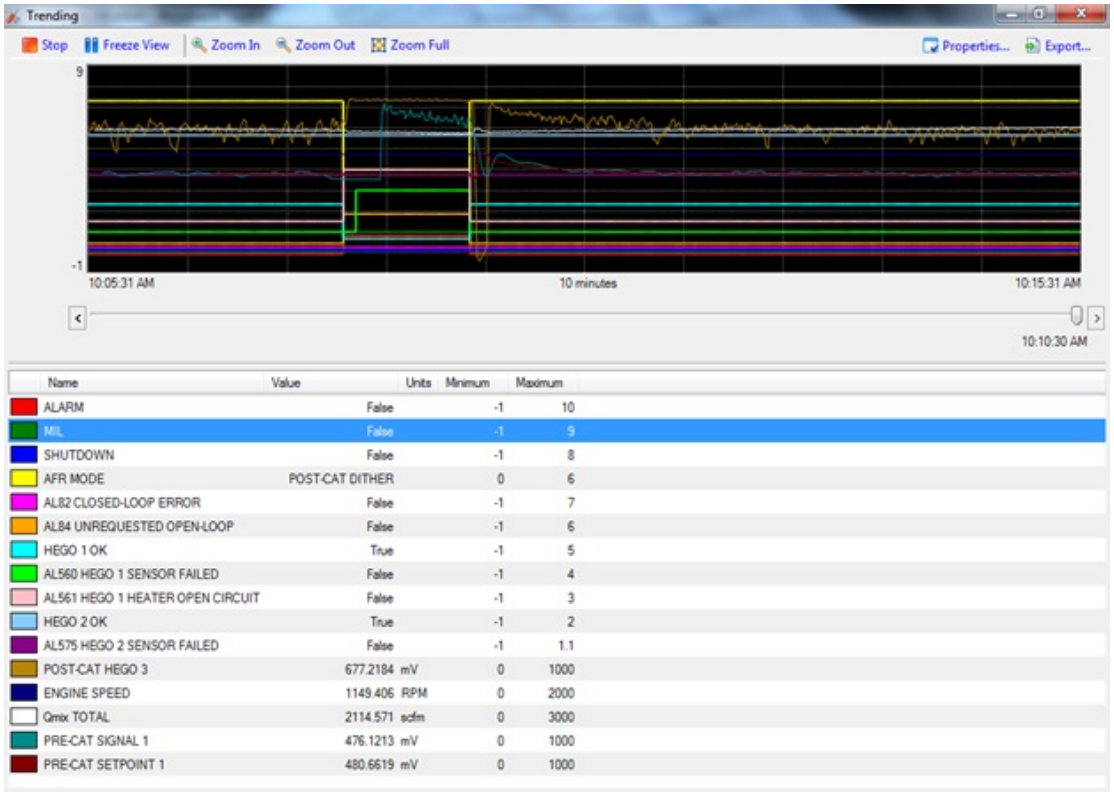
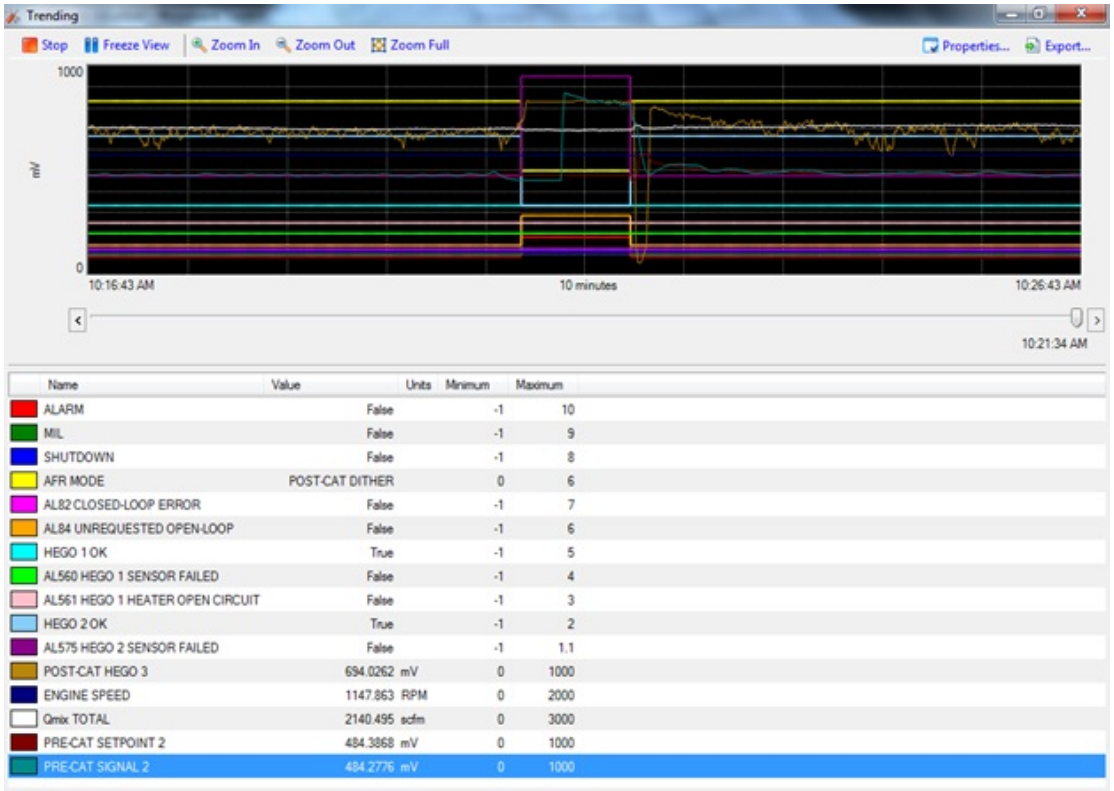


Figure 68: E3RB ToolKit trend displaying alarm incidents during simulated failure of the pre-catalyst HEGO sensors; AL560/HEGO 1 – Right bank (above) and AL575/HEGO 2 – Left bank (below).



Appendix D: Transient Response

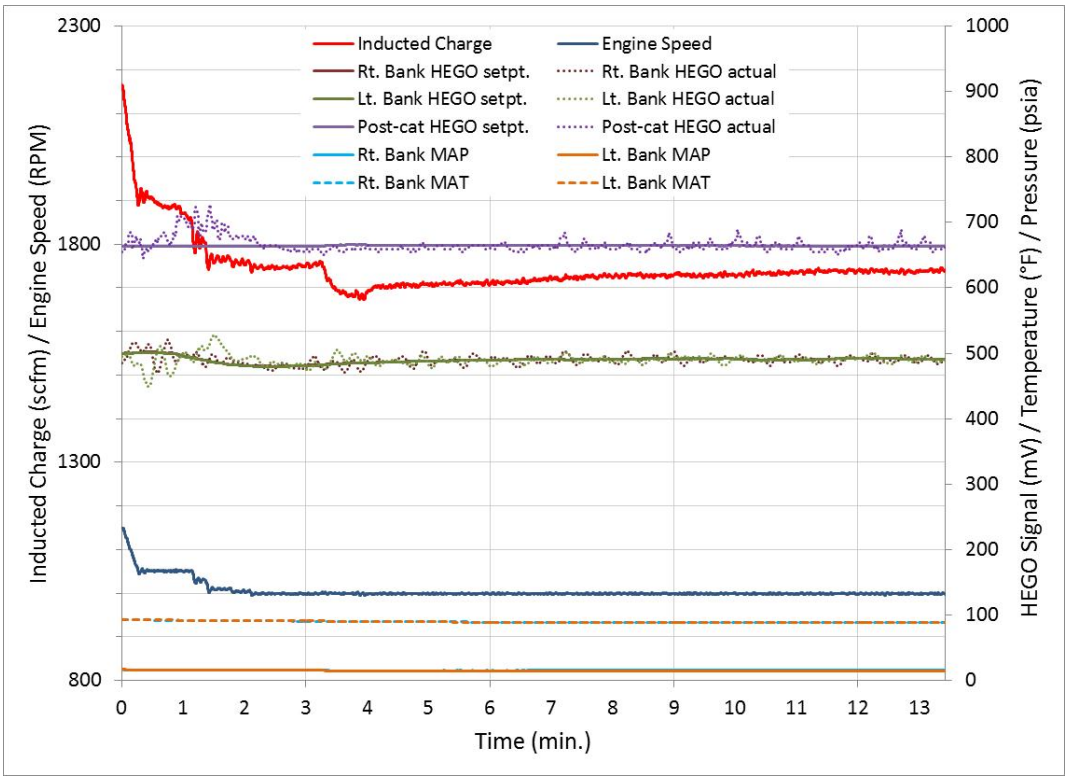


Figure 69: Transition from HS/HL to MS/ML on 27-Feb

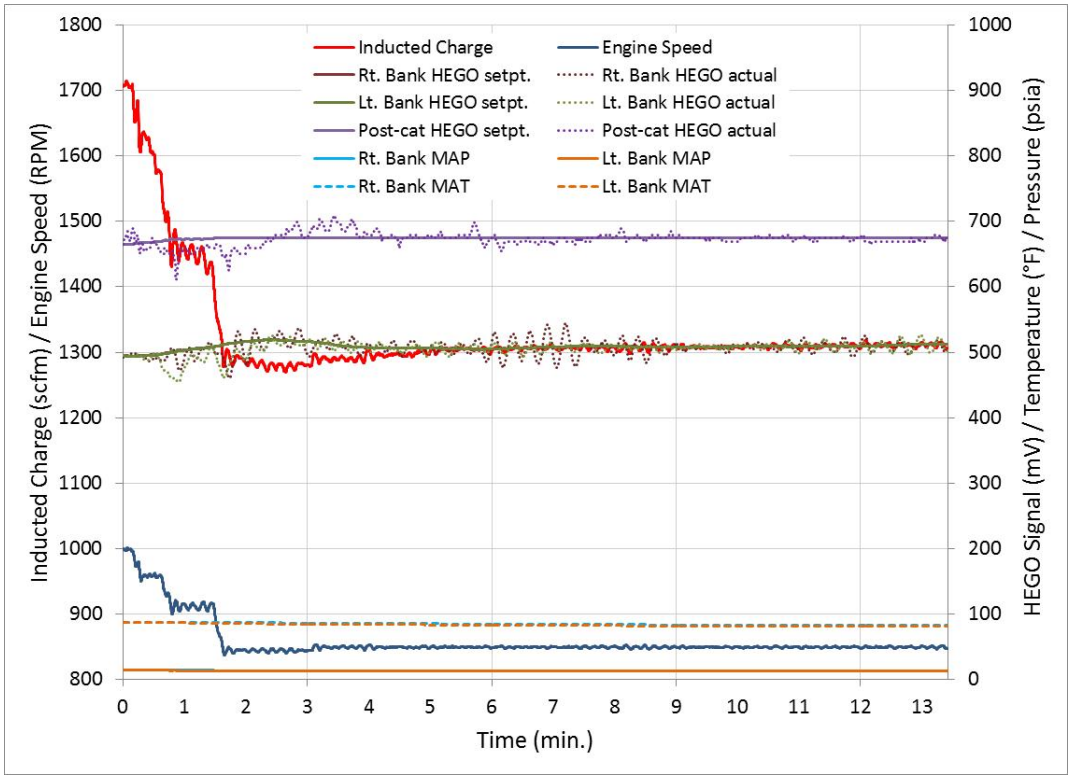


Figure 70: Transition from MS/ML to LS/LL on 27-Feb

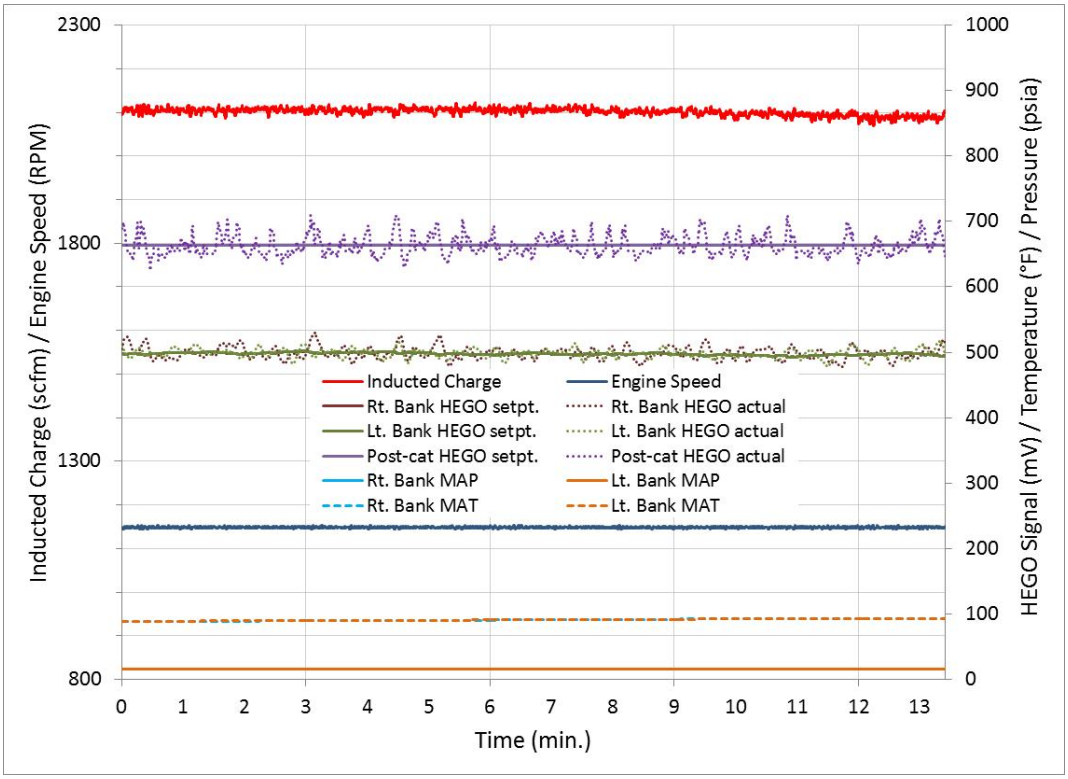


Figure 71: Transition from LS/LL to HS/HL on 27-Feb

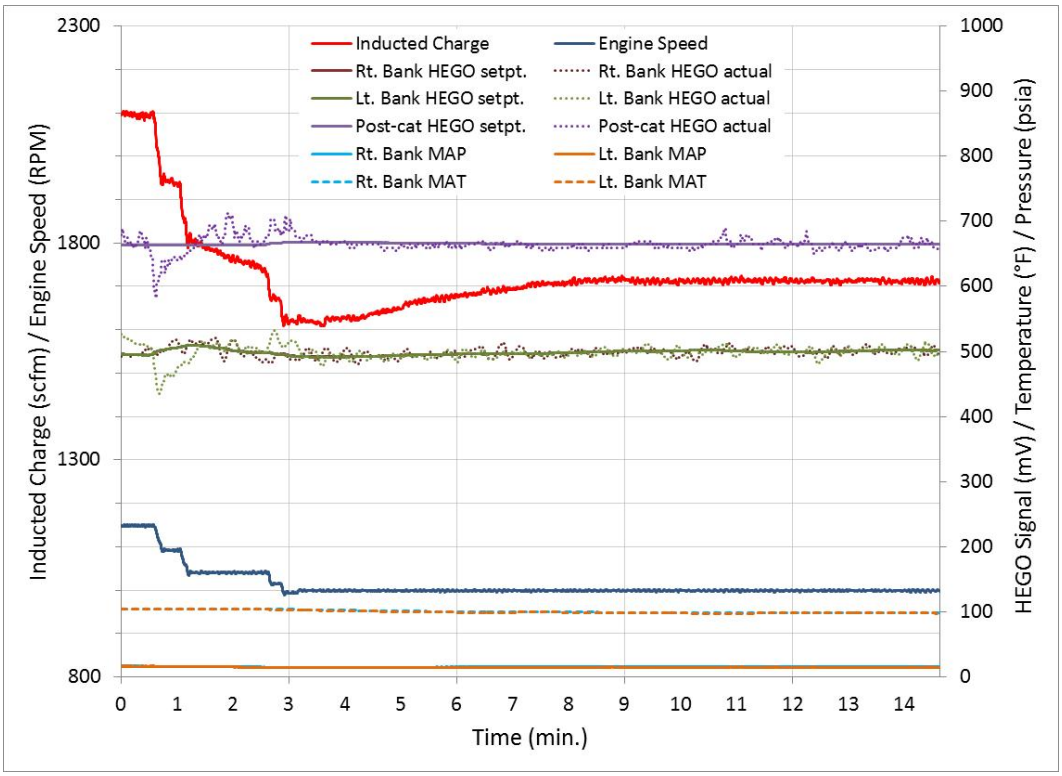


Figure 72: Transition from HS/HL to MS/ML on 13-Mar

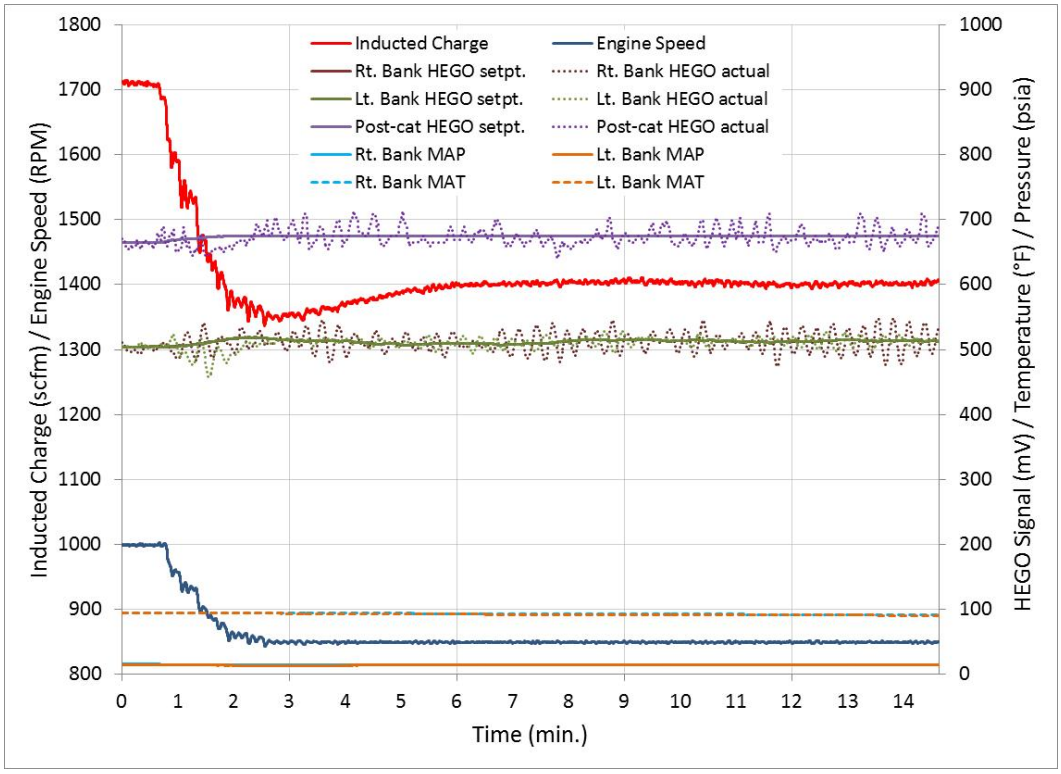


Figure 73: Transition from MS/ML to LS/LL on 13-Mar

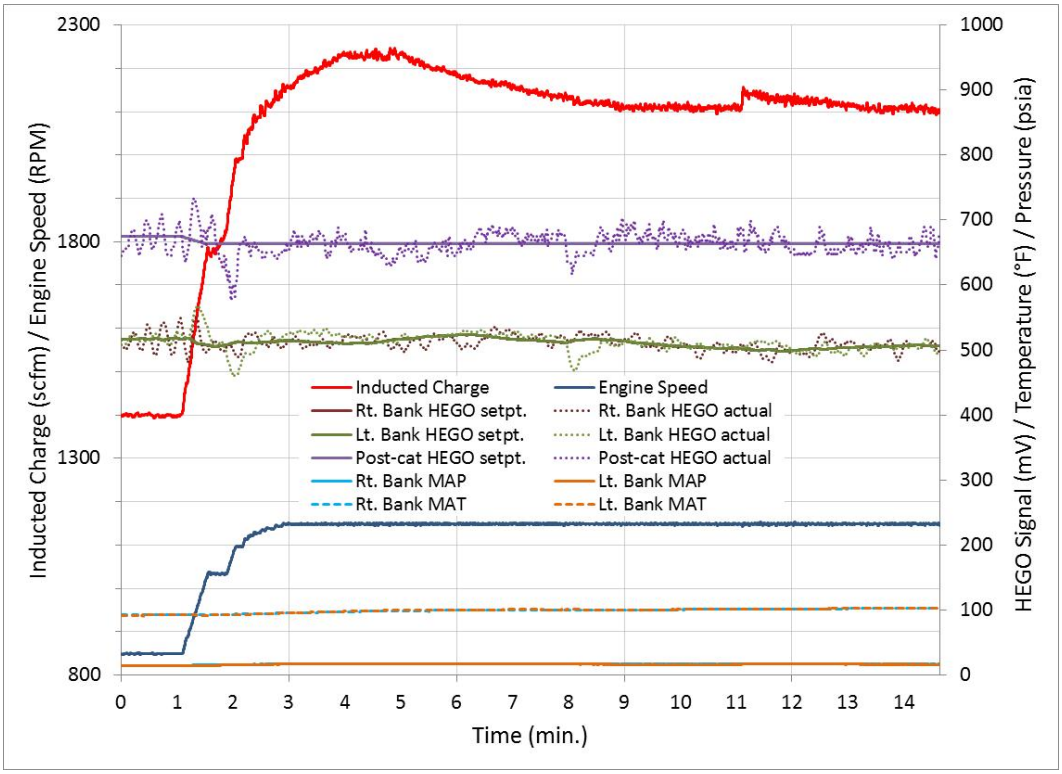


Figure 74: Transition from LS/LL to HS/HL on 13-Mar

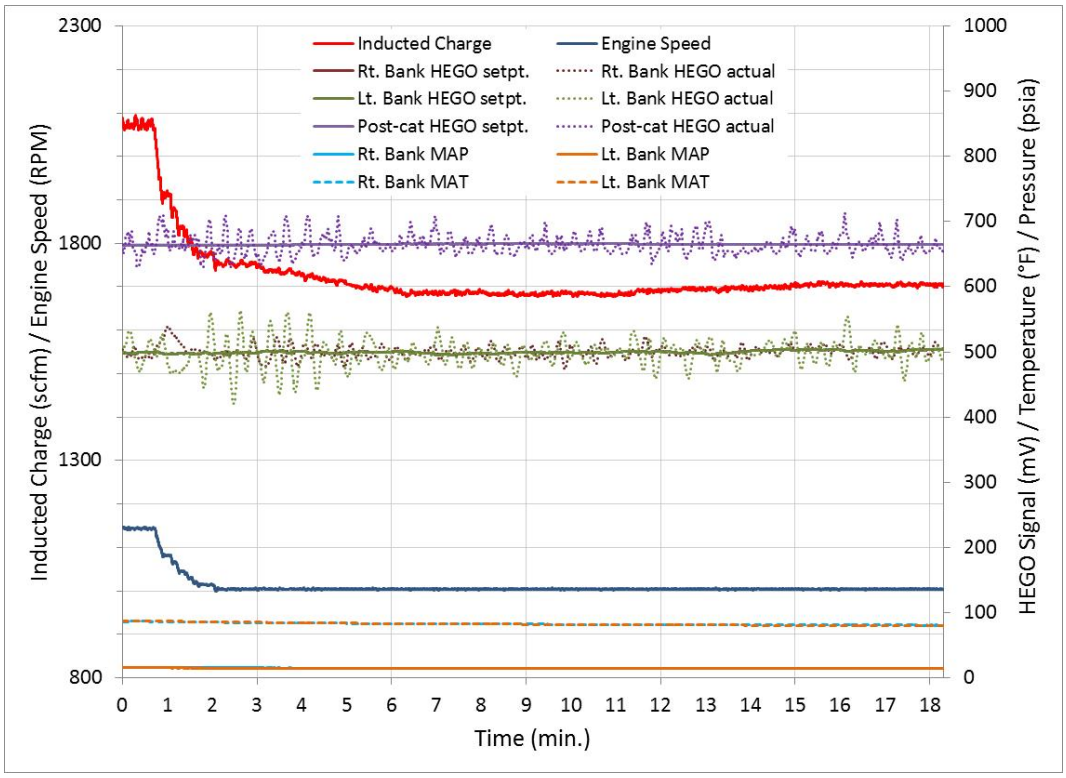


Figure 75: Transition from HS/HL to MS/ML on 02-Apr

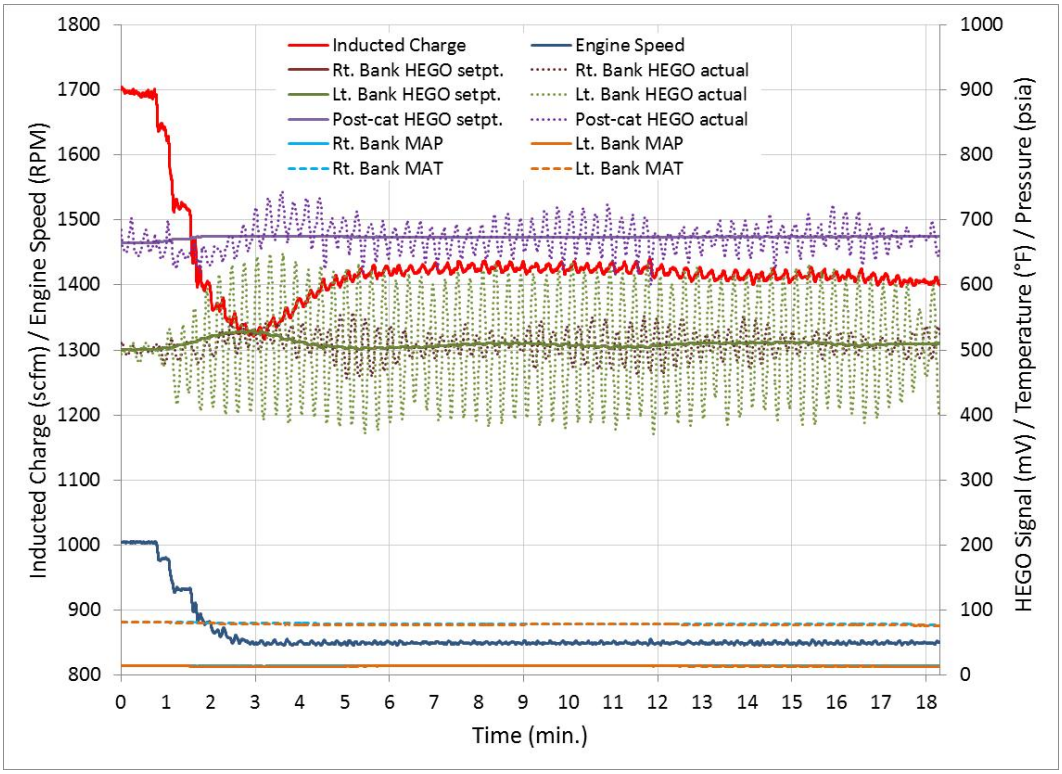


Figure 76: Transition from MS/ML to LS/LL on 02-Apr

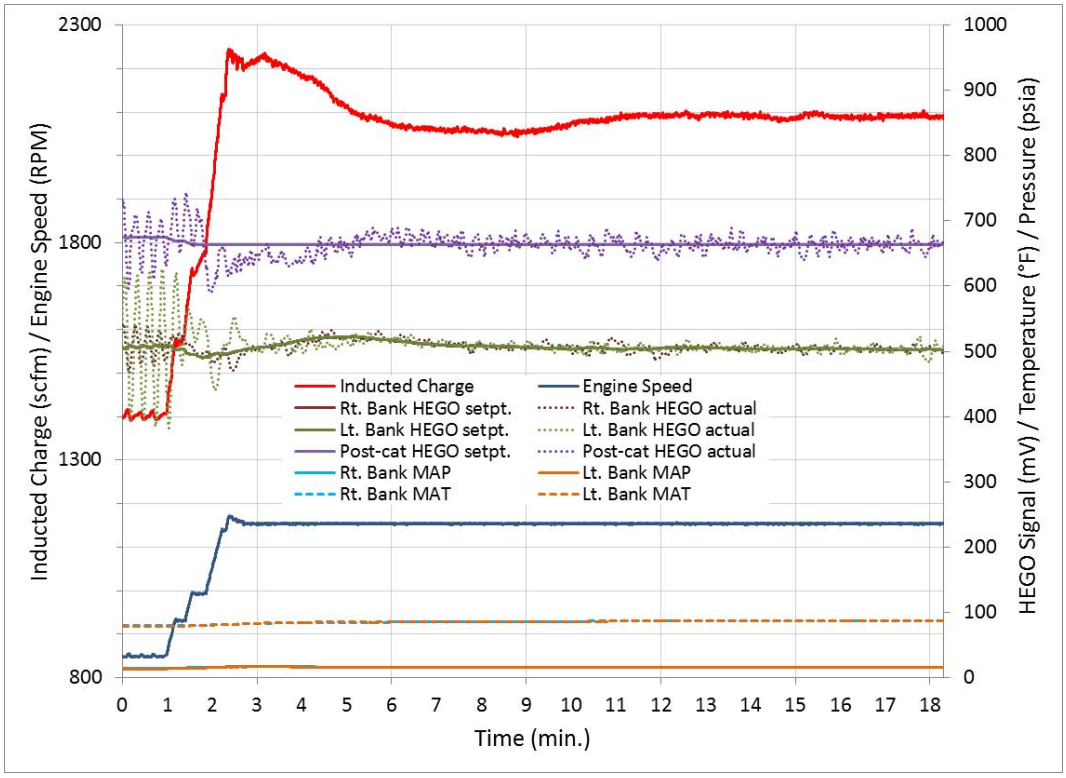


Figure 77: Transition from LS/LL to HS/HL on 02-Apr

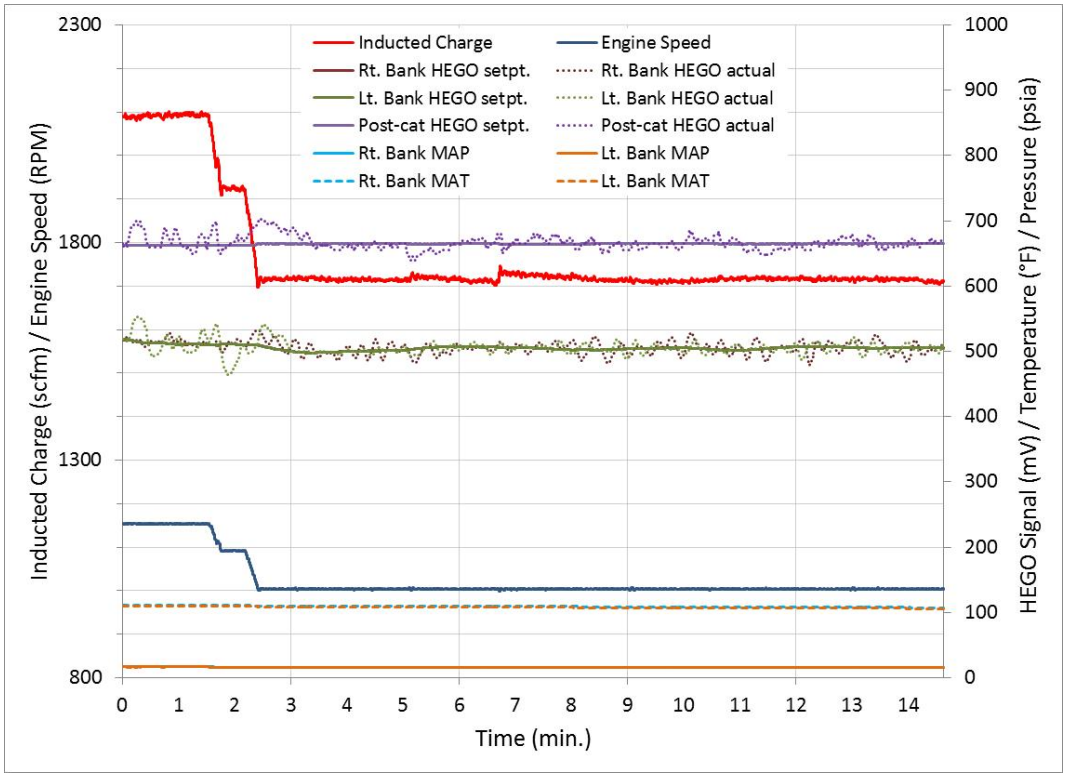


Figure 78: Transition from HS/HL to MS/ML on 15-May

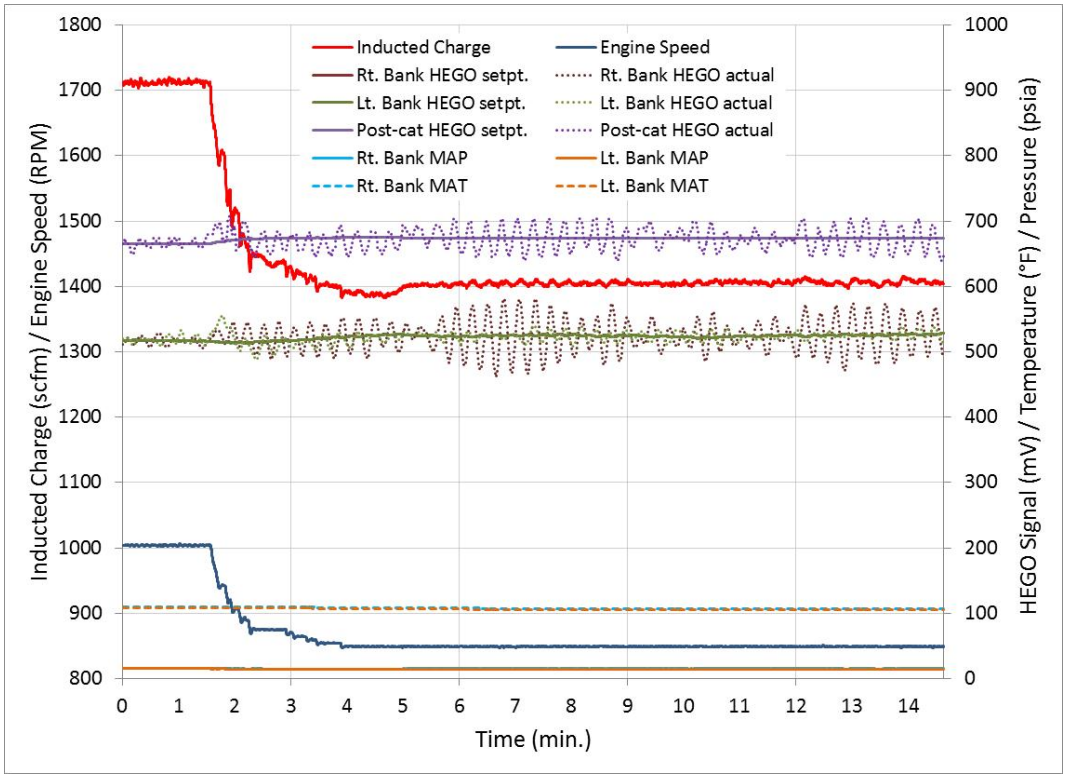


Figure 79: Transition from MS/ML to LS/LL on 15-May

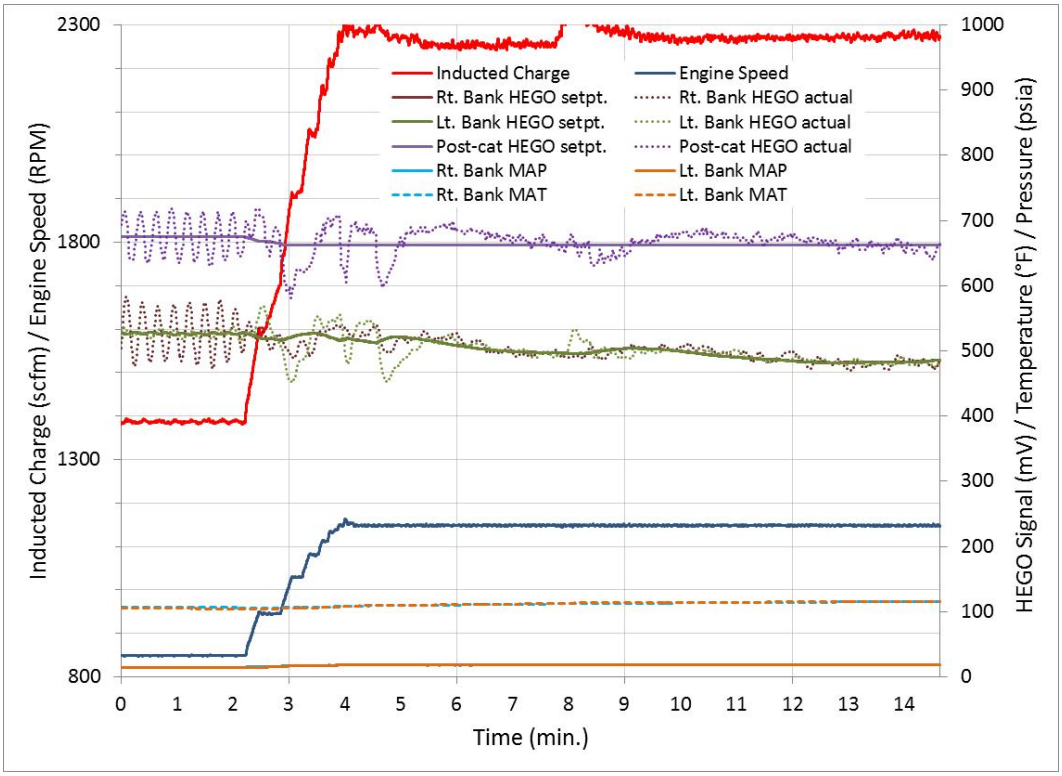


Figure 80: Transition from LS/LL to HS/HL on 15-May

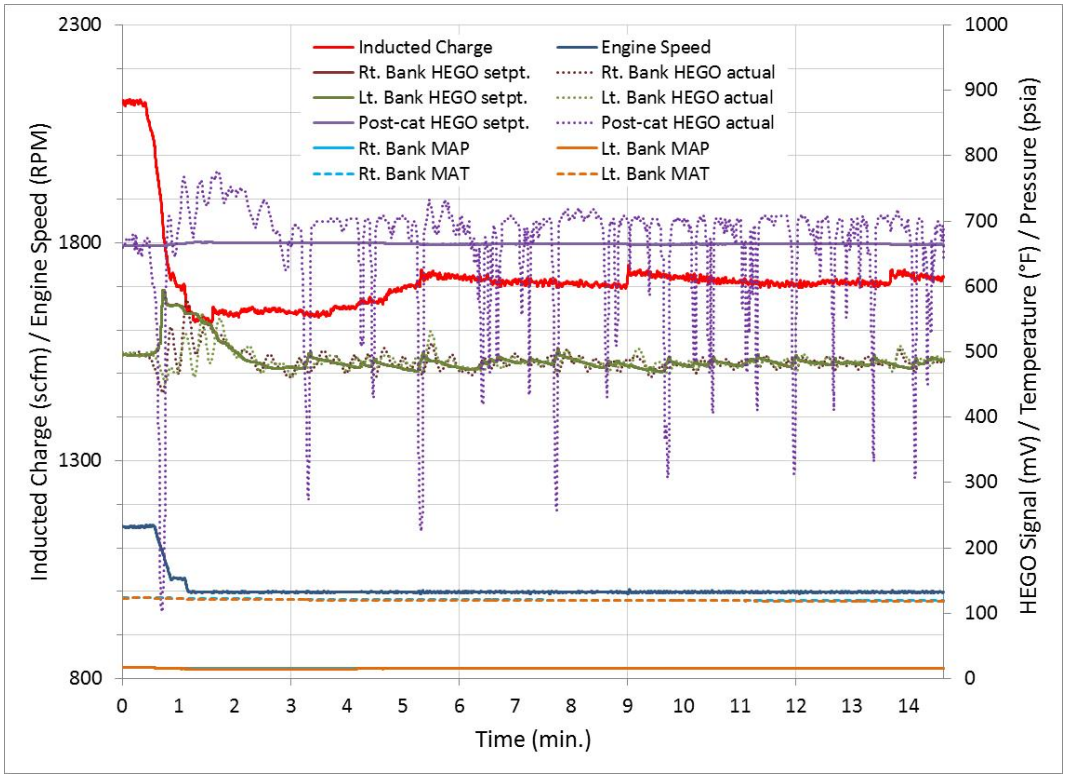


Figure 81: Transition from HS/HL to MS/ML on 25-Jun

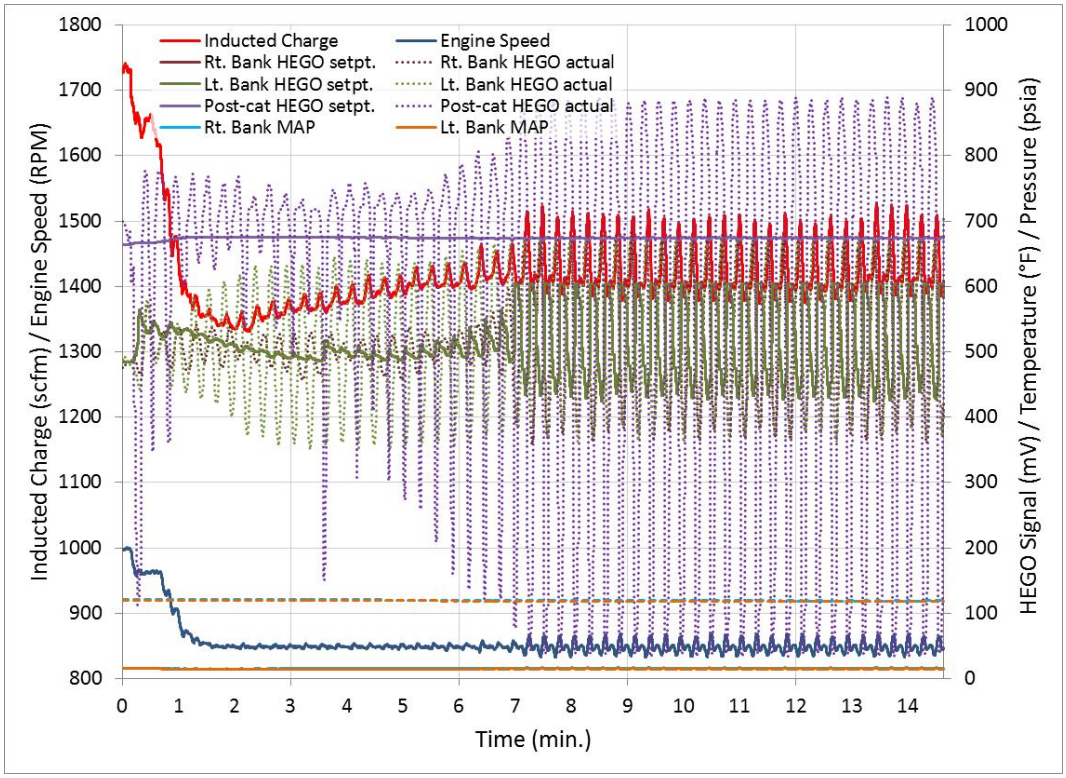


Figure 82: Transition from MS/ML to LS/LL on 25-Jun

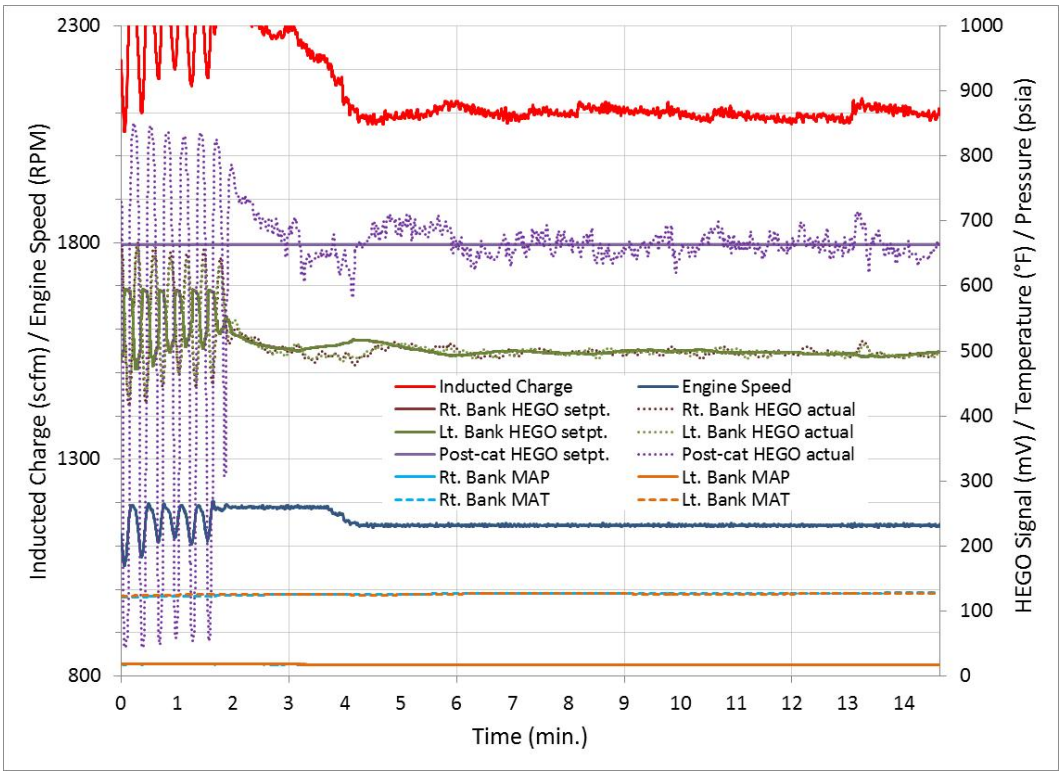


Figure 83: Transition from LS/LL to HS/HL on 25-Jun

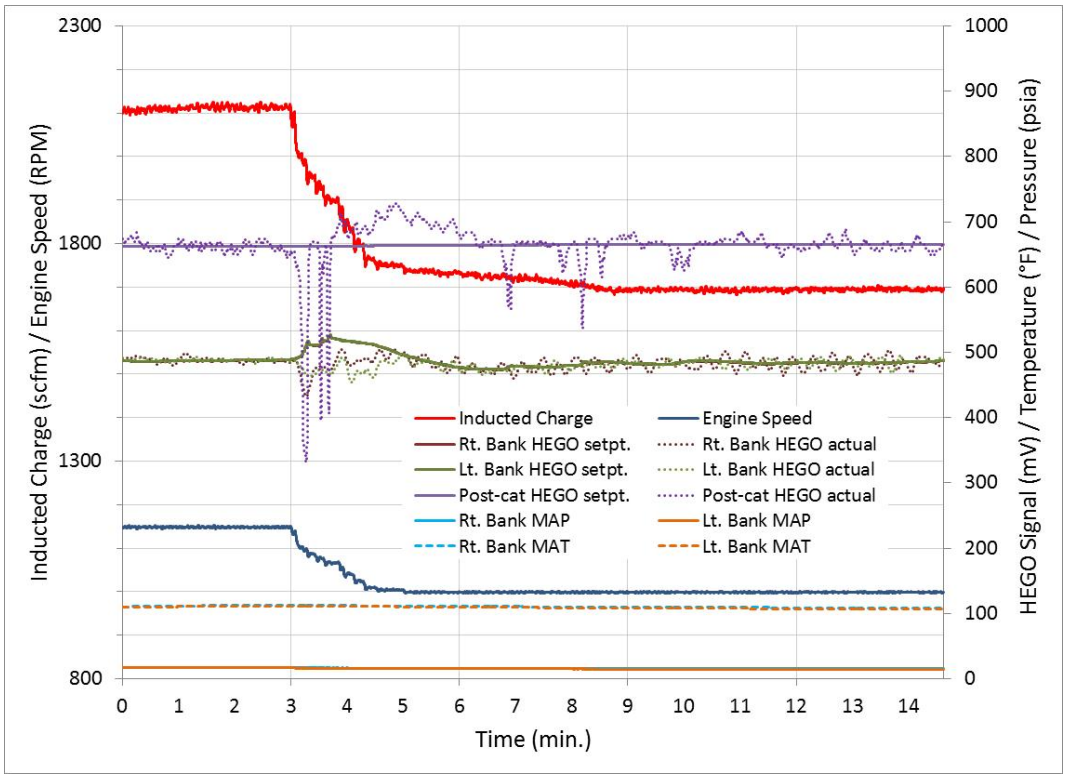


Figure 84: Transition from HS/HL to MS/ML on 20-Aug

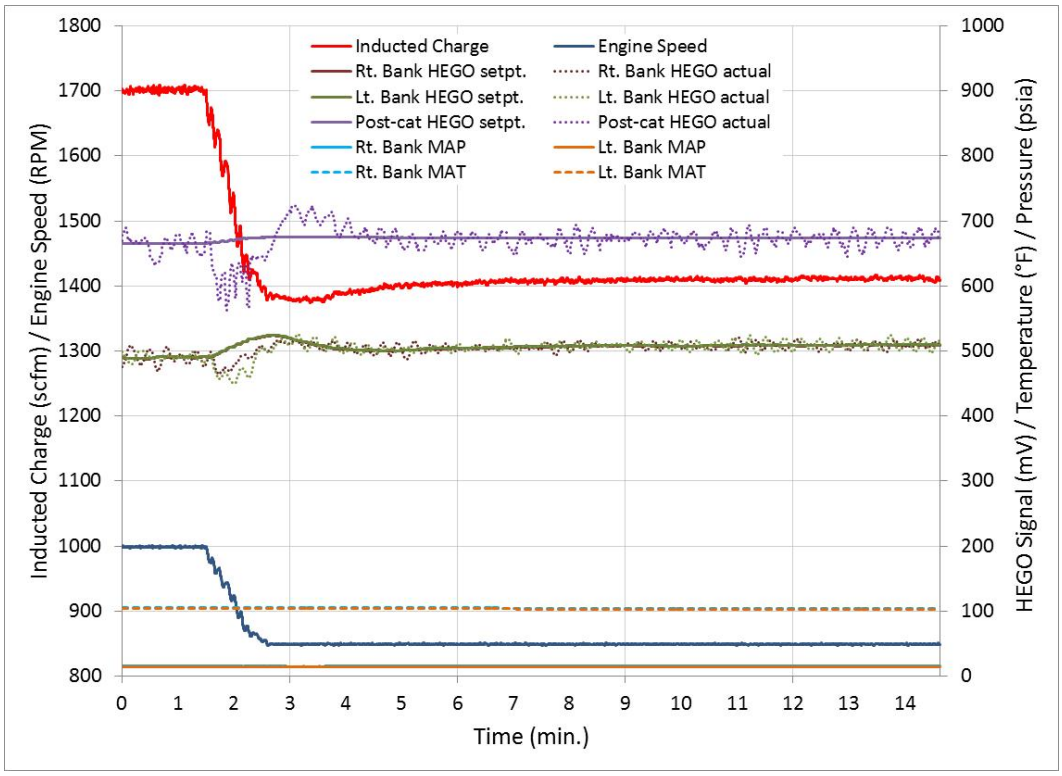


Figure 85: Transition from MS/ML to LS/LL on 20-Aug

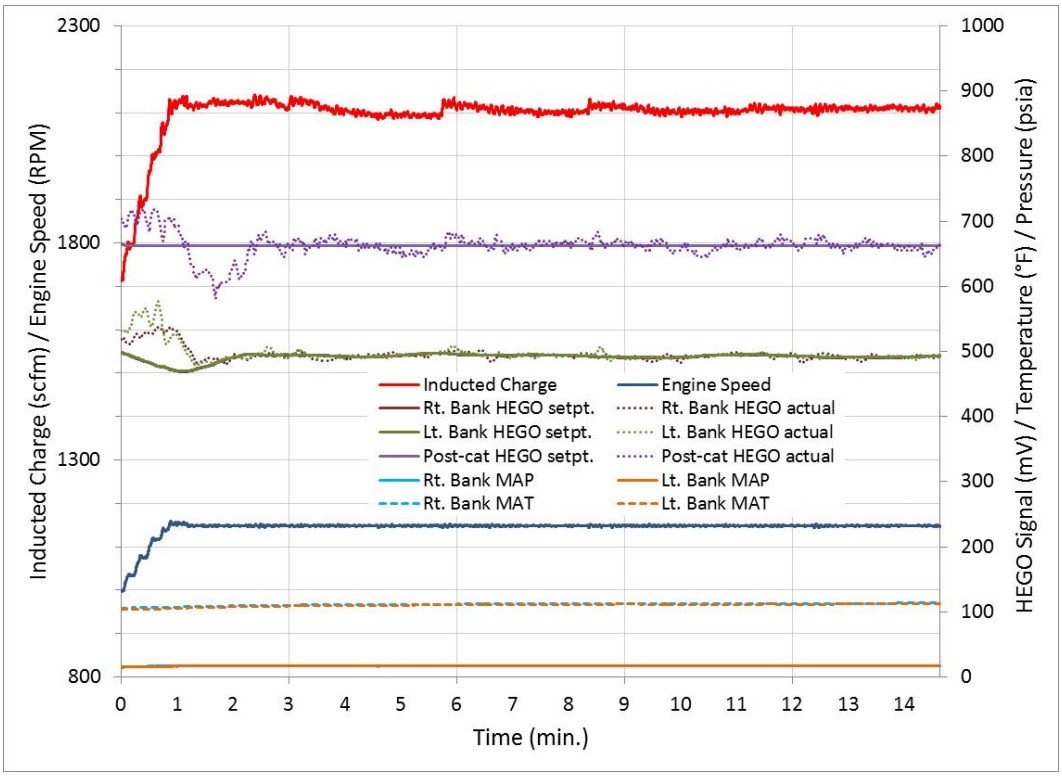


Figure 86: Transition from LS/LL to HS/HL on 20-Aug

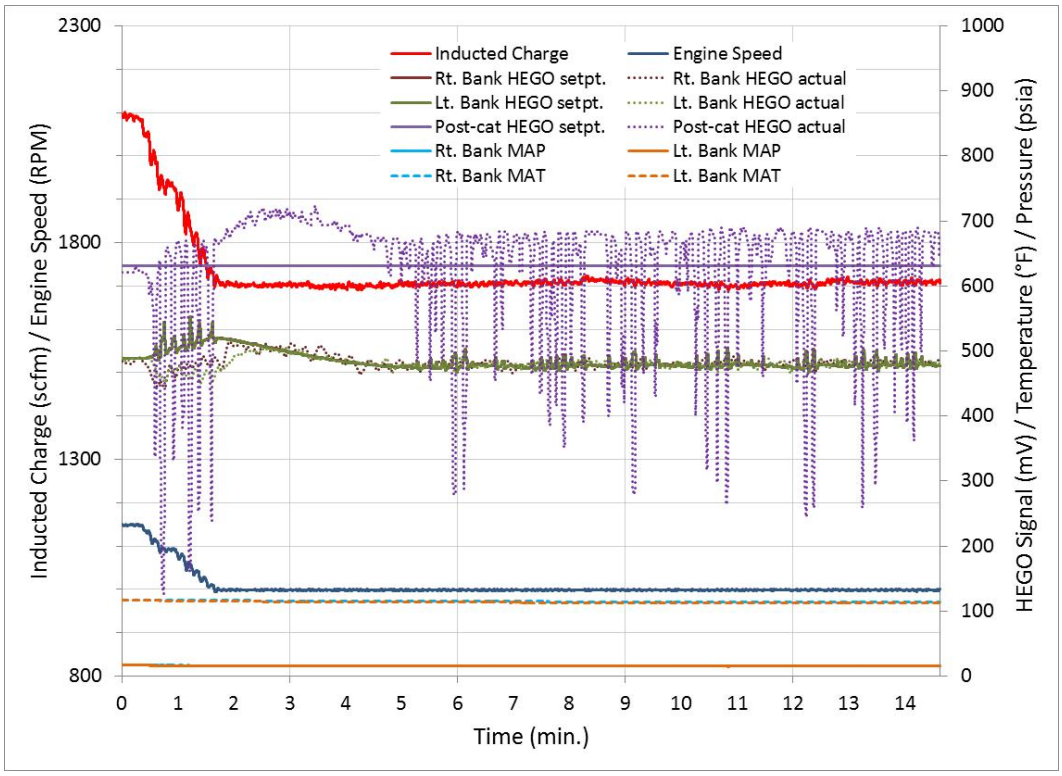


Figure 87: Transition from HS/HL to MS/ML on 24-Aug (after retuning)

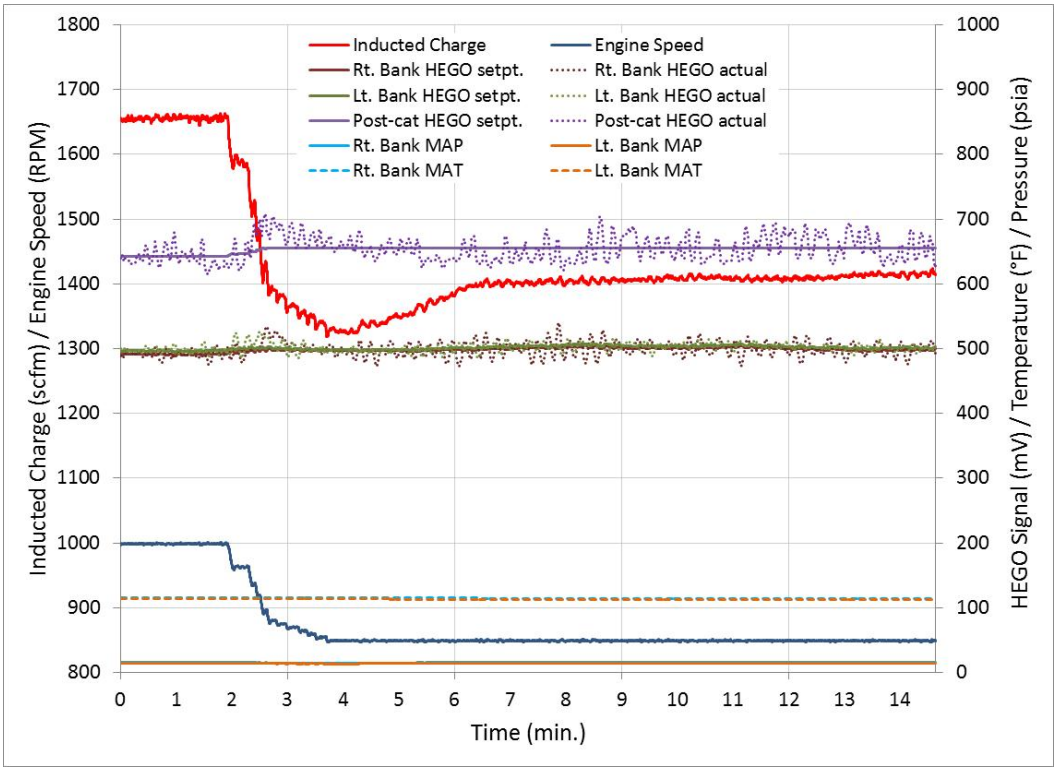


Figure 88: Transition from MS/ML to LS/LL on 24-Aug (after retuning)

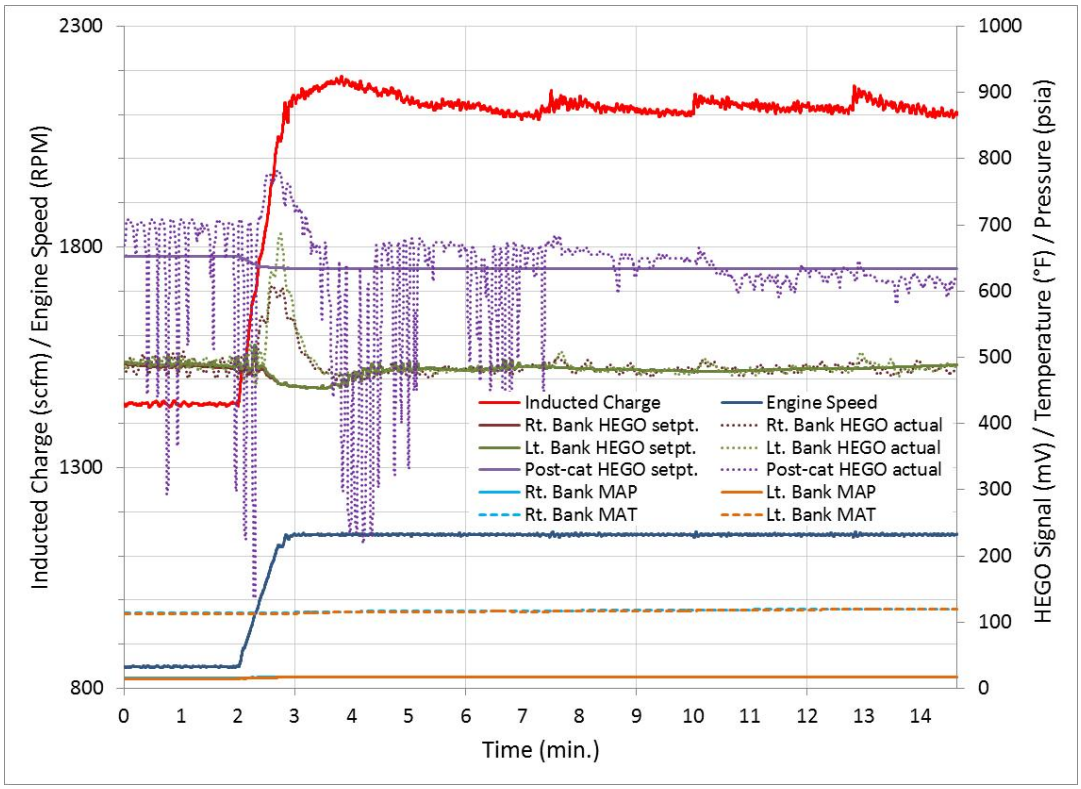


Figure 89: Transition from LS/LL to HS/HL on 24-Aug (after retuning)

Appendix E: Field Data

Table 9: Field data log from February 27 (Site visit # 1)

Run	1/1	1/2	2/1	2/2	3/1	3/2	4A/1	4A/2	4B
Date	27-Feb-12	27-Feb-12	27-Feb-12	27-Feb-12	27-Feb-12	27-Feb-12	27-Feb-12	27-Feb-12	27-Feb-12
Time	9:59	10:39	11:25	12:01	12:45	13:23	14:08	14:50	16:20
Qmix Setpoint	2100	2100	1700	1700	1300	1300	2100	2100	2100
Speed Setpoint	1150	1150	1000	1000	850	850	1150	1150	1150
Test Duration [min]	15	15	15	15	15	15	15	15	15
Speed/Load Characterization	HS/HL	HS/HL	MS/ML	MS/ML	LS/LL	LS/LL	HS/HL	HS/HL	HS/HL
Engine									
Engine Runtime [hr]	47595	47596	47597	47597	47598	47599	47599	47600	47602
Volumetric Flow [SCFM]	2050	2100	1765	1705	1306	1300	2095	2120	2095
Ambient Temperature [°F]	70.1	69.0	70.1	70.3	69.9	70.5	70.3	71.0	70.7
Suction Pressure [psig]	120	125	130	122	108	107	125	127	125
Discharge Pressure [psig]	924	929	917	914	900	895	915	909	904
Discharge Temperature [°F]	115	120	115	113	101	103	123	124	122
Right Bank MAP [psig]	5	5	4	4	2	3	5	5	5
Left Bank MAP [psig]	5	5	4	4	1	1	4	5	4
Jacket Water Temperature [°F]	177	178	178	177	176	176	178	179	178
Jacket Water Pressure [psig]	22	21	19	18	16	16	21	21	22
Oil temperature [°F]	194	194	193	193	193	193	194	193	193
Oil pressure [psig]	54	54	49	50	43	43	54	53	53
Average MAT [°F]									
Fuel Flow [SCFD]	62	65	46	43	24	24	64	67	64
ESM Load [%]	86	86	81	81	70	70	83	84	83
Throttle Position [%]	44	45	38	34	27	27	44	46	46
Ignition Timing	24	24	26	26	26	26	22 ↔ 24	24	24
Right Fuel/Air Pressure ["H2O]		1.0	3.0	4.0	4.5	5.0	3.0	2.0	
Left Fuel/Air Pressure ["H2O]		2.0	3.3	4.0	4.5	4.0	2.5	2.0	
Fuel pressure [psig]	142	142	146	146	147	147	142	142	142
Catalyst ΔP ["H2O]	6.0	6.2	4.7	4.4	2.8	3.0	6.0	6.1	6.0
POST CATALYST									
NO_x sensor [V] - NO_x 1	1.019	1.038	1.010	1.011	1.045	1.027	1.035	1.037	1.017
Outlet Temperature [°F]	1119	1120	1056	1046	956	953	1115	1116	1109
PRE CATALYST									
NO_x sensor [V] - NO_x 2	3.244	3.243	3.311	3.253	2.977	2.935	3.231	3.230	3.257
Inlet Temperature [°F]	1070	1072	1011	1005	937	935	1071	1075	1069
POST CATALYST Emissions									
Raw CO [ppm]	191	176	102	112	135	154	189	180	
Brake specific CO [g/bhp-hr]	0.49	0.45	0.26	0.28	0.33	0.38	0.48	0.46	
Raw NO_x [ppm]	34	34	29	31	39	43	37	36	
Brake specific NO_x [g/bhp-hr]	0.14	0.14	0.12	0.13	0.16	0.18	0.16	0.15	
PRE CATALYST Emissions									
Raw CO [ppm]									9431
Brake specific CO [g/bhp-hr]									22.73
Raw NO_x [ppm]									3692
Brake specific NO_x [g/bhp-hr]									14.61
CO_2 [%] / O_2 [%]									11.53/0.27

Table 10: Field data log from March 13 (Site visit # 2)

Run	14A/1	14A/2	14A/3	14B	15A/1	15A/2	16A/1	16A/2	17A/1	17A/2
Date	13-Mar-12	13-Mar-12	13-Mar-12	13-Mar-12	13-Mar-12	13-Mar-12	13-Mar-12	13-Mar-12	13-Mar-12	13-Mar-12
Time	10:44	11:25	12:13	12:36	13:33	14:00	14:04	15:03	15:51	16:14
Qmix Setpoint	2100	2100	2100	2100	1700	1700	1400	1400	2100	2100
Speed Setpoint	1150	1150	1150	1150	1000	1000	850	850	1150	1150
Test Duration [min]	15	15	15	15	15	15	15	15	15	15
Speed/Load Characterization	HS/HL	HS/HL	HS/HL	HS/HL	MS/ML	MS/ML	LS/LL	LS/LL	HS/HL	HS/HL
Engine										
Engine Runtime [hr]	47952	47953	47954	47954	47955	47955	47956	47956	47957	47958
Volumetric Flow [SCFM]	2065	2110	2090	2090	1710	1710	1403	1400	2103	2110
Ambient Temperature [°F]	79.3	78.2	77.1	78.4	76.6	77.5	78	78.2	78.8	75.7
Suction Pressure [psig]	120	124	124	123	121	120	123	123	126	122
Discharge Pressure [psig]	972	963	947	947	940	938	936	935	961	976
Discharge Temperature [°F]	124	121	112	117	98	97	90	93	108	106
Right Bank MAP [psig]	5	5	5	5	4	4	3	3	5	5
Left Bank MAP [psig]	5	5	5	5	3	3	3	3	5	5
Jacket Water Temperature [°F]	181	181	178	178	176	176	176	177	177	177
Jacket Water Pressure [psig]	21	22	21	21	19	18	16	16	22	21
Oil temperature [°F]	192	193	193	193	192	192	192	192	193	193
Oil pressure [psig]	54	54	53	54	51	51	43	43	53	53
Average MAT [°F]	107	106	102	103	96	96	90	92	102	102
Fuel Flow [SCFD]	62	66	65	65	44	43	28	28	66	65
ESM Load [%]	84	85	85	84	78	78	76	77	84	84
Throttle Position [%]	47	50	49	48	37	37	32	32	50	49
Ignition Timing	24	24	24	24	26	26	26	26	22↔24	23↔24
Right Fuel/Air Pressure ["H2O]										
Left Fuel/Air Pressure ["H2O]										
Fuel pressure [psig]	144	143	142	142	145	144	145	144	144	143
Catalyst ΔP ["H2O]	4.2	4.2	4.3	4.0	3.3	3.2	2.4	2.5	4.4	4.4
POST CATALYST										
NO_x sensor [V] - NO_x 1										
Outlet Temperature [°F]	1098	1096	1094	1088	1009	1008	929	929	1088	1086
PRE CATALYST										
NO_x sensor [V] - NO_x 2										
Inlet Temperature [°F]	1072	1072	1070	1063	993	993	936	934	1070	1066
POST CATALYST Emissions										
Raw CO [ppm]	234	199	212		115	117	152	170	230	191
Brake specific CO [g/bhp-hr]	0.60	0.51	0.54		0.29	0.29	0.38	0.42	0.59	0.49
Raw NO_x [ppm]	46	45	46		38	36	45	49	57	48
Brake specific NO_x [g/bhp-hr]	0.19	0.19	0.19		0.16	0.15	0.18	0.20	0.24	0.20
PRE CATALYST Emissions										
Raw CO [ppm]				9527						
Brake specific CO [g/bhp-hr]				22.97						
Raw NO_x [ppm]				3769						
Brake specific NO_x [g/bhp-hr]				14.93						
CO_2 [%] / O_2 [%]				11.51 / 0.3						

Table 11: Field data log from April 2 (Site visit # 3)

Run	19A/1	19A/2	20A/1	20A/2	21A/1	21A/2	21A/3	22A/1	22A/2	22B
Date	2-Apr-12	2-Apr-12	2-Apr-12	2-Apr-12	2-Apr-12	2-Apr-12	2-Apr-12	2-Apr-12	2-Apr-12	2-Apr-12
Time	14:40	15:05	15:50	16:15	17:05	17:30	18:00	18:40	19:05	19:30
Qmix Setpoint	2100	2100	1700	1700	1400	1400	1400	2100	2100	2100
Speed Setpoint	1150	1150	1000	1000	850	850	850	1150	1150	1150
Test Duration [min]	15	15	15	15	15	15	15	15	15	15
Speed/Load Characterization	HS/HL	HS/HL	MS/ML	MS/ML	LS/LL	LS/LL	LS/LL	HS/HL	HS/HL	HS/HL
Engine										
Engine Runtime [hr]	48432	48432	48433	48433	48434	48435	48435	48436	48436	48437
Volumetric Flow [SCFM]	2105	2070	1696	1700	1397	1398	1400	2075	2100	2097
Ambient Temperature [°F]	69.4	69.8	70	70.8	70.5	70.5	70.1	71.4	71.6	71.7
Suction Pressure [psig]	121	116	111	111	115	115	115	118	118	117
Discharge Pressure [psig]	978	1004	989	982	976	983	976	993	1006	1004
Discharge Temperature [°F]	96	93	91	94	103	105	105	115	115	114
Right Bank MAP [psig]	5	4	3	3	3	3	3	5	5	4
Left Bank MAP [psig]	4	4	2	2	1	2	2	4	4	4
Jacket Water Temperature [°F]	176	176	176	176	177	177	177	176	176	176
Jacket Water Pressure [psig]	18	18	15	15	12	12	12	17	17	17
Oil temperature [°F]	195	195	195	194	194	194	194	195	195	195
Oil pressure [psig]	53	52	50	50	42	42	43	52	53	53
Average MAT [°F]	85	84	80	81	79	80	80	86	86	85
Fuel Flow [SCFD]	140	140	128	127	104	27	27	62	63	62
ESM Load [%]	83	82	75	75	71	71	71	83	83	82
Throttle Position [%]	46	45	34	34	30	31	30	44	44	43
Ignition Timing	25	25	26	26	26	26	26	25	25	25
Right Fuel/Air Pressure ["H2O]										
Left Fuel/Air Pressure ["H2O]										
Fuel pressure [psig]	141	140	140	142	142	145	144	145	145	145
Catalyst ΔP ["H2O]	4.0	4.0	3.0	3.0	2.2	2.2	2.3	4.0	4.0	4.0
POST CATALYST										
NO_x sensor [V] - NO_x 1										
Outlet Temperature [°F]	1085	1081	1010	1014	947	945	948	1091	1078	1077
PRE CATALYST										
NO_x sensor [V] - NO_x 2										
Inlet Temperature [°F]	1073	1071	1008	1009	953	954	954	1075	1076	1074
POST CATALYST Emissions										
Raw CO [ppm]	238	251	176	203	176	338	247	208	203	
Brake specific CO [g/bhp-hr]	0.61	0.64	0.44	0.51	0.44	0.83	0.61	0.53	0.52	
Raw NO_x [ppm]	41	46	41	45	69	74	107	38	41	
Brake specific NO_x [g/bhp-hr]	0.17	0.19	0.17	0.19	0.28	0.30	0.43	0.16	0.17	
PRE CATALYST Emissions										
Raw CO [ppm]										8227
Brake specific CO [g/bhp-hr]										19.95
Raw NO_x [ppm]										3599
Brake specific NO_x [g/bhp-hr]										14.34
CO_2 [%] / O_2 [%]										11.57 / 0.21

Table 12: Field data log from May 15 – Part 1/2 (Site visit # 4)

Run	24A/1	24A/2	25A/1	25A/2	25A/3	25A/4	26A/1	26A/2
Date	15-May-12	15-May-12	15-May-12	15-May-12	15-May-12	15-May-12	15-May-12	15-May-12
Time	10:35	11:01	12:30	12:55	13:30	14:00	14:45	15:10
Qmix Setpoint	2100	2100	1700	1700	1700	1700	1400	1400
Speed Setpoint	1150	1150	1000	1000	1000	1000	850	850
Test Duration [min]	15	15	15	15	15	15	15	15
Speed/Load Characterization	HS/HL	HS/HL	MS/ML	MS/ML	MS/ML	MS/ML	LS/LL	LS/LL
Engine								
Engine Runtime [hr]	49443	49443	49445	49445	49446	49446	49447	49447
Volumetric Flow [SCFM]	2100		1710	1740	1725	1720	1409	1392
Ambient Temperature [°F]	89	90.1	91.7	91.5	93.3	94.4	95	94.2
Suction Pressure [psig]	99	99	98	98	98	98	102	100
Discharge Pressure [psig]	935	938	920	966	951	973	1004	1004
Discharge Temperature [°F]	109	108	108	111	108	111	109	111
Right Bank MAP [psig]	5	5	4	4	4	4	3	3
Left Bank MAP [psig]	5	5	3	3	3	3	3	3
Jacket Water Temperature [°F]	178	178	177	177	177	178	177	177
Jacket Water Pressure [psig]	22	21	18	18	18	17	15	15
Oil temperature [°F]	193	193	191	191	191	191	190	190
Oil pressure [psig]	52	52	49	49	49	49	42	42
Average MAT [°F]	109	110	107	109	109	109	107	107
Fuel Flow [SCFD]	64	----	41	41		42	29	29
ESM Load [%]	85	85	79	79	79	78	77	77
Throttle Position [%]	----	----	----	----	----	----	----	----
Ignition Timing	24	24	26	26	26	24↔26	26	26
Right Fuel/Air Pressure ["H2O]	-0.5↔3.5	2.0	0.5↔2.0	2.0↔3.5	2.0↔3.0	2.5↔4.0	4.0↔6.0	3.0↔6.0
Left Fuel/Air Pressure ["H2O]	2.0↔3.0	1.5	0.0↔1.0	2.0	3.0	3.0	3.5↔4.0	3.0↔3.5
Fuel pressure [psig]	149	150	152	152	153	153	148	144
Catalyst ΔP ["H2O]	4.0	4.0	3.0	3.0	3.0	3.0	2.2	2.2
POST CATALYST								
NO_x sensor [V] - NO_x 1	2.266		1.371	0.877	0.877	1.641	1.753	2.788
Outlet Temperature [°F]	1131	1131	1059	1062	1063	1063	992	990
PRE CATALYST								
NO_x sensor [V] - NO_x 2	3.567		3.541	3.558	3.601	3.519	3.176	3.404
Inlet Temperature [°F]	1084	1084	1015	1018	1020	1019	962	960
POST CATALYST Emissions								
Raw CO [ppm]	381	383	261	59	136	239	308	301
Brake specific CO [g/bhp-hr]	0.98	0.98	0.66	0.15	0.34	0.60	0.76	0.74
Raw NO_x [ppm]	95	106	69	34	67	58	61	62
Brake specific NO_x [g/bhp-hr]	0.40	0.45	0.29	0.14	0.28	0.24	0.25	0.25
PRE CATALYST Emissions								
Raw CO [ppm]								
Brake specific CO [g/bhp-hr]								
Raw NO_x [ppm]								
Brake specific NO_x [g/bhp-hr]								
CO_2 [%] / O_2 [%]								

Table 13: Field data log from May 15 and 16 – Part 2/2 (Site visit # 4)

Run	27A/1	27A/2	27B	28A/1	28A/2	28B
Date	15-May-12	15-May-12	15-May-12	16-May-12	16-May-12	16-May-12
Time	16:35	17:00	19:30	16:50	17:15	17:50
Qmix Setpoint	2100	2100	2100	2100	2100	2100
Speed Setpoint	1150	1150	1150	1150	1150	1150
Test Duration [min]	15	15	15	15	15	15
Speed/Load Characterization	HS/HL	HS/HL	HS/HL	HS/HL	HS/HL	HS/HL
Engine						
Engine Runtime [hr]	49449	Engine shutdown owing to excessive vibration. Run aborted.		49468	49469	49469
Volumetric Flow [SCFM]	2095			2095	2110	2140
Ambient Temperature [°F]	96.4			94.4	94.2	92.6
Suction Pressure [psig]	101			101	101	101
Discharge Pressure [psig]	965			1024	1081	1133
Discharge Temperature [°F]	113			112	113	114
Right Bank MAP [psig]	5			5	5	5
Left Bank MAP [psig]	6			5	5	5
Jacket Water Temperature [°F]	178			178	178	179
Jacket Water Pressure [psig]	21			21	21	20
Oil temperature [°F]	193			192	193	193
Oil pressure [psig]	53			53	52	51
Average MAT [°F]	115			114	115	115
Fuel Flow [SCFD]	70					
ESM Load [%]	86			84	85	86
Throttle Position [%]	- - - -			- - - -	- - - -	- - - -
Ignition Timing	22↔23			24	24	23
Right Fuel/Air Pressure ["H2O]	0.5↔3.0			0.5↔2.0	0.0↔2.0	0.5↔2.0
Left Fuel/Air Pressure ["H2O]	1.0↔2.5			0.5↔1.5	1.5↔2.0	1.0↔2.0
Fuel pressure [psig]	141			122	130	130
Catalyst ΔP ["H2O]	4.2			4.2	4.3	4.3
POST CATALYST						
NO_x sensor [V] - NO_x 1	2.77			2.898	2.267	2.817
Outlet Temperature [°F]	1138			1126	1134	1137
PRE CATALYST						
NO_x sensor [V] - NO_x 2	3.553			3.702	3.771	3.761
Inlet Temperature [°F]	1094			1077	1085	1089
POST CATALYST Emissions						
Raw CO [ppm]	421			365	422	
Brake specific CO [g/bhp-hr]	1.08			0.93	1.08	
Raw NO_x [ppm]	94			73	86	
Brake specific NO_x [g/bhp-hr]	0.40			0.31	0.36	
PRE CATALYST Emissions						
Raw CO [ppm]			9979			9876
Brake specific CO [g/bhp-hr]			23.99			23.77
Raw NO_x [ppm]			3382			3544
Brake specific NO_x [g/bhp-hr]			13.36			14.01
CO_2 [%] / O_2 [%]			11.5 / 0.3			11.5/0.3

Table 14: Field data log from June 25 (Site visit # 5)

Run	30A/1	30A/2	31A/1	31A/2	32A/1	32A/2	33A/1	33A/2	33B
Date	25-Jun-12	25-Jun-12	25-Jun-12	25-Jun-12	25-Jun-12	25-Jun-12	25-Jun-12	25-Jun-12	25-Jun-12
Time	12:35	13:00	13:45	14:15	15:00	15:20	16:05	16:30	17:00
Qmix Setpoint	2100	2100	1700	1700	1400	1400	2100	2100	2100
Speed Setpoint	1150	1150	1000	1000	850	850	1150	1150	1150
Test Duration [min]	15	15	15	15	15	15	15	15	15
Speed/Load Characterization	HS/HL	HS/HL	MS/ML	MS/ML	LS/LL	LS/LL	HS/HL	HS/HL	HS/HL
Engine									
Engine Runtime [hr]	50410	50410	50411	50411	50412	50413	50413	50414	50414
Volumetric Flow [SCFM]	2089	2110	1700	1700	1400	1450	2100	2100	2075
Ambient Temperature [°F]	108	108	109	110	111	111	111	111	106
Suction Pressure [psig]	91	91	90	90	96	94	92	92	92
Discharge Pressure [psig]	876	896	893	912	849	861	909	922	859
Discharge Temperature [°F]	116	118	116	118	119	116	121	120	119
Right Bank MAP [psig]	5	5	4	4	4	4	5	5	5
Left Bank MAP [psig]	5	5	4	4	3	3	6	6	6
Jacket Water Temperature [°F]	180	180	179	179	180	179	183	181	181
Jacket Water Pressure [psig]	22	22	18	19	16	16	22	22	22
Oil temperature [°F]	193	193	190	190	190	190	194	193	193
Oil pressure [psig]	52	51	47	47	41	41	50	50	51
Average MAT [°F]	124	124	121	122	121	120	131	129	127
Fuel Flow [SCFD]	75	74	48	49	30	35	73	72	71
ESM Load [%]	84	85	79	80	78	77	86	86	84
Throttle Position [%]	57	59	45	46	41	41	64	65	58
Ignition Timing	20↔24	21↔24	26	22↔26	26	26	21↔23	21↔23	21↔24
Right Fuel/Air Pressure ["H2O]	0.0↔3.5	0.0↔3.0	3.0↔5.5	3.0↔4.5	4.5↔7.0	4.0↔6.5	0.5↔3.0	0.0↔2.0	
Left Fuel/Air Pressure ["H2O]	3.0↔4.0	3.5↔5.0	4.0↔5.5	4.0↔5.5	5.0↔5.5	4.5↔6.0	4.0↔5.0	3.0↔4.0	
Fuel pressure [psig]	140	141	142	142	147	146	145	146	143
Catalyst ΔP ["H2O]	4.0	4.2	3.0	3.0	2.2	2.1	4.2	4.2	4.2
POST CATALYST									
NO_x sensor [V] - NO_x 1	2.08	1.206	1.396	5.078	5.079	5.078	0.956	1.446	1.245
Outlet Temperature [°F]	1173	1172	1095	1095	1010	1007	1179	1181	1165
PRE CATALYST									
NO_x sensor [V] - NO_x 2	3.178	3.189	3.406	3.394	4.464	4.284	3.501	3.104	3.54
Inlet Temperature [°F]	1092	1087	1017	1022	942	941	1093	1098	1081
POST CATALYST Emissions									
Raw CO [ppm]	221	186	16	12	7257	6971	216	233	
Brake specific CO [g/bhp-hr]	0.57	0.48	0.04	0.03	17.06	16.43	0.55	0.60	
Raw NO_x [ppm]	68	63	229	220	1013	1025	57	62	
Brake specific NO_x [g/bhp-hr]	0.29	0.27	0.95	0.91	3.91	3.97	0.24	0.26	
PRE CATALYST Emissions									
Raw CO [ppm]									12469
Brake specific CO [g/bhp-hr]									29.39
Raw NO_x [ppm]									3232
Brake specific NO_x [g/bhp-hr]									12.51
CO_2 [%] / O_2 [%]					11.6/0.2	11.6/0.2			11.5/0.3

Table 15: Field data log from 24-hour test on June 26 – Part 1/4 (Site visit # 5)

Run	35A	36A	37A	38A	39A	40A
Date	26-Jun-12	26-Jun-12	26-Jun-12	26-Jun-12	26-Jun-12	26-Jun-12
Time	14:05	15:05	16:05	17:05	18:05	19:05
Qmix Setpoint	As found	As found	As found	As found	As found	As found
Speed Setpoint	1140	1140	1140	1140	1140	1140
Test Duration [min]	15	15	15	15	15	15
Speed/Load Characterization	As found	As found	As found	As found	As found	As found
Engine						
Engine Runtime [hr]	50435	50436	50437	50438	50439	50440
Volumetric Flow [SCFM]	2120	2140	2110	2118	2120	2117
Ambient Temperature [°F]	103	104	103	108	106	105
Suction Pressure [psig]	97	94	97	97	97	97
Discharge Pressure [psig]	925	924	916	905	924	917
Discharge Temperature [°F]	118	119	119	120	118	117
Right Bank MAP [psig]	6	5	5	5	5	5
Left Bank MAP [psig]	6	5	5	5	5	5
Jacket Water Temperature [°F]	182	182	182	181	182	180
Jacket Water Pressure [psig]	21	22	22	22	22	22
Oil temperature [°F]	193	194	194	194	193	193
Oil pressure [psig]	50	50	50	50	50	51
Average MAT [°F]	128	129	128	128	127	124
Fuel Flow [SCFD]	77	77	76	75	75	75
ESM Load [%]	86	86	85	85	85	86
Throttle Position [%]	68	69	67	67	65	65
Ignition Timing	23	23	24	24	23	23
Right Fuel/Air Pressure ["H2O]	Hour 0	Hour 1	Hour 2	Hour 3	Hour 4	Hour 5
Left Fuel/Air Pressure ["H2O]	- -	- -	- -	- -	- -	- -
Fuel pressure [psig]	138	138	140	138	139	138
Catalyst ΔP ["H2O]	4.2	4.2	4.2	4.2	4.2	4.2
POST CATALYST						
NO_x sensor [V] - NO_x 1	2.01	1.053	0.882	1.094	1.463	2.155
Outlet Temperature [°F]	1161	1157	1152	1156	1156	1156
PRE CATALYST						
NO_x sensor [V] - NO_x 2	3.702	3.619	3.682	3.691	3.701	3.7
Inlet Temperature [°F]	1080	1077	1074	1076	1077	1077
POST CATALYST Emissions						
Raw CO [ppm]	243	233	211	217	227	236
Brake specific CO [g/bhp-hr]	0.62	0.60	0.54	0.56	0.58	0.60
Raw NO_x [ppm]	52	60	56	58	61	61
Brake specific NO_x [g/bhp-hr]	0.22	0.25	0.24	0.24	0.26	0.26

Table 16: Field data log from 24-hour test on June 26 and 27 – Part 2/4 (Site visit # 5)

Run	41A	42A	43A	44A	45A	46A
Date	26-Jun-12	26-Jun-12	26-Jun-12	27-Jun-12	27-Jun-12	27-Jun-12
Time	20:05	21:05	23:05	0:05	1:05	2:05
Qmix Setpoint	As found	As found	As found	As found	As found	As found
Speed Setpoint	1140	1140	1140	1140	1140	1140
Test Duration [min]	15	15	15	15	15	15
Speed/Load Characterization	As found	As found	As found	As found	As found	As found
Engine						
Engine Runtime [hr]	50441	50442	50444	50445	50446	50447
Volumetric Flow [SCFM]	2135	2140	2150	2180	2200	2214
Ambient Temperature [°F]	102	98	93	91	86	88
Suction Pressure [psig]	97	97	97	97	97	97
Discharge Pressure [psig]	930	936	950	1010	1046	1055
Discharge Temperature [°F]	114	111	108	109	110	110
Right Bank MAP [psig]	5	5	5	6	6	6
Left Bank MAP [psig]	5	5	5	5	6	6
Jacket Water Temperature [°F]	178	178	177	178	178	178
Jacket Water Pressure [psig]	22	21	22	22	21	21
Oil temperature [°F]	192	192	192	192	192	192
Oil pressure [psig]	50	51	51	51	50	51
Average MAT [°F]	121	115	110	110	109	108
Fuel Flow [SCFD]	76	77	77	78	79	81
ESM Load [%]	86	86	86	87	88	88
Throttle Position [%]	67	62	62	67	66	71
Ignition Timing	24	24	24	23	23	23
Right Fuel/Air Pressure ["H2O]	Hour 6	Hour 7	Hour 9	Hour 10	Hour 11	Hour 12
Left Fuel/Air Pressure ["H2O]	- -	- -	- -	- -	- -	- -
Fuel pressure [psig]	138	138	136	138	138	135
Catalyst ΔP ["H2O]	4.2	4.2	4.2	4.3	4.3	4.4
POST CATALYST						
NO_x sensor [V] - NO_x 1	2.145	1.113	2.095	2.222	1.593	1.59
Outlet Temperature [°F]	1154	1153	1156	1158	1159	1165
PRE CATALYST						
NO_x sensor [V] - NO_x 2	3.611	3.645	3.632	3.629	3.667	3.566
Inlet Temperature [°F]	1075	1076	1078	1083	1084	1084
POST CATALYST Emissions						
Raw CO [ppm]	221	229	277	276	286	276
Brake specific CO [g/bhp-hr]	0.57	0.59	0.71	0.71	0.73	0.71
Raw NO_x [ppm]	59	56	66	68	69	63
Brake specific NO_x [g/bhp-hr]	0.25	0.24	0.28	0.29	0.29	0.26

Table 17: Field data log from 24-hour test on June 27 – Part 3/4 (Site visit # 5)

Run	47A	48A	49A	50A	51A	52A
Date	27-Jun-12	27-Jun-12	27-Jun-12	27-Jun-12	27-Jun-12	27-Jun-12
Time	3:05	4:05	5:05	6:05	7:05	8:05
Qmix Setpoint	As found	As found	As found	As found	As found	As found
Speed Setpoint	1140	1140	1140	1140	1140	1140
Test Duration [min]	15	15	15	15	15	15
Speed/Load Characterization	As found	As found	As found	As found	As found	As found
Engine						
Engine Runtime [hr]	50448	50449	50450	50451	50452	50453
Volumetric Flow [SCFM]	2200	2220	2206	2160	2160	2150
Ambient Temperature [°F]	85	89	89	90	90	88
Suction Pressure [psig]	97	97	97	97	97	97
Discharge Pressure [psig]	1023	1056	1031	924	933	936
Discharge Temperature [°F]	108	111	112	105	107	107
Right Bank MAP [psig]	6	6	6	5	5	5
Left Bank MAP [psig]	6	6	6	6	6	6
Jacket Water Temperature [°F]	177	178	178	177	177	177
Jacket Water Pressure [psig]	21	22	22	22	21	21
Oil temperature [°F]	191	192	192	191	191	191
Oil pressure [psig]	51	51	51	52	51	51
Average MAT [°F]	105	108	107	104	106	106
Fuel Flow [SCFD]	81	80	80	74	77	77
ESM Load [%]	89	88	88	87	87	87
Throttle Position [%]	65	68	63	56	56	56
Ignition Timing	23	23	23	23	23	23
Right Fuel/Air Pressure ["H2O]	Hour 13	Hour 14	Hour 15	Hour 16	Hour 17	Hour 18
Left Fuel/Air Pressure ["H2O]	- -	- -	- -	- -	- -	- -
Fuel pressure [psig]	134	135	134	136	134	134
Catalyst ΔP ["H2O]	4.4	4.4	4.4	4.2	4.2	4.2
POST CATALYST						
NO_x sensor [V] - NO_x 1	1.9	1.723	2.24	2.14	1.49	2.535
Outlet Temperature [°F]	1166	1172	1172	1158	1146	1148
PRE CATALYST						
NO_x sensor [V] - NO_x 2	3.577	3.613	3.631	3.632	3.661	3.581
Inlet Temperature [°F]	1085	1087	1086	1077	1077	1077
POST CATALYST Emissions						
Raw CO [ppm]	272	279	268	281	263	274
Brake specific CO [g/bhp-hr]	0.70	0.71	0.69	0.72	0.67	0.70
Raw NO_x [ppm]	61	63	63	69	74	76
Brake specific NO_x [g/bhp-hr]	0.26	0.26	0.26	0.29	0.31	0.32

Table 18: Field data log from 24-hour test on June 27 – Part 4/4 (Site visit # 5)

Run	53A	54A	55A
Date	27-Jun-12	27-Jun-12	27-Jun-12
Time	9:05	10:05	12:05
Qmix Setpoint	As found	As found	As found
Speed Setpoint	1140	1140	1140
Test Duration [min]	15	15	15
Speed/Load Characterization	As found	As found	As found
Engine			
Engine Runtime [hr]	50454	50455	50457
Volumetric Flow [SCFM]	2160	2150	2150
Ambient Temperature [°F]	91	94	98
Suction Pressure [psig]	97	98	98
Discharge Pressure [psig]	941	941	940
Discharge Temperature [°F]	112	113	114
Right Bank MAP [psig]	5	5	5
Left Bank MAP [psig]	6	6	6
Jacket Water Temperature [°F]	178	178	179
Jacket Water Pressure [psig]	21	22	21
Oil temperature [°F]	191	191	192
Oil pressure [psig]	52	51	50
Average MAT [°F]	109	112	119
Fuel Flow [SCFD]	77	79	79
ESM Load [%]	87	87	88
Throttle Position [%]	59	61	66
Ignition Timing	23	23	20↔23
Right Fuel/Air Pressure ["H2O]	Hour 19	Hour 20	Hour 22
Left Fuel/Air Pressure ["H2O]	- -	- -	- -
Fuel pressure [psig]	134	134	138
Catalyst ΔP ["H2O]	4.2	4.2	4.2
POST CATALYST			
NO_x sensor [V] - NO_x 1	2.303	2.833	2.505
Outlet Temperature [°F]	1149	1151	1155
PRE CATALYST			
NO_x sensor [V] - NO_x 2	3.597	3.638	3.545
Inlet Temperature [°F]	1076	1081	1088
POST CATALYST Emissions			
Raw CO [ppm]	268	265	310
Brake specific CO [g/bhp-hr]	0.69	0.68	0.79
Raw NO_x [ppm]	74	72	80
Brake specific NO_x [g/bhp-hr]	0.31	0.30	0.34

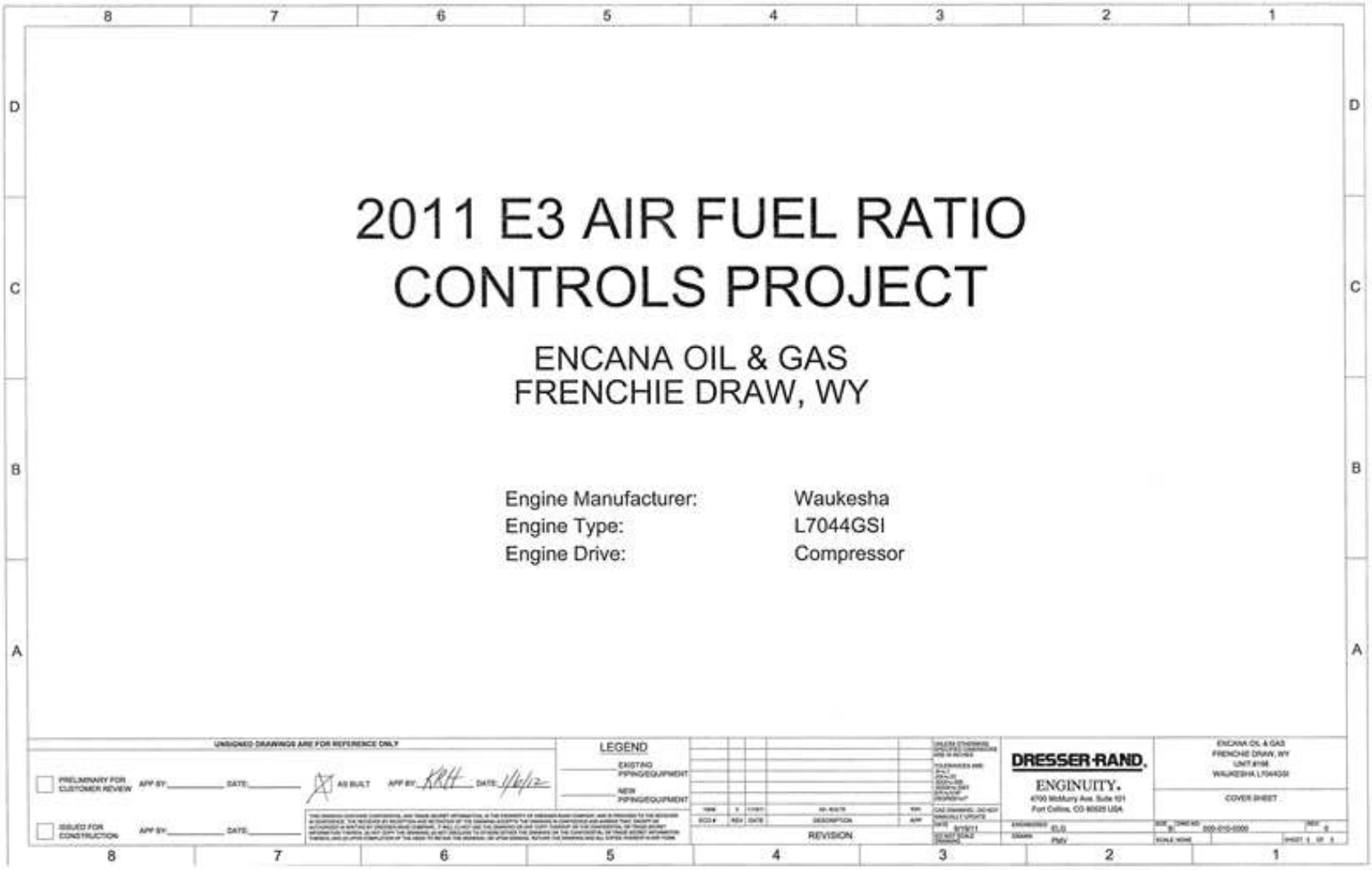
Table 19: Field data log from August 20 (Site visit # 6)

Run	57A/1	57A/2	58A/1	58A/2	59A/1	59A/2	60A/1	60A/2	60B
Date	20-Aug-12	20-Aug-12	20-Aug-12	20-Aug-12	20-Aug-12	20-Aug-12	20-Aug-12	20-Aug-12	20-Aug-12
Time	11:05	11:30	12:15	12:40	13:55	14:20	15:05	15:35	16:00
Qmix Setpoint	2100	2100	1700	1700	1400	1400	2100	2100	2100
Speed Setpoint	1150	1150	1000	1000	850	850	1150	1150	1150
Test Duration [min]	15	15	15	15	15	15	15	15	15
Speed/Load Characterization	HS/HL	HS/HL	MS/ML	MS/ML	LS/LL	LS/LL	HS/HL	HS/HL	HS/HL
Engine									
Engine Runtime [hr]	46873	46874	46874	46875	46876	46876	46877	46878	46878
Volumetric Flow [SCFM]	2105	2110	1690	1695	1405	1395	2100	2090	2100
Ambient Temperature [°F]	95	95	95	94	95	96	96	98	97
Suction Pressure [psig]	93	93	89	89	93	93	90	91	91
Discharge Pressure [psig]	920	915	918	928	928	934	943	934	916
Discharge Temperature [°F]	103	101	98	98	99	101	105	106	105
Right Bank MAP [psig]	5	5	5	5	4	4	5	5	5
Left Bank MAP [psig]	5	5	4	4	3	3	5	5	5
Jacket Water Temperature [°F]	179	178	178	177	179	179	179	180	179
Jacket Water Pressure [psig]	18	18	15	14	12	12	18	18	18
Oil temperature [°F]	193	193	190	191	191	191	193	193	193
Oil pressure [psig]	51	51	49	47	41	42	51	51	51
Average MAT [°F]	112	111	106	105	105	107	115	117	116
Fuel Flow [SCFD]	77	76	49	50	33	33	76	75	74
ESM Load [%]	85	85	82	81	78	78	84	84	83
Throttle Position [%]	--	--	--	--	--	--	--	--	--
Ignition Timing	24	24	26	26	26	26	22↔24	23↔24	24
Right Fuel/Air Pressure ["H2O]	--	--	--	--	--	--	--	--	--
Left Fuel/Air Pressure ["H2O]	--	--	--	--	--	--	--	--	--
Fuel pressure [psig]	130	130	133	134	136	135	134	134	134
Catalyst ΔP ["H2O]	4.9	4.7	3.4	3.4	2.6	2.6	4.8	4.8	4.8
POST CATALYST									
NO_x sensor [V] - NO_x 1	1.531	2.301	1.49	2.357	2.627	3.34	1.37	1.881	2.212
Outlet Temperature [°F]	1136	1134	1056	1053	985	984	1140	1140	1134
PRE CATALYST									
NO_x sensor [V] - NO_x 2	3.599	3.651	3.469	3.602	3.183	3.402	3.516	3.454	3.067
Inlet Temperature [°F]	1075	1073	1003	1002	955	954	1077	1079	1072
POST CATALYST Emissions									
Raw CO [ppm]	546	556	589	612	877	848	580	594	
Brake specific CO [g/bhp-hr]	1.40	1.40	1.48	1.54	2.16	2.08	1.48	1.52	
Raw NO_x [ppm]	50	52	61	65	100	102	51	54	
Brake specific NO_x [g/bhp-hr]	0.21	0.21	0.25	0.27	0.40	0.41	0.21	0.23	
PRE CATALYST Emissions									
Raw CO [ppm]									12407
Brake specific CO [g/bhp-hr]									29.49
Raw NO_x [ppm]									3090
Brake specific NO_x [g/bhp-hr]									12.06
CO_2 [%] / O_2 [%]									11.5/0.4

Table 20: Field data log from August 24 – after retuning (Site visit # 6)

Run	84A	85A	86A	87A	88A	89A	89B
Date	24-Aug-12	24-Aug-12	24-Aug-12	24-Aug-12	24-Aug-12	24-Aug-12	24-Aug-12
Time	10:15	12:05	13:52	14:25	15:15	15:45	16:05
Qmix Setpoint	2100	2100	1700	1400	1400	2100	2100
Speed Setpoint	1150	1150	1000	850	850	1150	1150
Test Duration [min]	15	15	15	15	15	15	15
Speed/Load Characterization	HS/HL	HS/HL	MS/ML	LS/LL	LS/LL	HS/HL	HS/HL
Engine							
Engine Runtime [hr]	46968	46970	46972	46972	46973	46973	46974
Volumetric Flow [SCFM]	2090	2090	1675	1425	1450	2090	2110
Ambient Temperature [°F]	99	99	99	98	99	99	99
Suction Pressure [psig]	89	91	86	93	93	87	88
Discharge Pressure [psig]	914	890	937	986	1042	1055	1057
Discharge Temperature [°F]	103	107	108	107	109	113	112
Right Bank MAP [psig]	5	6	4	4	4	5	5
Left Bank MAP [psig]	5	5	3	2	3	5	5
Jacket Water Temperature [°F]	178	179	179	180	180	180	180
Jacket Water Pressure [psig]	18	18	14	12	12	18	18
Oil temperature [°F]	192	193	191	190	190	193	194
Oil pressure [psig]	52	51	49	41	42	50	50
Average MAT [°F]	113	118	117	115	115	121	121
Fuel Flow [SCFD]	78	76	49	35	36	77	78
ESM Load [%]	86	85	77	76	78	84	84
Throttle Position [%]	--	--	--	--	--	--	--
Ignition Timing	22	23	26	26	26	21↔24	22↔24
Right Fuel/Air Pressure ["H2O]	633	631	640	654	653	634	
Left Fuel/Air Pressure ["H2O]	--	--	--	--	--	--	--
Fuel pressure [psig]	129	133	141	134	135	132	132
Catalyst ΔP ["H2O]	4.7	4.7	3.4	2.6	2.7	4.8	4.8
POST CATALYST							
NO_x sensor [V] - NO_x 1							
Outlet Temperature [°F]	1139	1134	1055	994	997	1131	1133
PRE CATALYST							
NO_x sensor [V] - NO_x 2							
Inlet Temperature [°F]	1078	1076	1007	956	957	1074	1077
POST CATALYST Emissions							
Raw CO [ppm]	10	92	160	338	6	161	
Brake specific CO [g/bhp-hr]	0.03	0.24	0.40	0.83	0.01	0.41	
Raw NO_x [ppm]	173	25	30	55	327	36	
Brake specific NO_x [g/bhp-hr]	0.73	0.11	0.12	0.22	1.33	0.15	
PRE CATALYST Emissions							
Raw CO [ppm]							10543
Brake specific CO [g/bhp-hr]							25.24
Raw NO_x [ppm]							3668
Brake specific NO_x [g/bhp-hr]							14.42
CO_2 [%] / O_2 [%]							11.5/0.4

Appendix F: Installation Details


2011 E3 AIR FUEL RATIO
CONTROLS PROJECT
ENCANA OIL & GAS
FRENCHIE DRAW, WY
Engine Manufacturer: Waukesha
Engine Type: L7044GSI
Engine Drive: Compressor
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COVER SHEET

SPECIFICATIONS

INCL THIS ISSUE	REV	DRAWING #	TITLE
X	5	12334	TORQUE TENSION RELATIONSHIP SPECIFICATION

P & I DIAGRAM

INCL THIS ISSUE	REV	DRAWING #	TITLE
X	7	11906	SYMBOL & LEGEND P & I DIAGRAM
X	0	000-010-0004	FUEL AND EXHAUST INSTALLATION

DEMOLITION

INCL THIS ISSUE	REV	DRAWING #	TITLE
X	0	000-010-1800	FUEL GAS PIPE

ENGINE MECHANICAL

INCL THIS ISSUE	REV	DRAWING #	TITLE
X	0	000-010-1700	FUEL & EXHAUST SYSTEM COMPONENTS

FUEL SUPPLY

INCL THIS ISSUE	REV	DRAWING #	TITLE
X	0	000-010-0600	FUEL PIPING RIGHT BANK
X	0	000-010-0601	FUEL PIPING LEFT BANK

EXHAUST

INCL THIS ISSUE	REV	DRAWING #	TITLE
X	0	000-010-0800 SHT 1	O2 SENSOR & THERMOCOUPLE INSTALLATION
X	0	000-010-0800 SHT 2	O2 SENSOR & THERMOCOUPLE INSTALLATION
X	0	000-010-0800 SHT 3	MAT & MAP SENSOR INSTALLATION

IGNITION SYSTEM

INCL THIS ISSUE	REV	DRAWING #	TITLE
X	0	000-010-1805 SHT 1	MAGNETIC PICKUP INSTALLATION
X	0	000-010-1805 SHT 2	MAGNETIC PICKUP INSTALLATION

ELECTRICAL

INCL THIS ISSUE	REV	DRAWING #	TITLE
X	0	000-010-0200	CONDUIT INSTALLATION

CABINET LAYOUT

INCL THIS ISSUE	REV	DRAWING #	TITLE
X	0	000-010-0101 SHT 1	CABINET EXTERIOR LAYOUT
X	0	000-010-0101 SHT 2	CABINET INTERIOR LAYOUT
X	0	000-010-0101 SHT 3	TERMINAL STRIP DETAILS
X	0	000-010-0103	LABEL PRINTING

ELECTRICAL SCHEMATICS

INCL THIS ISSUE	REV	DRAWING #	TITLE
X	D	000-010-0111 SHT 1	COVERSHEET AND INDEX
X	D	000-010-0111 SHT 2	GENERAL NOTES AND SYMBOLS
X	D	000-010-0111 SHT 3	POWER DISTRIBUTION
X	D	000-010-0111 SHT 4	E3 WIRING
X	D	000-010-0111 SHT 5	COMMUNICATION ISOLATION / CONVERSION

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ENCANA OIL & GAS

FRENCHIE DRAW, WY

UNIT #198

WAUKESHA L7044GSI

INDEX SHEET

ENGINEERED ELG

DRAWN PMV

SIZE B DWG NO. 000-010-0001 REV 0

SCALE NONE SHEET 1 OF 1

TORQUE TENSION RELATIONSHIP FOR SAE J429 GRADE BOLTS

NOMINAL THREAD SIZE	SAE J429 GRADE 2 CLAMP LOAD (LBS)	SAE J429 GRADE 2 TIGHTENING TORQUE K=.15	SAE J429 GRADE 2 TIGHTENING TORQUE K=.20	SAE J429 GRADE 5 CLAMP LOAD (LBS)	SAE J429 GRADE 5 TIGHTENING TORQUE K=.15	SAE J429 GRADE 5 TIGHTENING TORQUE K=.20	SAE J429 GRADE 8 CLAMP LOAD (LBS)	SAE J429 GRADE 8 TIGHTENING TORQUE K=.15	SAE J429 GRADE 8 TIGHTENING TORQUE K=.20
UNIFIED COARSE THREAD SERIES									
1/4-20	1,300	49 in-lbs	65 in-lbs	2,000	75 in-lbs	100 in-lbs	2,850	107 in-lbs	143 in-lbs
5/16-18	2,150	101	134	3,350	157	210	4,700	220	305
3/8-16	3,200	15 ft-lbs	20 ft-lbs	4,950	23 ft-lbs	31 ft-lbs	6,950	32.5 ft-lbs	44 ft-lbs
7/16-14	4,400	24	30	6,800	37	50	9,600	53	70
1/2-13	5,850	36.5	49	9,050	57	75	12,800	80	107
9/16-12	7,500	53	70	11,600	82	109	16,400	115	154
5/8-11	9,300	73	97	14,500	113	151	20,300	159	211
3/4-10	13,800	129	173	21,300	200	266	30,100	282	376
7/8-9	11,425	125	166	29,435	321	430	41,550	454	606
1-8	15,000	187.5	250	38,600	482.5	640	54,540	680	900
UNIFIED FINE THREAD SERIES									
1/4-28	1,500	55 in-lbs	75 in-lbs	2,300	85 in-lbs	115 in-lbs	3,250	120 in-lbs	163 in-lbs
5/16-24	2,400	112	150	3,700	173	230	5,200	245	325
3/8-24	3,600	17 ft-lbs	22.5 ft-lbs	5,600	26ft-lbs	35 ft-lbs	7,900	37 ft-lbs	50 ft-lbs
7/16-20	4,900	27	36	7,550	42	55	10,700	59	78
1/2-20	6,600	41	55	10,200	64	85	14,400	90	120
9/16-18	8,400	59	79	13,000	92	122	18,300	129	172
5/8-18	10,600	83	110	16,300	128	170	23,000	180	240
3/4-16	15,400	144	193	23,800	223	298	33,600	315	420
7/8-14	12,610	138	184	32,480	355	473	45,855	500	668
1-12	16,410	205	273	42,270	528	704	59,670	745	995

CAUTION: ALL TORQUE VALUES INCLUDED IN THESE CHARTS ARE ADVISORY ONLY, AND THEIR USE BY ANYONE IS ENTIRELY VOLUNTARY. RELIANCE ON THE CONTENTS FOR ANY PURPOSE BY ANYONE IS THE SOLE RISK OF THAT PERSON AND ENGINUITY IS NOT RESPONSIBLE FOR ANY LOSS, CLAIM OR DAMAGES ARISING THEREFROM. IN DEVELOPING THIS INFORMATION, ENGINUITY HAS MADE A DETERMINED EFFORT TO PRESENT ITS CONTENT ACCURATELY. EXTREME CAUTION SHOULD ALWAYS BE USED WHEN USING A FORMULA FOR TORQUE TENSION RELATIONSHIPS. TORQUE IS ONLY AN INDIRECT INDICATION OF TENSION.

CLAMP LOAD ESTIMATED AS 75% OF PROOF LOAD FOR SPECIFIC BOLTS.

TORQUE VALUES FOR 1/4 AND 5/16 INCH SERIES ARE IN INCH-POUNDS. ALL OTHER TORQUE VALUES ARE FOOT-POUNDS.

TORQUE VALUES CALCULATED FROM FORMULA T=KDF WHERE: K=0.15 FOR "LUBRICATED" CONDITIONS AND K=0.20 FOR "DRY" CONDITIONS.

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LEGEND

EXISTING PIPING/EQUIPMENT

NEW PIPING/EQUIPMENT

ECO #	REV	DATE	DESCRIPTION	APP
	5		UPDATED TITLEBLOCK	
1344A	4		CORRECTED FTXLBS TO FT-LBS	
	3		UPDATED TITLEBLOCK	
	2		UPDATED TITLEBLOCK	
	1		CORRECTED NOTES	

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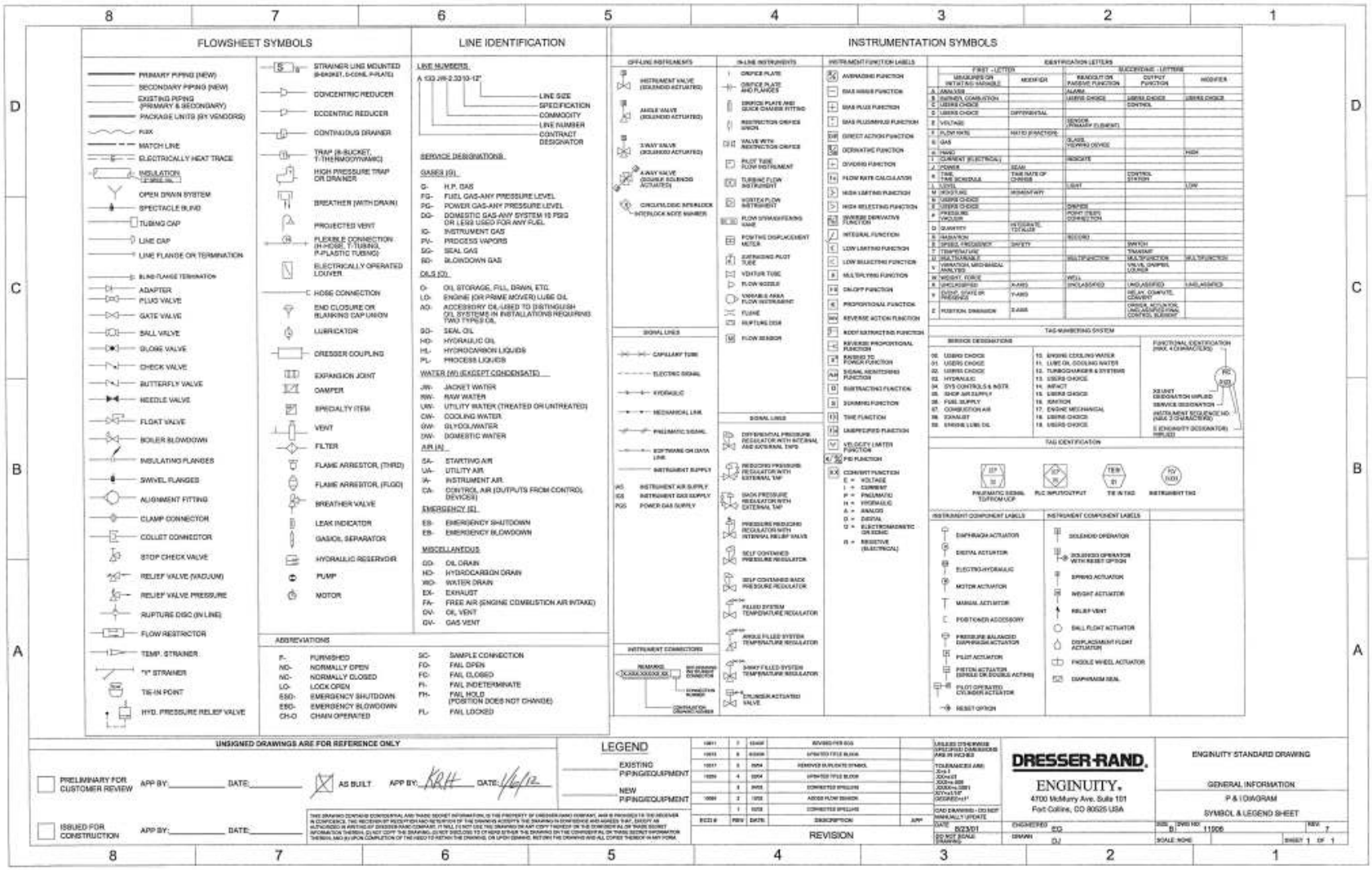
GENERAL INFORMATION

SPECIFICATION

TORQUE TENSION RELATIONSHIP

ENGINEERED: EG DRAWN: DJ SCALE: NONE SHEET 1 OF 1 REV: 5


FLOWSHEET SYMBOLS
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INSTRUMENTATION SYMBOLS
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NEW P/P/INGIEQUIPMENT
REVISION

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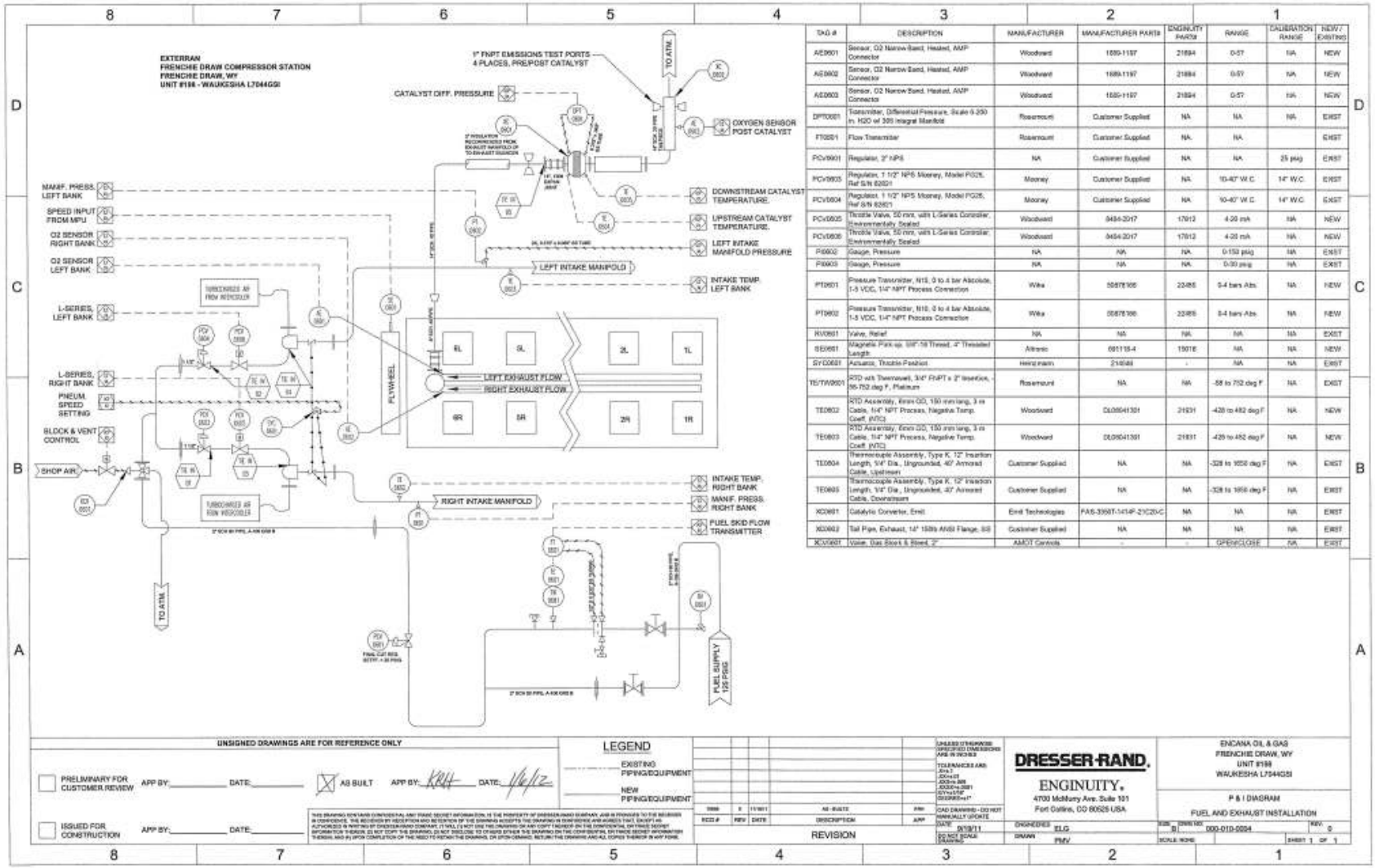
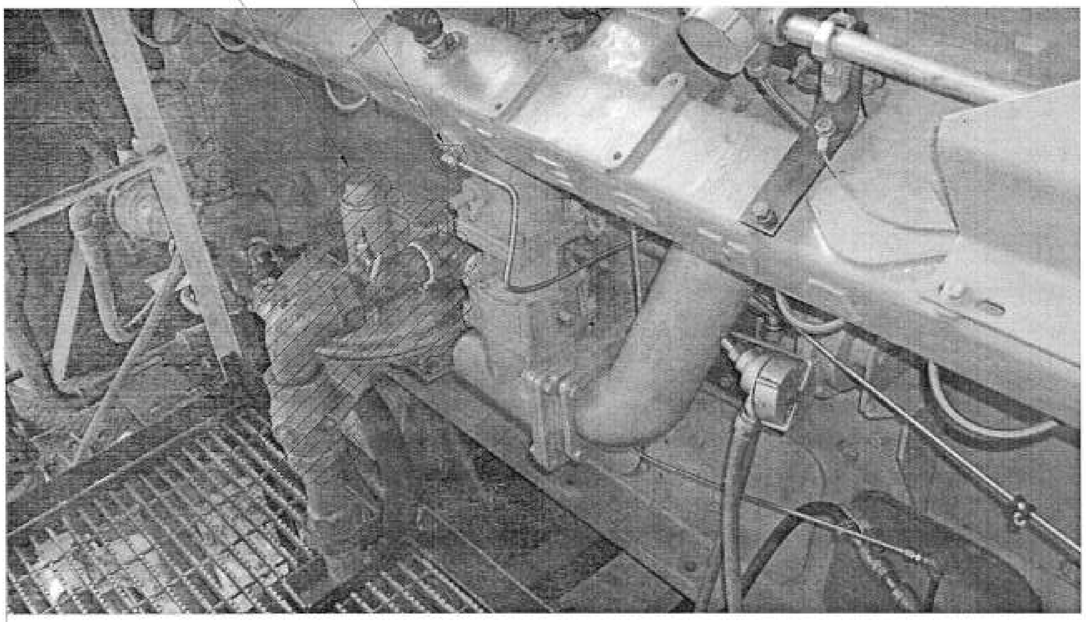


TAG #	DESCRIPTION	MANUFACTURER	MANUFACTURER PART#	ENGINUITY PART#	RANGE	CALIBRATION RANGE	NEW? / EXISTING
AE0601	Sensor, O2 Narrow Band, Heated, AMP Connector	Woodward	1689-1197	21894	0-5T	NA	NEW
AE0602	Sensor, O2 Narrow Band, Heated, AMP Connector	Woodward	1689-1197	21894	0-5T	NA	NEW
AE0603	Sensor, O2 Narrow Band, Heated, AMP Connector	Woodward	1689-1197	21894	0-5T	NA	NEW
DPT0601	Transmitter, Differential Pressure, Scale 0-250 in. H2O w/ 305 Integral Manifold	Rosemount	Customer Supplied	NA	NA	NA	EXIST
FT0201	Flow Transmitter	Rosemount	Customer Supplied	NA	NA		EXIST
PCV0601	Regulator, 2" NPS	NA	Customer Supplied	NA	NA	25 psig	EXIST
PCV0603	Regulator, 1 1/2" NPS Mooney, Model FG2S, Ref S/N 62021	Mooney	Customer Supplied	NA	10-40" W.C.	14" W.C.	EXIST
PCV0604	Regulator, 1 1/2" NPS Mooney, Model FG2S, Ref S/N 62021	Mooney	Customer Supplied	NA	10-40" W.C.	14" W.C.	EXIST
PCV0605	Throttle Valve, 50 mm, with L-Series Controller, Environmentally Sealed	Woodward	9484-2017	17012	4-20 mA	NA	NEW
PCV0606	Throttle Valve, 50 mm, with L-Series Controller, Environmentally Sealed	Woodward	9484-2017	17012	4-20 mA	NA	NEW
PI0602	Gauge, Pressure	NA	NA	NA	0-152 psig	NA	EXIST
PI0603	Gauge, Pressure	NA	NA	NA	0-30 psig	NA	EXIST
PT0601	Pressure Transmitter, N1S, 0 to 4 bar Absolute, 1-5 VDC, 1/4" NPT Process Connection	Wika	55878166	22486	0-4 bars Abs.	NA	NEW
PT0602	Pressure Transmitter, N1S, 0 to 4 bar Absolute, 1-5 VDC, 1/4" NPT Process Connection	Wika	55878166	22486	0-4 bars Abs.	NA	NEW
RV0601	Valve, Relief	NA	NA	NA	NA	NA	EXIST
SE0601	Magnetic Pick-up, 3/8"-16 Thread, 4" Threaded Length	Altronic	601116-4	15016	NA	NA	NEW
SY0601	Actuator, Throttle Position	Heinzmann	214549	-	NA	NA	EXIST
TE/TW0601	RTD with Thermowell, 3/4" FnPT x 2" Insertion, -50-752 deg F, Platinum	Rosemount	NA	NA	-58 to 752 deg F	NA	EXIST
TE0602	RTD Assembly, 6mm OD, 150 mm long, 3 m Cable, 1/4" NPT Process, Negative Temp. Coeff. (NTC)	Woodward	DL06041301	21931	-428 to 482 deg F	NA	NEW
TE0603	RTD Assembly, 6mm OD, 150 mm long, 3 m Cable, 1/4" NPT Process, Negative Temp. Coeff. (NTC)	Woodward	DL06041301	21931	-428 to 482 deg F	NA	NEW
TE0604	Thermocouple Assembly, Type K, 12" Insertion Length, 1/4" Dia., Ungrounded, 40' Armored Cable, Upstream	Customer Supplied	NA	NA	-328 to 1650 deg F	NA	EXIST
TE0605	Thermocouple Assembly, Type K, 12" Insertion Length, 1/4" Dia., Ungrounded, 40' Armored Cable, Downstream	Customer Supplied	NA	NA	-328 to 1650 deg F	NA	EXIST
XC0601	Catalytic Converter, Emit	Emit Technologies	PAS-3350T-1414F-21C20-C	NA	NA	NA	EXIST
XC0602	Tail Pipe, Exhaust, 14" 150lb ANSI Flange, SS	Customer Supplied	NA	NA	NA	NA	EXIST
XCV0601	Valve, Gas Block & Bleed, 2"	AMOT Controls	-	-	OPEN/CLOSE	NA	EXIST



NOTES:

1. REMOVE EXISTING MOONEY REGULATOR, DO NOT DISCARD. SEE DRAWING 000-010-0800 FOR DETAILS.
2. REMOVE EXISTING 1/2" NPT PLUG. SEE DRAWING 000-010-0800 SHT 3 FOR INSTALLATION DETAILS.

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NEW PIPING/EQUIPMENT

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ECO #	REV	DATE	DESCRIPTION	APP
	0		AS BUILTS	KRH

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ENGINEERED ELG

DRAWN PMY

EXTERRAN OIL & GAS

FRENCHIE DRAW, WY

UNIT #198

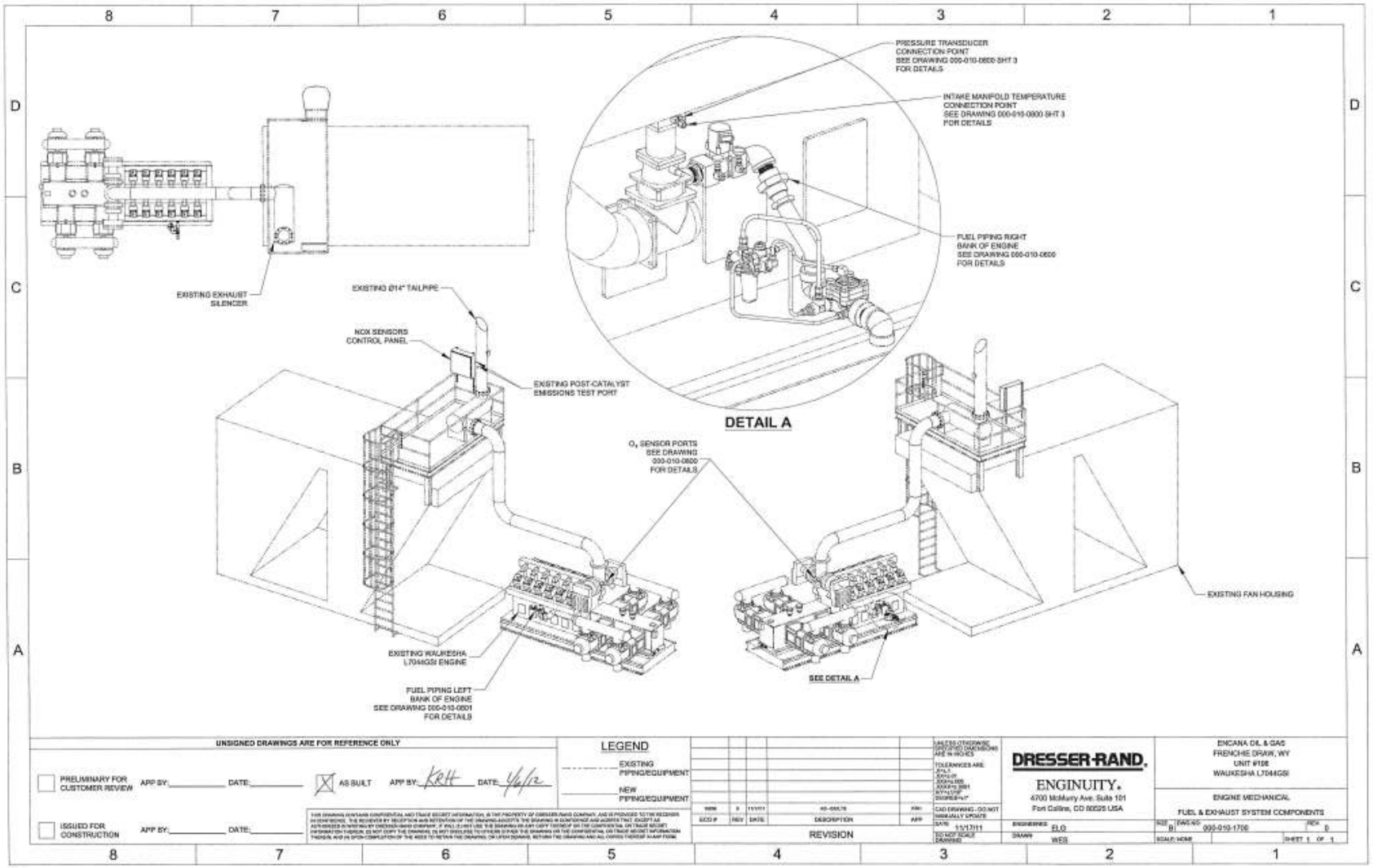
WAUKESHA L7044GSI

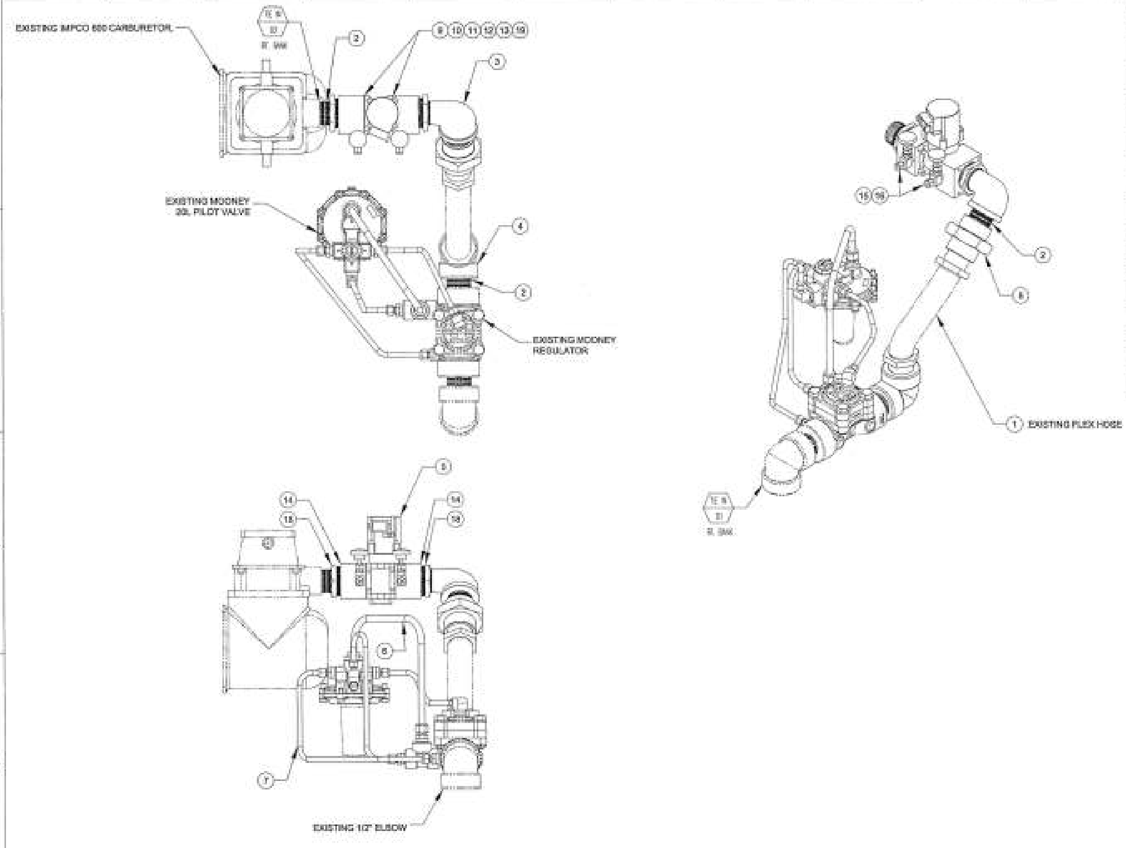
DEMOLITION

FUEL GAS PIPE

SIZE B DWG NO 000-010-1800 REV 0

SCALE: NONE SHEET 1 OF 1


PRESSURE TRANSDUCER CONNECTION POINT SEE DRAWING 000-010-0600 SHT 3 FOR DETAILS
INTAKE MANIFOLD TEMPERATURE CONNECTION POINT SEE DRAWING 000-010-0600 SHT 3 FOR DETAILS
FUEL PIPING RIGHT BANK OF ENGINE SEE DRAWING 000-010-0600 FOR DETAILS
EXISTING EXHAUST SILENCER
EXISTING Ø14" TAILPIPE
NOX SENSORS CONTROL PANEL
EXISTING POST-CATALYST EMISSIONS TEST PORT
DETAIL A
O2 SENSOR PORTS SEE DRAWING 000-010-0600 FOR DETAILS
EXISTING FAN HOUSING
EXISTING WAUKESHA L7044GSI ENGINE
FUEL PIPING LEFT BANK OF ENGINE SEE DRAWING 000-010-0601 FOR DETAILS
SEE DETAIL A
UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY
PRELIMINARY FOR CUSTOMER REVIEW
APP BY: DATE:
AS BUILT
APP BY: KH DATE: 4/6/12
ISSUED FOR CONSTRUCTION
APP BY: DATE:
LEGEND
EXISTING PIPING/EQUIPMENT
NEW PIPING/EQUIPMENT
REVISION
ECO # REV DATE DESCRIPTION APP
DRESSER-RAND
ENGINUITY
4700 McMurry Ave, Suite 101
Fort Collins, CO 80525 USA
ENGINEER: ELG
DRAWN: WES
CAD DRAWING - DO NOT MANUALLY UPDATE
DATE: 11/17/11
DO NOT SCALE DRAWING
ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #108
WAUKESHA L7044GSI
ENGINE MECHANICAL
FUEL & EXHAUST SYSTEM COMPONENTS
SIZE: B
DWG NO: 000-010-1706
REV: 0
SCALE: NONE
SHEET 1 OF 1



ITEM	QTY	DESCRIPTION	MANUFACTURER	MANUFACTURER PART#	ENGINUITY PART#
1	REF	Extra-Flex PTFE Hose with SS Wire Braid, 1-1/2" MNPT, OAL 20"	McMaster-Carr	5468K205	20281
2	3	Nipple, Close, 1 1/2" Schedule 80 ASTM A-106 Grade B	Red Man Pipe & Supply Co	3477840	15127
3	1	Elbow, Street, 1 1/2" Sch 80 ASME B16.9 ASTM A234 WPB	Red Man Pipe & Supply Co	18000154	22357
4	1	Elbow, 1 1/2" 3000#, Screwed, 90 deg, C.S. ASTM 105 Grade 2	Red Man Pipe & Supply Co		20279
5	1	Throttle Valve, 50 mm, with L-Series Controller, Environmentally Sealed	Woodward	8404-2017	17812
6	3 ft	1/2" x .083" SS Tubing - ASTM A269 Gr 304/316 80 HRB Max-Seamless	Tubing	1/2 TUBING	13456
7	10 ft	3/4" x .083" SS Tubing - ASTM A269Gr Gr 304 80 HRB Maximum-Seamless	Tubing	3/4 TUBING	18692
8	1	Union 1 1/2" NPT Sch 80 ASME B16.11 ASTM A105 grade II	Red Man Pipe & Supply Co	3362040	14861
9	2	Gasket, Valve Flange, Woodward L-Series, 50mm	Woodward	8108-06-018	18024
10	8	Cap Screw, Hex Head, 1/4-20 x 3", Grade 8 Yellow Zinc	Fastenal	15015	18874
11	8	Hex Nut, 1/4-20, Zinc Plated	Fastenal	36120	13116
12	8	Lock Washer, Medium Split, 1/4", Zinc Plated	Fastenal	33618	10716
13	8	Flat Washer, 1/4", SAE Zinc Plated	Fastenal	33078	10704
14	2	Adapter, Valve Flange, Woodward L-Series, 50mm, With 1/4FNPT Port	Enginuity	19153	19153
15	2	Integral Bonnet Needle Valve, 0.37 Cv, 1/4 in. MNPT x 1/4 in. Swagelok Tube Fitting, Regulating Stem, SS	Swagelok	SS-1RM4-S4	17176
16	2	Plug, 1/4" O.D., SS	Swagelok	SS-400-P	11054
17	REF	SWAK Anaerobic Pipe Thread Sealant (250 cc)	Swagelok	MS-PTS-250	16219
18	2	Reducing Bushing, Pipe Hex, 2" MNPT X 1 1/2" FNPT-3000#, C.S. ASTM A105	Red Man Pipe & Supply Co	3337080	15125
19	1	Deutsch Connector Assembly, Woodward L-Series Valve	Woodward	8928-396	15886

NOTES:

1. COAT ALL PIPING THREADS WITH SWAK, ITEM #17, BEFORE ASSEMBLY.

UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY

☐ PRELIMINARY FOR CUSTOMER REVIEW APP BY:______ DATE:______

☒ AS BUILT APP BY: KAH DATE: 1/2/12

☐ ISSUED FOR CONSTRUCTION APP BY:______ DATE:______

LEGEND

EXISTING PIPING/EQUIPMENT

NEW PIPING/EQUIPMENT

REVISION

ECO #	REV	DATE	DESCRIPTION	APP
1068	0	11/17/11	AS BUILT	RW

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

CAD DRAWING - DO NOT MANUALLY UPDATE

DATE 11/17/11 — DO NOT SCALE DRAWING

ENGINEERED ELG — DRAWN WES

DRESSER-RAND.

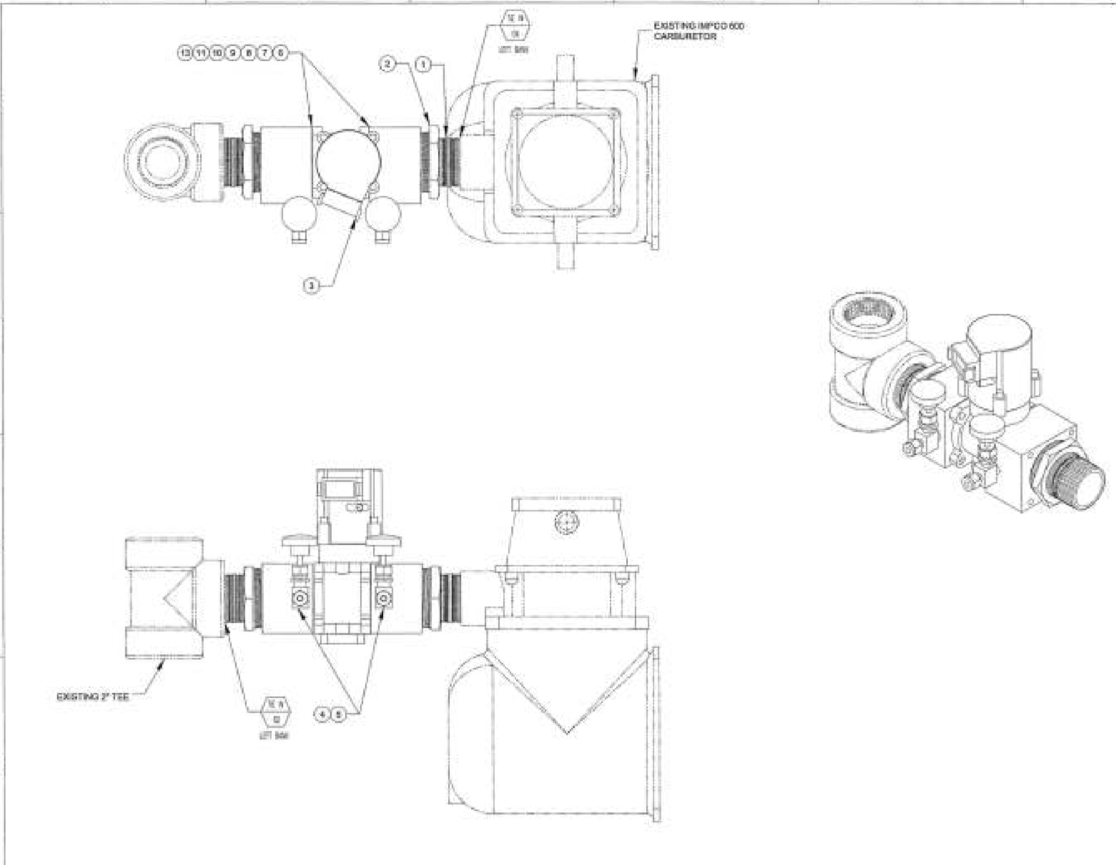
ENGINUITY.

4700 McMurry Ave. Suite 101
Fort Collins, CO 80525 USA

ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #198
WAUKESHA L7044GSI

FUEL SUPPLY
FUEL PIPING RIGHT BANK

SIZE B — DWG NO 000-010-0030 — REV 0 — SHEET 1 OF 1



ITEM	QTY	DESCRIPTION	MANUFACTURER	MANUFACTURER PART#	ENGINUITY PART#
1	2	Nipple, Close, 1 1/2" Schedule 80 ASTM A-106 Grade B	Red Man Pipe & Supply Co.	3477848	15127
2	2	Reducing Bushing, Pipe Hex, 2" MNPT X 1 1/2" FNPT-3000#, C.S. ASTM A105	Red Man Pipe & Supply Co.	3337080	15125
3	1	Throttle Valve, 50 mm, with L-Series Controller, Environmentally Sealed	Woodward	8404-2017	17612
4	2	Integral Bonnet Needle Valve, 0.37 Cv, 1/4 in. MNPT x 1/4 in. Swagelok Tube Fitting, Regulating Stem, SS	Swagelok	SS-1RS4-S4	17179
5	2	Plug, 1/4" O.D., SS	Swagelok	SS-400-P	11064
6	2	Gasket, Valve Flange, Woodward L-Series, 50mm	Woodward	5109-00-018	16004
7	8	Cap Screw, Hex Head, 1/4-20 x 3", Grade 8 Yellow Zinc	Fastenal	15015	15674
8	8	Hex Nut, 1/4-20, Zinc Plated	Fastenal	36103	10115
9	8	Lock Washer, Medium Split, 1/4", Zinc Plated	Fastenal	33618	10716
10	8	Flat Washer, 1/4", SAE Zinc Plated	Fastenal	33078	10724
11	2	Adapter, Valve Flange, Woodward L-Series, 50mm, With 1/4FNPT Port	Enginuity	19150	19153
12	REF	SWAK Anaerobic Pipe Thread Sealant (250 cc)	Swagelok	MS-PTS-250	15219
13	1	Deutsch Connector Assembly, Woodward L-Series Valve	Woodward	8928-396	15566

NOTES:

1. COAT ALL PIPING THREADS WITH SWAK, ITEM #12, BEFORE ASSEMBLY.

UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY

PRELIMINARY FOR CUSTOMER REVIEW APP BY:______ DATE:______

ISSUED FOR CONSTRUCTION APP BY:______ DATE:______

AS BUILT APP BY: KRH DATE: 1/6/12

LEGEND

EXISTING PIPING/EQUIPMENT

NEW PIPING/EQUIPMENT

REVISION

ECO #	REV	DATE	DESCRIPTION	APP
	0	1/21/11	AS-BUILTS	

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

CAD DRAWING - DO NOT MANUALLY UPDATE

DATE 11/17/11

DO NOT SCALE DRAWING

DRESSER-RAND.

ENGINUITY.

4700 McMurry Ave. Suite 101
Fort Collins, CO 80525 USA

ENGINEERED ELG

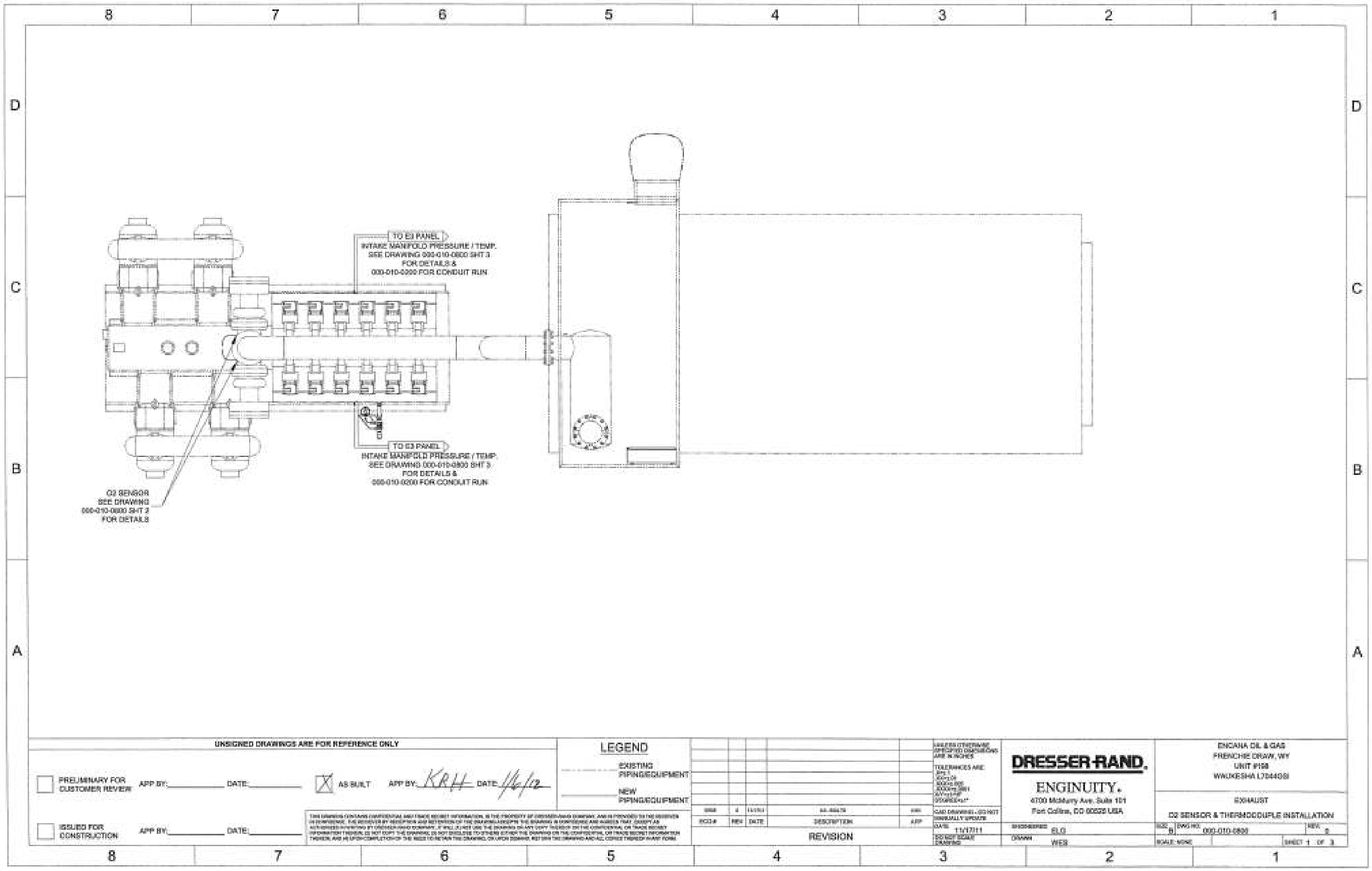
DRAWN WES

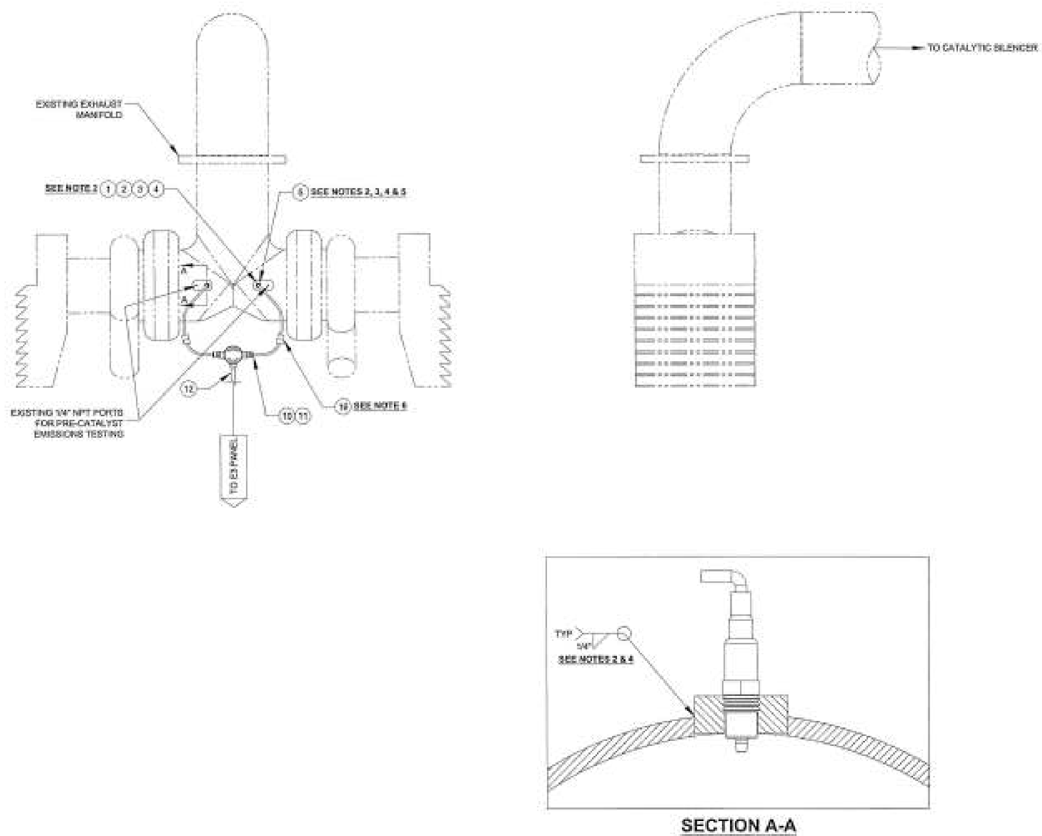
ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #198
WAUKESHA L7044GSI

FUEL SUPPLY
FUEL PIPING LEFT BANK

SIZE B DWG NO 000-010-0901 REV. 0

SCALE: NONE SHEET 1 OF 1


TO E3 PANEL
INTAKE MANIFOLD PRESSURE / TEMP.
SEE DRAWING 000-010-0800 SHT 3
FOR DETAILS &
000-010-0200 FOR CONDUIT RUN
TO E3 PANEL
INTAKE MANIFOLD PRESSURE / TEMP.
SEE DRAWING 000-010-0800 SHT 3
FOR DETAILS &
000-010-0200 FOR CONDUIT RUN
O2 SENSOR
SEE DRAWING
000-010-0800 SHT 2
FOR DETAILS
UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY
PRELIMINARY FOR CUSTOMER REVIEW
APP BY:
DATE:
AS BUILT
APP BY: KRH
DATE: 1/6/12
ISSUED FOR CONSTRUCTION
APP BY:
DATE:
LEGEND
EXISTING PIPING/EQUIPMENT
NEW PIPING/EQUIPMENT
REVISION
ECO #
REV
DATE
DESCRIPTION
APP
DRESSER-RAND.
ENGINUITY.
4700 McMurry Ave. Suite 101
Fort Collins, CO 80525 USA
ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #198
WAUKESHA L7044GSI
EXHAUST
O2 SENSOR & THERMOCOUPLE INSTALLATION
DATE 11/17/11
ENGINEERED ELG
DRAWN WEB
SIZE B
DWG NO. 000-010-0800
REV. 0
SCALE: NONE
SHEET 1 OF 3



ITEM	QTY	DESCRIPTION	MANUFACTURER	MANUFACTURER PART#	ENGINUITY PART#
1	2	Sensor, O2 Narrow Band, Heated, AMP Connector	Woodward	1689-1157	21894
2	1	Hand Tap, M18x1.5 mm, High Speed Steel, TiN-Coated, Taper, 16.5 mm Drill	McMaster-Carr	26475A469	21183
3	1	Drill Bit, 16.5 mm, High Speed Steel, Black-Oxide Surface, Straight Shank	McMaster-Carr	2958A178	21184
4	REF	Anti-Seize, High Temperature, 2000 Deg. F. Max, 16 Oz. Bottle, White	Loctite	34518	21273
5	2	Mounting Pad, For Oxygen Sensor, 18mm x 1.5 Dia., Gray Cast Iron	Enginuity	21890	21890
6	2	Thermocouple, Type K, 0 Deg Bend, 5' Armored Cable, 10" Insertion Length, Ungrounded	Omega	CF-000-K-10-60-1-UNGR	20313
7	2	Reducing Bushing, NPT x NPT, 1/2" Reduced to 1/4", Yellow Brass, ASME B1.20.1	McMaster Carr	5162K228	21170
8	2	Branch Tee, 1/4" FNPT - 1/4" FNPT - 1/4" MNPT, Yellow Brass, 1200 psi	McMaster-Carr	50785K222	21949
9	2	Male Connector, 1/4 in. OD - 1/4 in. MNPT, Stainless	Swagelok	SS-400-1-4	10947
10	4	Cord Grip, 3/4" NPT w/ Gland Nut and Bushing, .125-.250 Cable Dia.	Crouse Hinds	CGB292	16047
11	2	Condulet Conduit Outlet Box, 3/4" Hub 3" Cover Opening, With cover	Crouse Hinds	GUAT26	10585
12	REF	3/4" Rigid Steel Conduit	Conduit	3/4" Conduit	12772
13	2	Plug, 1/4" O.D., SS	Swagelok	SS-400-P	11054
14	1	Drill Bit, 45/64", High-Speed Steel, Uncoated, 6-1/2" Lng	McMaster-Carr	29315A182	21958
15	1	Tap, 1/2-14 NPTF	McMaster-Carr	2525A216	21957
16	2	Kit, Connector, O2 Sensor, 4 Pin AMP	Woodward	8928-7363	21904
17	REF	Crimp Tool Die Set for AMP Junior Power Timer Contacts	Ballenger Motorsports	TOOL-00927	21520
18	REF	Tyco AMP Ergocrimp Tool w/o dies	Ballenger Motorsports	TOOL-00899	21521

NOTES:

1. INSTALLATION DWG APPLIES TO BOTH BANKS OF ENGINE.
2. CUT HOLE IN EXISTING EXHAUST MANIFOLD PAD AND WELD IN O2 SENSOR MOUNTING PAD PER RECOMMENDATIONS. IF THIS METHOD IS UNAVAILABLE, DRILL AND TAP EXHAUST MANIFOLD FOR OXYGEN SENSOR FINDING LOCATION THAT IS EASILY ACCESSIBLE FOR MAINTENANCE PURPOSES.
3. USE HIGH-TEMPERATURE ANTI-SEIZE WHEN INSTALLING THERMOCOUPLE & O2 SENSOR IN EXHAUST PIPING.
4. INSTALLED OXYGEN SENSOR MOUNTING PAD MUST NOT EXTEND INTO STACK INTERIOR AS SHOWN.
5. DRILL AND TAP EXHAUST ELBOW IN LOCATION SHOWN WITH ITEMS 14 AND 15 OR USE AN EXISTING ELBOW BOSS WHICH CAN ACCEPT A 1/2 -14 NPTF.
6. INSTALL MATING CONNECTOR, ITEMS 16, 17 & 18 TO THE END OF THE CONDUIT CABLE RUN AND ATTACH TO OXYGEN SENSOR CONNECTOR. MAINTAIN A SERVICE LOOP FOR EASE OF INSTALLATION.

UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY

PRELIMINARY FOR CUSTOMER REVIEW APP BY: DATE:

ISSUED FOR CONSTRUCTION APP BY: DATE:

☒ AS BUILT APP BY: KRH DATE: 1/6/12

LEGEND

EXISTING PIPING/EQUIPMENT

NEW PIPING/EQUIPMENT

REVISION

DRESSER-RAND.

ENGINUITY.

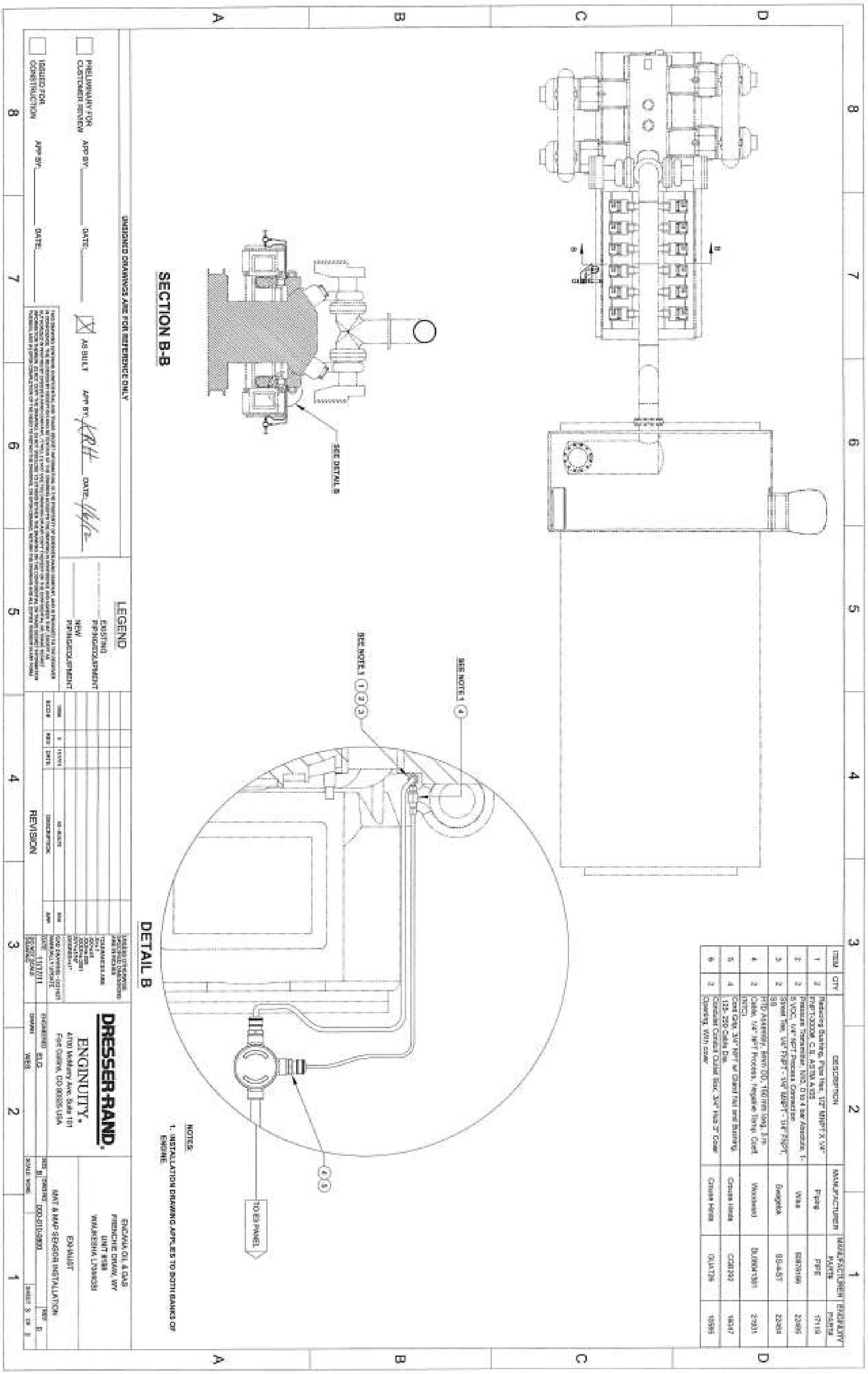
4700 McMurry Ave. Suite 101
Fort Collins, CO 80525 USA

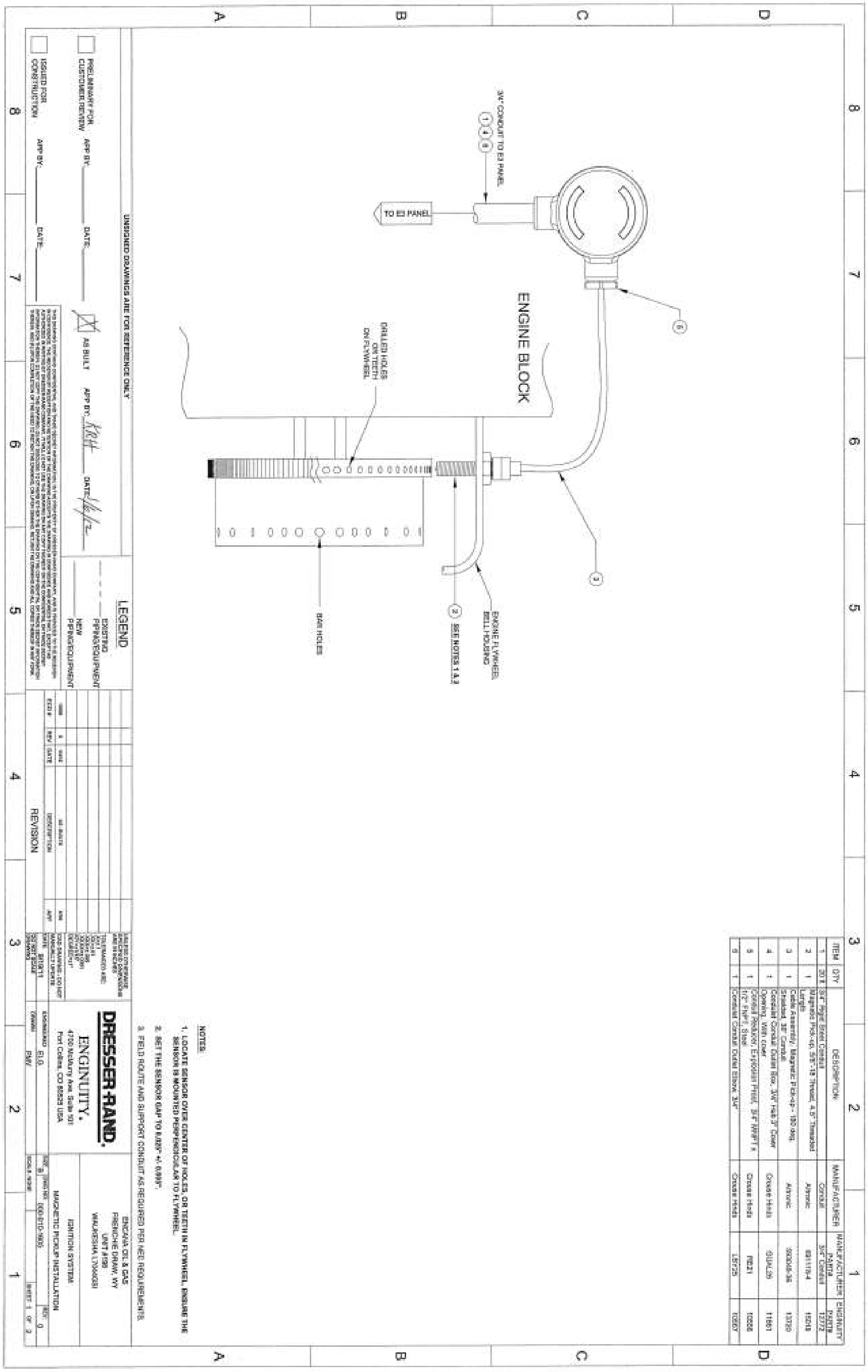
ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #198
WAUKESHA L7044GSI

EXHAUST

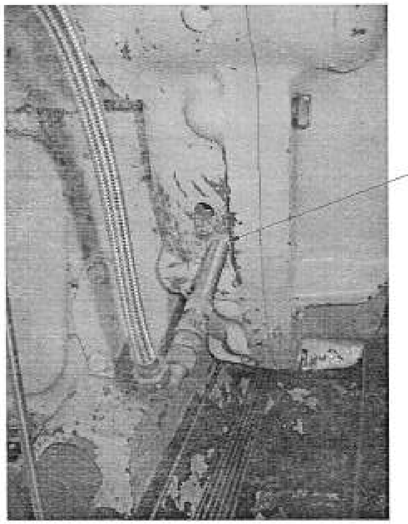
O2 SENSOR & THERMOCOUPLE INSTALLATION

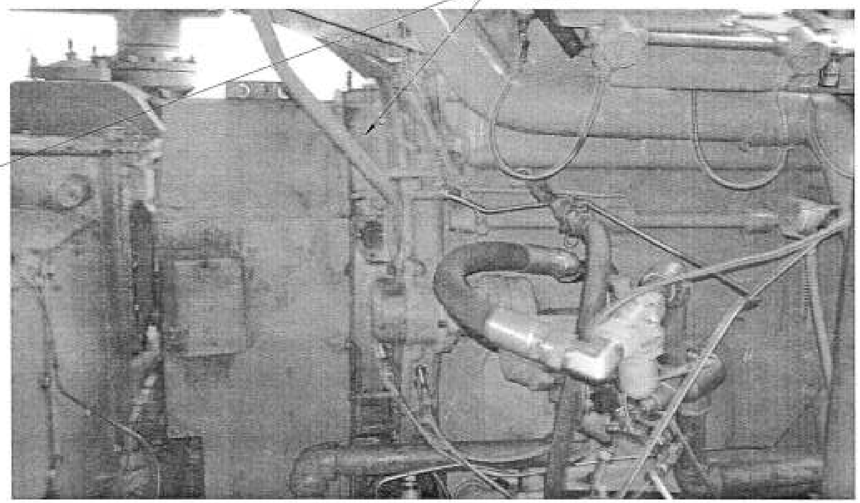
DATE 11/17/11 ENGINEERED ELG DRAWN WES SIZE B DWG NO 000-010-0800 REV 0 SCALE NONE SHEET 2 OF 3


SECTION B-B
SEE DETAIL B
DETAIL B
SEE NOTE 1 4
SEE NOTE 1 1 2 3
4 5
TO E3 PANEL
ITEM | QTY | DESCRIPTION | MANUFACTURER | MANUFACTURER PART# | ENGINUITY PART#
1 | 2 | Reducing Bushing, Pipe Hex, 1/2" MNPT X 1/4" FNPT-3000#, C.S. ASTM A 105 | Piping | PIPE | 17119
2 | 2 | Pressure Transmitter, N10, 0 to 4 bar Absolute, 1-5 VDC, 1/4" NPT Process Connection | Wika | 50878166 | 22495
3 | 2 | Street Tee, 1/4" FNPT - 1/4" MNPT - 1/4" FNPT, SS | Swagelok | SS-4-ST | 22484
4 | 2 | RTD Assembly, 6mm OD, 150 mm long, 3 m Cable, 1/4" NPT Process, Negative Temp. Coeff. (NTC) | Woodward | DL08041301 | 21931
5 | 4 | Cord Grip, 3/4" NPT w/ Gland Nut and Bushing, .125-.250 Cable Dia. | Crouse Hinds | CGB292 | 18047
6 | 2 | Conduit Condut Outlet Box, 3/4" Hub 3" Cover Opening, With cover | Crouse Hinds | GUAT26 | 18585
NOTES:
1. INSTALLATION DRAWING APPLIES TO BOTH BANKS OF ENGINE.
UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY
PRELIMINARY FOR CUSTOMER REVIEW APP BY: DATE:
ISSUED FOR CONSTRUCTION APP BY: DATE:
AS BUILT APP BY: KRH DATE: 1/6/12
LEGEND
EXISTING PIPING/EQUIPMENT
NEW PIPING/EQUIPMENT
REVISION
DRESSER-RAND.
ENGINUITY.
4700 McMurry Ave. Suite 101
Fort Collins, CO 80525 USA
ENCANA OIL & GAS
FRENCHIE DRAW, WY
EXHAUST
MAT & MAP SENSOR INSTALLATION
DATE 11/17/11
ENGINEERED ELG
DRAWN WES
DWG NO. 000-010-0800
REV D


ENGINE BLOCK
TO E3 PANEL
3/4" CONDUIT TO E3 PANEL
DRILLED HOLES OR TEETH ON FLYWHEEL
BAR HOLES
ENGINE FLYWHEEL BELL HOUSING
SEE NOTES 1 & 2
NOTES:
1. LOCATE SENSOR OVER CENTER OF HOLES, OR TEETH IN FLYWHEEL. ENSURE THE SENSOR IS MOUNTED PERPENDICULAR TO FLYWHEEL.
2. SET THE SENSOR GAP TO 0.025" +/- 0.005".
3. FIELD ROUTE AND SUPPORT CONDUIT AS REQUIRED PER NEC REQUIREMENTS.
LEGEND
REVISION
UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY
DRESSER-RAND
ENGINUITY
MAGNETIC PICKUP INSTALLATION
IGNITION SYSTEM

ITEM	QTY	DESCRIPTION	MANUFACTURER	MANUFACTURER PART#	ENGINUITY PART#
1	REF	Magnetic Pick-up, 5/8"-18 Thread, 4.5" Threaded Length	Altronic	691118-4	15010
2	1	Hand Tap, High Speed Steel, TiN Coated, 5/8"-18, Taper, 37/64" Drill Size	McMaster-Carr	2606A341	21153
3	1	Drill Bit, 1/2" Shank, 37/64"	McMaster-Carr	29410A25	15980





EXAMPLE MAGNETIC PICKUP INSTALLATION IN FLYWHEEL GUARD

NOTES:

1. LOCATE SENSOR OVER FLYWHEEL TEETH. ENSURE THE SENSOR IS MOUNTED PERPENDICULAR TO FLYWHEEL.
2. SET THE SENSOR GAP TO 0.025" +/- 0.005"
3. MOUNT MAGNETIC PICKUP APPROXIMATELY 2" FROM FRAME END OF FLYWHEEL EDGE. CONSULT DRESSER RAND SITE SUPERVISOR BEFORE DRILLING AND TAPPING FLYWHEEL GUARD.

UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY

PRELIMINARY FOR CUSTOMER REVIEW APP BY: DATE:

ISSUED FOR CONSTRUCTION APP BY: DATE:

AS BUILT APP BY: KRH DATE: 1/6/12

LEGEND

EXISTING PIPING/EQUIPMENT

NEW PIPING/EQUIPMENT

REVISION

DRESSER-RAND.

ENGINUITY.

4700 McMurry Ave. Suite 101
Fort Collins, CO 80525 USA

ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #198
WAUKESHA L7044GSI

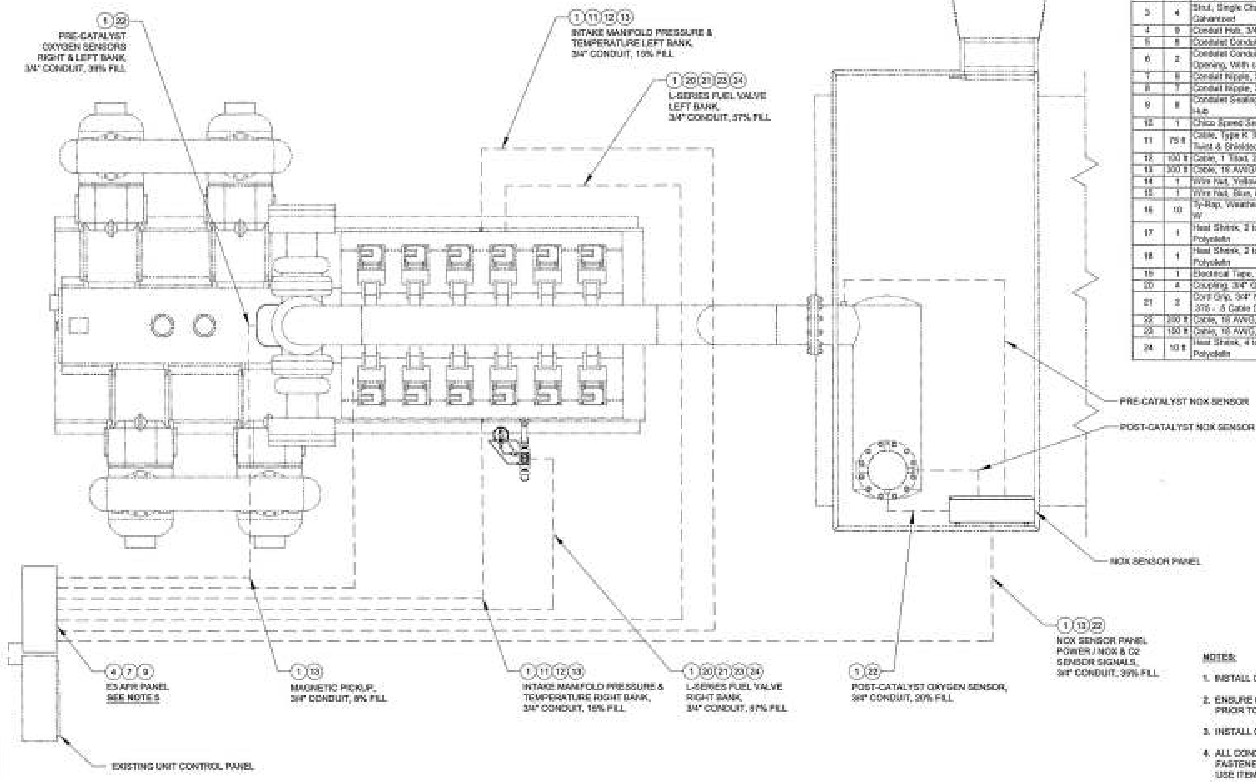
IGNITION SYSTEM

MAGNETIC PICKUP INSTALLATION

DATE 9/19/11 ENGINEERED ELG DRAWN PMV

SIZE B DWG NO 000-010-1085 REV 0

SCALE NONE SHEET 2 OF 2



ITEM	QTY	DESCRIPTION	MANUFACTURER	MANUFACTURER PART#	ENGINUITY PART#
1	300 ft	3/4" Rigid Steel Conduit	Conduit	3/4" Conduit	12772
2	20	Clamp, Strut Channel Mount, For 3/4" Pipe Sz, Steel, Zinc Plated	McMaster-Carr	3115T15	10638
3	4	Strut, Single Channel Unslotted, 1 5/8" x 1 5/8" Galvanized	McMaster-Carr	3310T37	15702
4	9	Conduit Hub, 3/4" Conduit, Steel	Crouse Hinds	HUB2	12309
5	8	Condulet Conduit Outlet Elbow, 3/4"	Crouse Hinds	LBY25	10567
6	2	Condulet Conduit Outlet Box, 3/4" Hub 3" Cover Opening, With cover	Crouse Hinds	GUAT26	10585
7	6	Conduit Nipple, 3/4" Conduit X 2" Short, Steel	Crouse Hinds	1809	11651
8	7	Conduit Nipple, 3/4" Conduit X 6", Steel	Crouse Hinds	1813	14568
9	8	Condulet Sealing Fitting, 3/4" Male and Female Hub	Crouse Hinds	EYS210	10560
10	1	Chico Speed Seal, 8 OZ	Crouse Hinds	CHICO-SS8	19160
11	75 ft	Cable, Type K Thermocouple Extension Grade, Twist & Shielded, 20 ga UL Listed	Anixter	327-221-2001-KX	17312
12	100 ft	Cable, 1 Triad, 20 AWG, Shielded, 300V, PLTC	Belden	8084	18164
13	300 ft	Cable, 18 AWG/2C Shld, 300V PLTC/ITC/CL3	Belden	8318	17379
14	1	Wire Nut, Yellow, Size 451, Box of 100	Ideal	30-451	15505
15	1	Wire Nut, Blue, Model 726	Ideal	726	19574
16	10	Ty-Rap, Weather Resistant Nylon 6/6, 8" L x 0.14" W	Thomas and Betts	TY5242MX	17065
17	1	Heat Shrink, 2 to 1, 1/4" I.D., Black, Irradiated Polyolefin	Alpha	FIT-221-1/4	18716
18	1	Heat Shrink, 2 to 1, 1/2" I.D., Black, Irradiated Polyolefin	Alpha	FIT-221-1/2	18717
19	1	Electrical Tape, Scotch Super 33+, 66' Roll	3M	3/4x66'	15505
20	4	Coupling, 3/4" Galvanized Rigid Conduit	Conduit	3/4" GRC Coupling	17081
21	2	Cord Grip, 3/4" NPT w/ Gland Nut and Bushing, .375 - .5 Cable Dia.	Crouse-Hinds	CGB294	17076
22	200 ft	Cable, 18 AWG, 2 Pair, Shielded, PLTC	Belden	9682	21380
23	150 ft	Cable, 18 AWG, 4 Pair, Shielded, PLTC	Belden	9684	22323
24	10 ft	Heat Shrink, 4 to 1, 1" I.D., Black, Irradiated Polyolefin	Alpha	FIT-421-1	18735

NOTES:

1. INSTALL CONDUIT PER NEC REQUIREMENTS FOR CLASS 1, DIVISION 2 AREA.
2. ENSURE CONDUIT AND FITTINGS ARE CLEAN AND FREE OF SHARP EDGES PRIOR TO PULLING WIRES / CABLES.
3. INSTALL CONDUIT LINERS IF NEEDED PRIOR TO PULLING WIRES / CABLES.
4. ALL CONDUIT TO FOLLOW CONTOURS OF EQUIPMENT AND TO BE SECURELY FASTENED TO UNIT AT VARIOUS POINTS SO AS TO OBTAIN A NEAT APPEARANCE. USE ITEMS 2 & 3 AS NECESSARY.
5. E3 AFR PANEL MAY BE REMOTELY MOUNTED IN A CONVENIENT LOCATION AND COMMUNICATION PROVIDED BACK TO THE EXISTING UNIT CONTROL PANEL.

UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY

PRELIMINARY FOR CUSTOMER REVIEW APP BY:____ DATE:____

[X] AS BUILT APP BY: KRH DATE: 1/6/12

ISSUED FOR CONSTRUCTION APP BY:____ DATE:____

LEGEND

EXISTING PIPING/EQUIPMENT

NEW PIPING/EQUIPMENT

REVISION

ECO #	REV	DATE	DESCRIPTION	APP
	0	1/6/12	AS-BUILTS	

DRESSER-RAND.

ENGINUITY.

4700 McMurry Ave. Suite 101
Fort Collins, CO 80525 USA

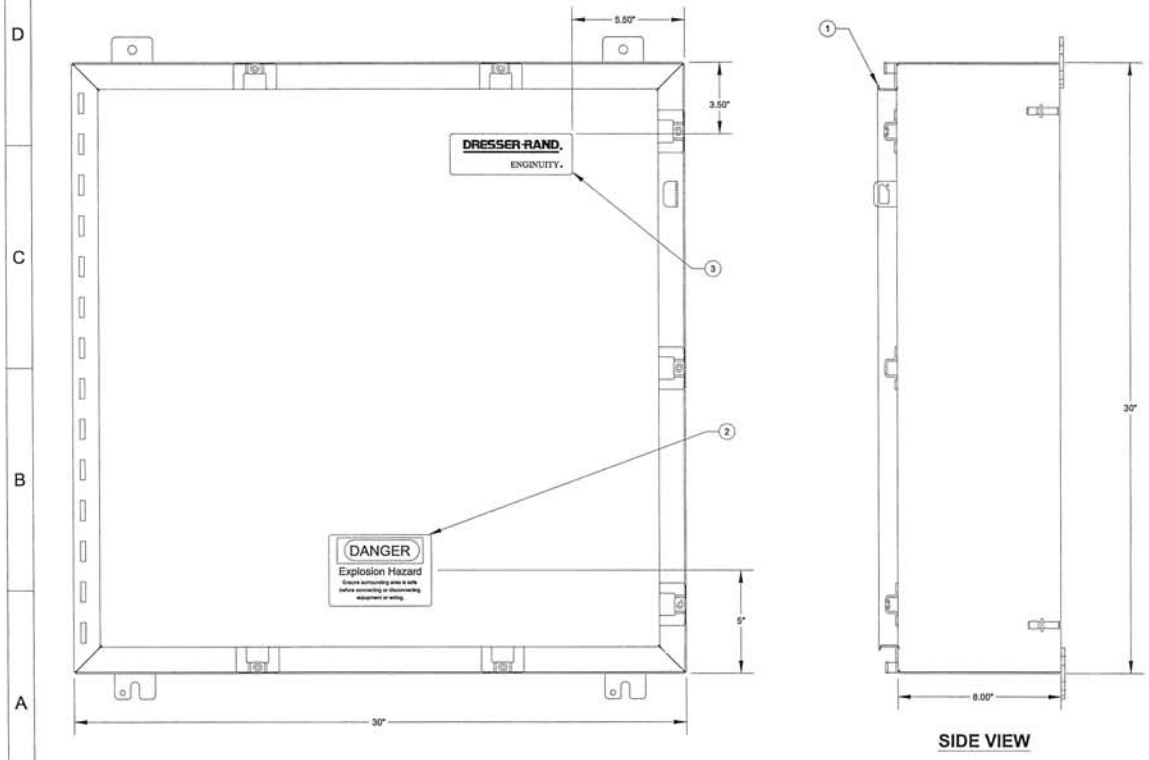
ENGINEERED ELG
DRAWN PMV
DATE 9/19/11

ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #198
WAUKESHA L7044GSI

ELECTRICAL
CONDUIT INSTALLATION

SIZE B DWG NO. 000-010-0200 REV. 0
SCALE: NONE SHEET 1 OF 1

ITEM	QTY	DESCRIPTION	MANUFACTURER	MANUFACTURER PART#	ENGINUITY PART#
1	1	Enclosure, Single Door Wall Mount, Type 12&13, 30"H X 30" W x 8"D	Hoffman	A30308LP	22254
2	1	Explosion Warning Label, 5" x 3.5", Pre-Printer Danger, Laser Printable Polyester, Permanent Adhesive	Enginuity	21508	21508
3	1	Control Panel Logo	Enginuity	20813	20813



SIDE VIEW

UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY

☐ PRELIMINARY FOR CUSTOMER REVIEW APP BY:_____ DATE:_____ ☒ AS BUILT APP BY: KRH DATE: 1/6/12

☐ ISSUED FOR CONSTRUCTION APP BY:_____ DATE:_____

LEGEND

EXISTING PIPING/EQUIPMENT

NEW PIPING/EQUIPMENT

ECO #	REV	DATE	DESCRIPTION	APP
10008	0	1/4/12	AS - BUILTS	KRH

REVISION

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

TOLERANCES ARE:
X=±1
.XX=±.01
.XXX=±.005
.XXXX=±.0001
X/Y=±1/16"
DEGREES=±1°

CAD DRAWING - DO NOT MANUALLY UPDATE

DATE 9/19/11

DO NOT SCALE DRAWING

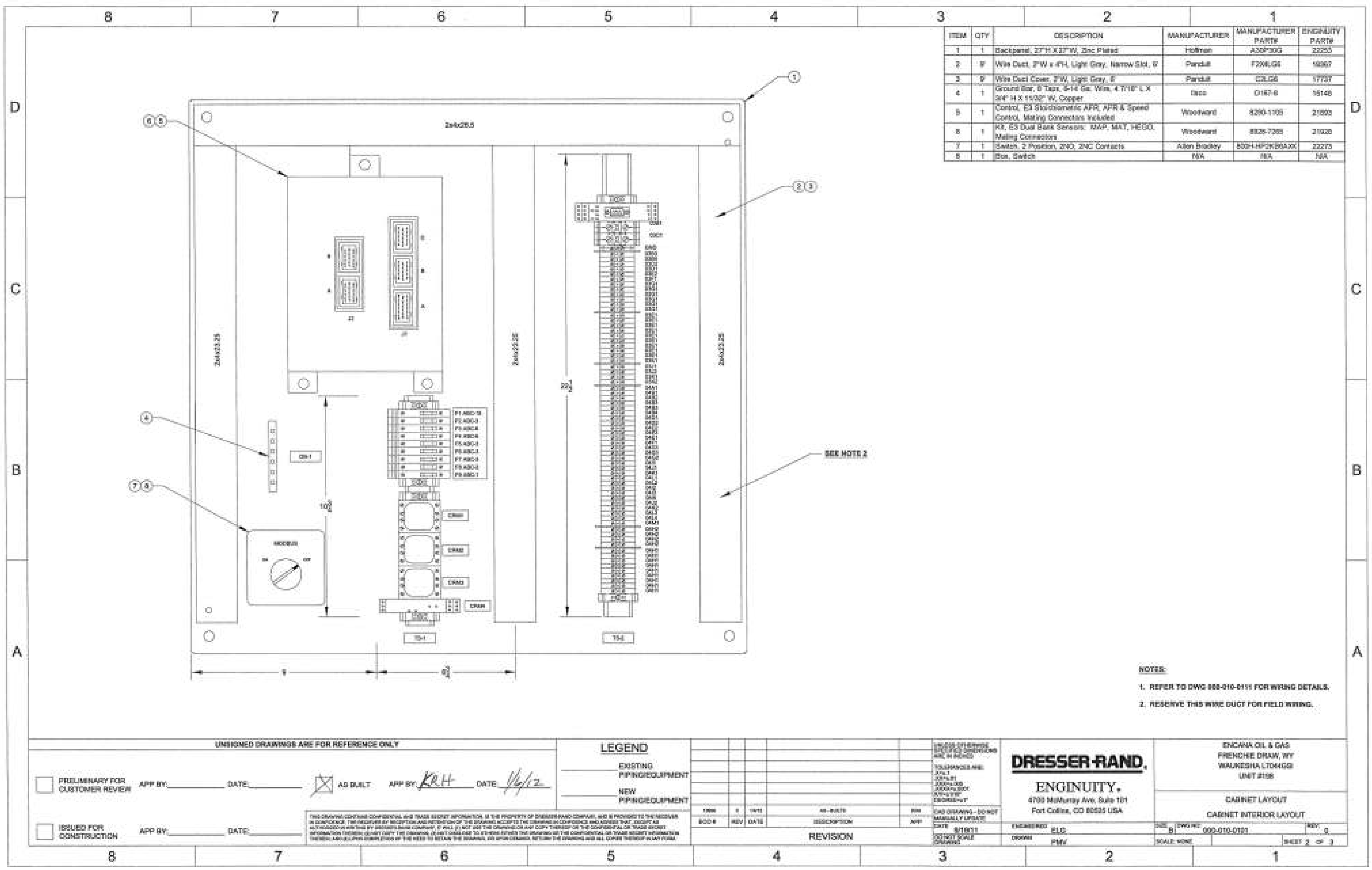
DRESSER-RAND.
ENGINUITY.
4700 McMurry Ave. Suite 101
Fort Collins, CO 80525 USA

ENGINEERED ELG
DRAWN PMV

ENCANA OIL & GAS
FRENCHIE DRAW, WY
WAUKESHA L7044GSI
UNIT #198

CABINET LAYOUT
CABINET EXTERIOR LAYOUT

SIZE B DWG NO. 000-010-0101 REV. 0
SCALE: NONE SHEET 1 OF 3



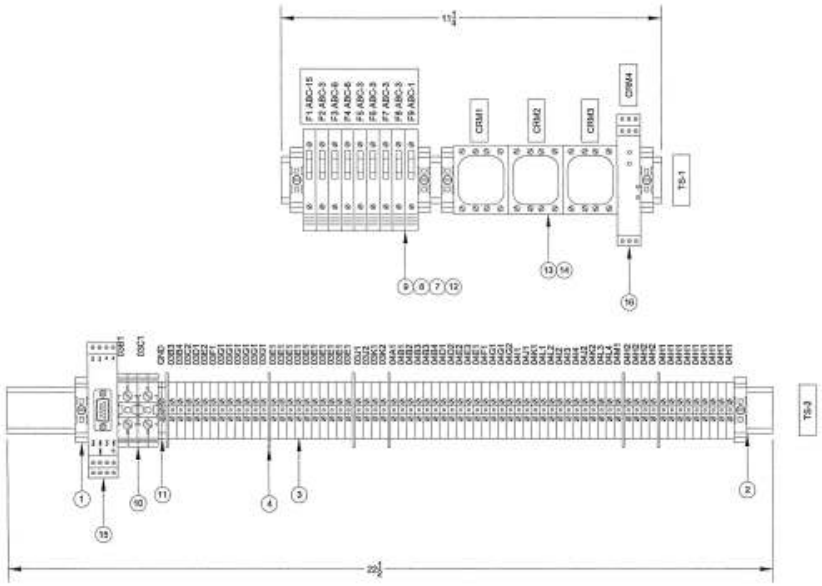
ITEM	QTY	DESCRIPTION	MANUFACTURER	MANUFACTURER PART#	ENGINUITY PART#
1	1	Backpanel, 27"H X 27"W, Zinc Plated	Hoffman	A30P30G	22253
2	9'	Wire Duct, 2"W x 4"H, Light Gray, Narrow Slot, 6'	Panduit	F2X4LG6	19367
3	9'	Wire Duct Cover, 2"W, Light Gray, 6'	Panduit	C2LG6	17737
4	1	Ground Bar, 6 Taps, 6-14 Ga. Wire, 4 7/16" L X 3/4" H X 11/32" W, Copper	Ilsco	D167-6	15146
5	1	Control, E3 Stoichiometric AFR, AFR & Speed Control, Mating Connectors Included	Woodward	8290-1105	21693
6	1	Kit, E3 Dual Bank Sensors: MAP, MAT, HEGO, Mating Connectors	Woodward	8928-7365	21926
7	1	Switch, 2 Position, 2NO, 2NC Contacts	Allen Bradley	500H-HP2KB6AXX	22273
8	1	Box, Switch	N/A	N/A	N/A

NOTES:

1. REFER TO DWG 000-010-0111 FOR WIRING DETAILS.
2. RESERVE THIS WIRE DUCT FOR FIELD WIRING.

ITEM	QTY	DESCRIPTION	MANUFACTURER	MANUFACTURER PART#	ENGINUITY PART#
1	6	Terminal Block End Bracket, E/NS 35 N	Phoenix Contact	08 00 88 6	16052
2	39"	DIN Rail, Cu Free At, 2.28" H x 0.28" L	Allen-Bradley	1492-DHB	21563
3	69	Terminal Block, UK5N	Phoenix Contact	30 04 36 2	16700
4	6	Partition Plate, ATP-UK, for UK5N Terminal Block	Phoenix Contact	30 03 22 4	14908
5	3	Insertion Bridge, Fixed, 10 pos Center, FBI 10-6, for UK5N Terminal Block	Phoenix Contact	02 03 25 0	14907
6	69	Marker Strip, ZB 6, for 6.2 mm Terminal Block, Blank	Phoenix Contact	10 51 00 3	14915
7	5	Fuse, 3A, Ceramic, 1/4 x 1 1/4, Fast Acting	Bussman	ABC-3	21291
8	1	Fuse, 15A, 1/4 x 1-1/4, Ceramic, Fast Acting	Bussman	ABC-15	19915
9	2	Fuse, 6A, 1/4 x 1-1/4, Ceramic, Fast Acting	Bussman	ABC-6	22257
10	2	Terminal Block, UK 35	Phoenix Contact	30 06 18 2	21661
11	1	Grounding Terminal Block, USLKG5	Phoenix Contact	04 41 93 4	13170
12	9	Fuseholder, DIN Mount, for 6.3 x 32 mm Fuses, UK6 3-HE	Phoenix Contact	30 04 17 1	17097
13	3	Relay Base, 8 Pin Octal Style, Din/Panel Mount, DPDT	Magnecraft	70-464-1	17543
14	3	Relay, DPDT, Hermetically Sealed, 24 VDC Coil, Class I Div 2	Magnecraft	750R64-24D	17544
15	1	RS232-RS485 / USB Converter with Terminals	Woodward	1784-1106	22487
16	1	Relay, PLC-RSC- 24DC/21-21ATEX, DPDT, 24 VDC, Din Rail Mount, Haz locations	Phoenix Contact	28 80 46 1	21656

SEE NOTE 2



NOTES:

1. ITEMS 5 & 6 NOT REFERENCED. INSTALL AS REQUIRED.

UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY

☐ PRELIMINARY FOR CUSTOMER REVIEW APP BY:_____ DATE:_____

☒ AS BUILT APP BY: KRH DATE: 1/6/12

☐ ISSUED FOR CONSTRUCTION APP BY:_____ DATE:_____

LEGEND

EXISTING PIPING/EQUIPMENT

NEW PIPING/EQUIPMENT

DWG #	REV	DATE	DESCRIPTION	APP
			AS-BUILT	KRH

REVISION

CAD DRAWING - DO NOT MANUALLY UPDATE

DATE: 9/19/11

DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

TOLERANCES ARE:
X=±
.XX=±.03
.XXX=±.005
.XXXX=±.0001
ANGULAR=±1°

DRESSER-RAND

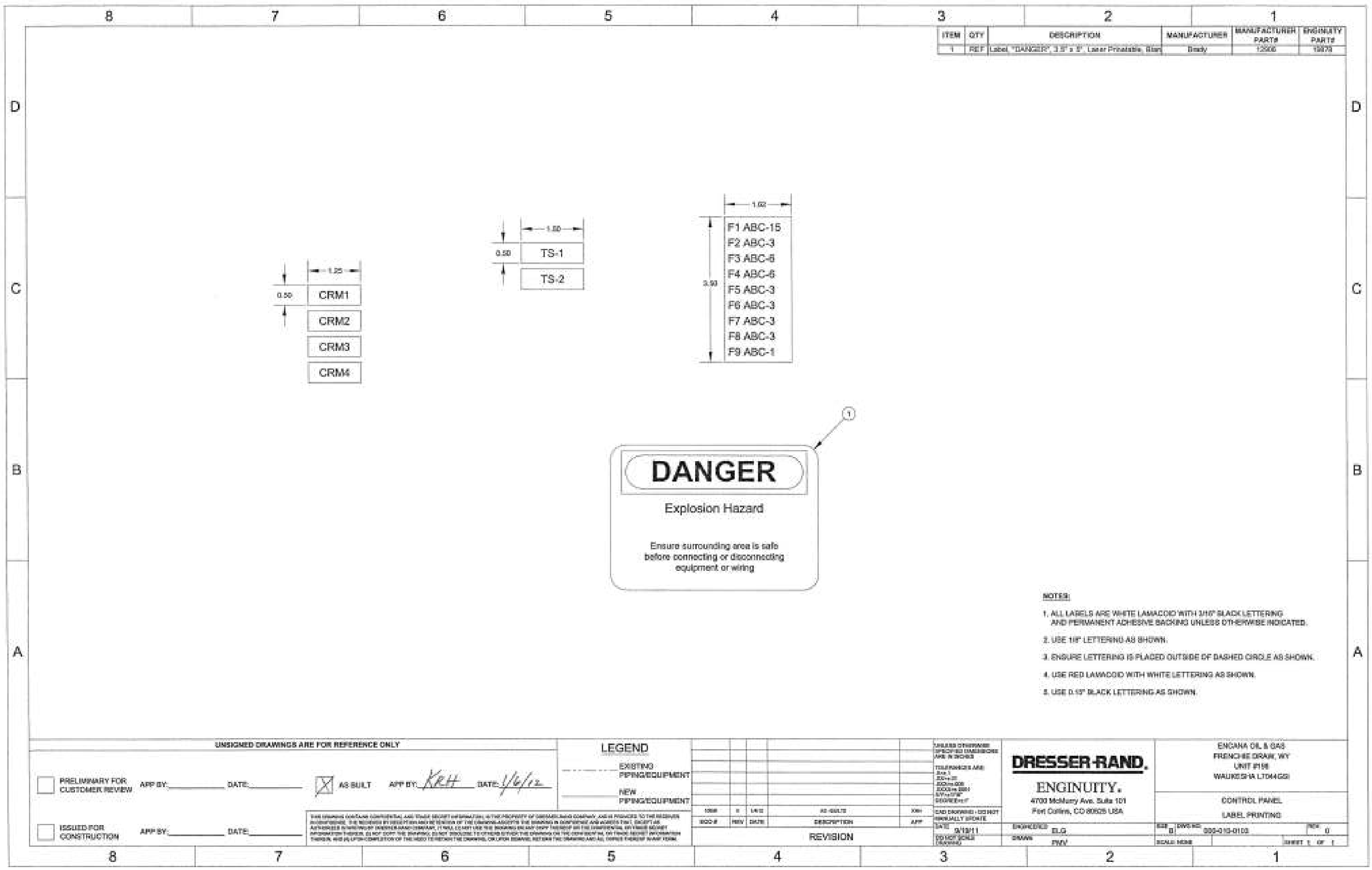
ENGINUITY.

4700 McMurry Ave. Suite 101
Fort Collins, CO 80525 USA

ENCANA OIL & GAS
FRENCHIE DRAW, WY
WAUKESHA L7044GSI
UNIT #190

TERMINAL STRIP DETAILS

DRAWN BY:	ELG	SIZE: B	DWG NO: 009-010-0101 REV: 0
CHECKED:	PMV	SCALE: NONE	SHEET 3 OF 3


ITEM | QTY | DESCRIPTION | MANUFACTURER | MANUFACTURER PART# | ENGINUITY PART#
1 | REF | Label, "DANGER", 3.5" x 5", Laser Printable | Brady | 12906 | 19878
CRM1
CRM2
CRM3
CRM4
TS-1
TS-2
F1 ABC-15
F2 ABC-3
F3 ABC-6
F4 ABC-6
F5 ABC-3
F6 ABC-3
F7 ABC-3
F8 ABC-3
F9 ABC-1
DANGER
Explosion Hazard
Ensure surrounding area is safe before connecting or disconnecting equipment or wiring
NOTES:
1. ALL LABELS ARE WHITE LAMACOID WITH 3/16" BLACK LETTERING AND PERMANENT ADHESIVE BACKING UNLESS OTHERWISE INDICATED.
2. USE 1/8" LETTERING AS SHOWN.
3. ENSURE LETTERING IS PLACED OUTSIDE OF DASHED CIRCLE AS SHOWN.
4. USE RED LAMACOID WITH WHITE LETTERING AS SHOWN.
5. USE 0.15" BLACK LETTERING AS SHOWN.
UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY
PRELIMINARY FOR CUSTOMER REVIEW
ISSUED FOR CONSTRUCTION
AS BUILT
LEGEND
EXISTING PIPING/EQUIPMENT
NEW PIPING/EQUIPMENT
REVISION
DRESSER-RAND.
ENGINUITY.
4700 McMurry Ave. Suite 101
Fort Collins, CO 80525 USA
ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #156
WAUKESHA L7044GSI
CONTROL PANEL
LABEL PRINTING

Control Wiring Diagram

E3 Air Fuel Ratio
Controls Project
Encana Oil & Gas
Frenchie Draw, WY

Engine Manufacturer	Waukesha
Engine Model	L7044GSI
Engine Drive	Compressor
Control Type	RELi

Pg.	Description
1	Cover Sheet and Index
2	General Notes and Symbols
3	Power Distribution
4	E3 Wiring
5	Communication Isolation / Conversion

UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY

☐ PRELIMINARY FOR CUSTOMER REVIEW APP BY:________ DATE:________

☐ ISSUED FOR CONSTRUCTION APP BY:________ DATE:________

☒ AS BUILT APP BY: KRH DATE: 1/6/12

LEGEND

– – – – FIELD WIRING

——— CABINET WIRING

REVISION

ECO #	REV	DATE	DESCRIPTION	APP
	0		AS BUILT	

CAD DRAWING – DO NOT MANUALLY UPDATE

DATE 9/19/11

DO NOT SCALE DRAWING

DRESSER-RAND.

ENGINUITY.

4100 McMurry Ave. Suite 101
Fort Collins, CO 80525 USA

ENGINEERED PGN

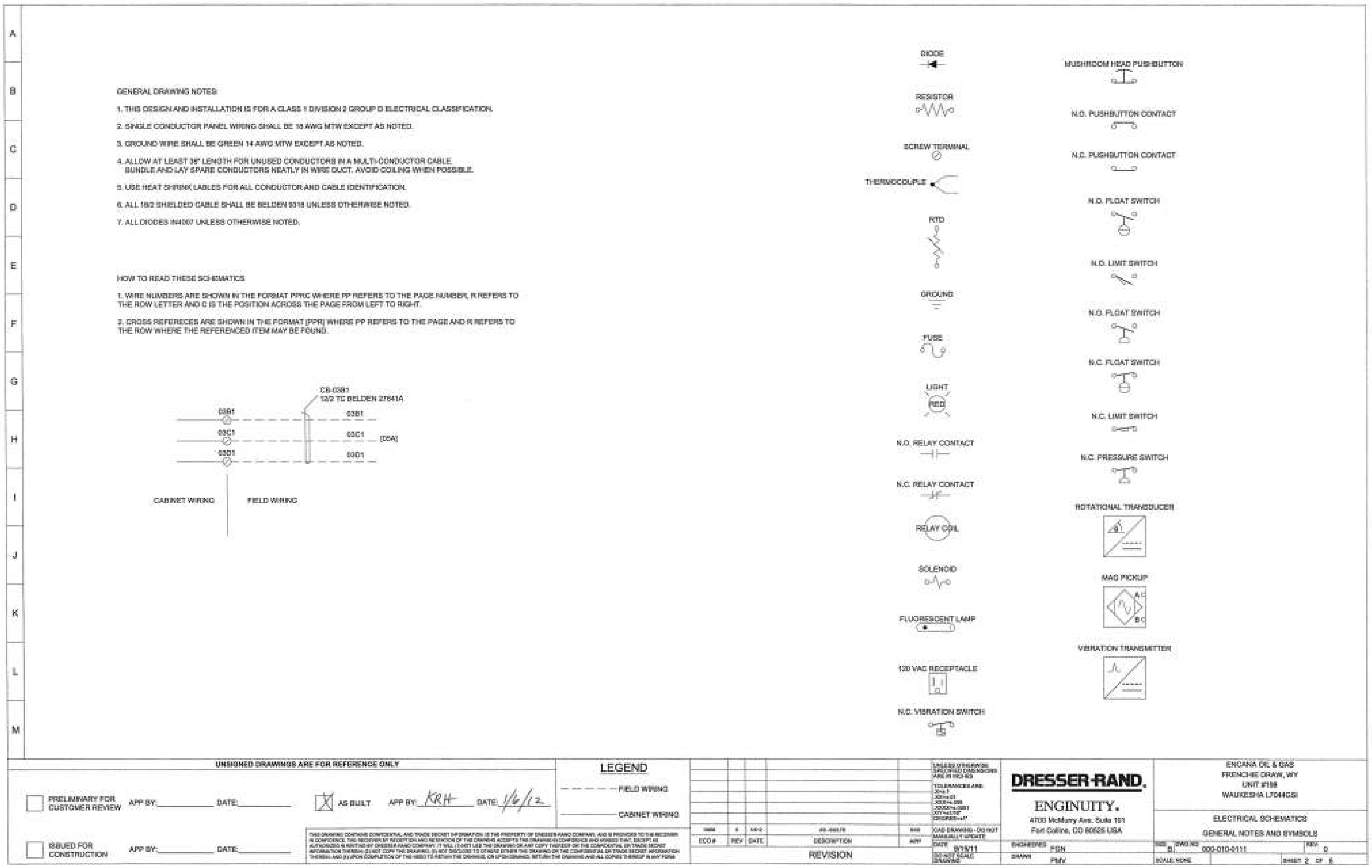
DRAWN PMV

ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #198
WAUKESHA L7044GSI

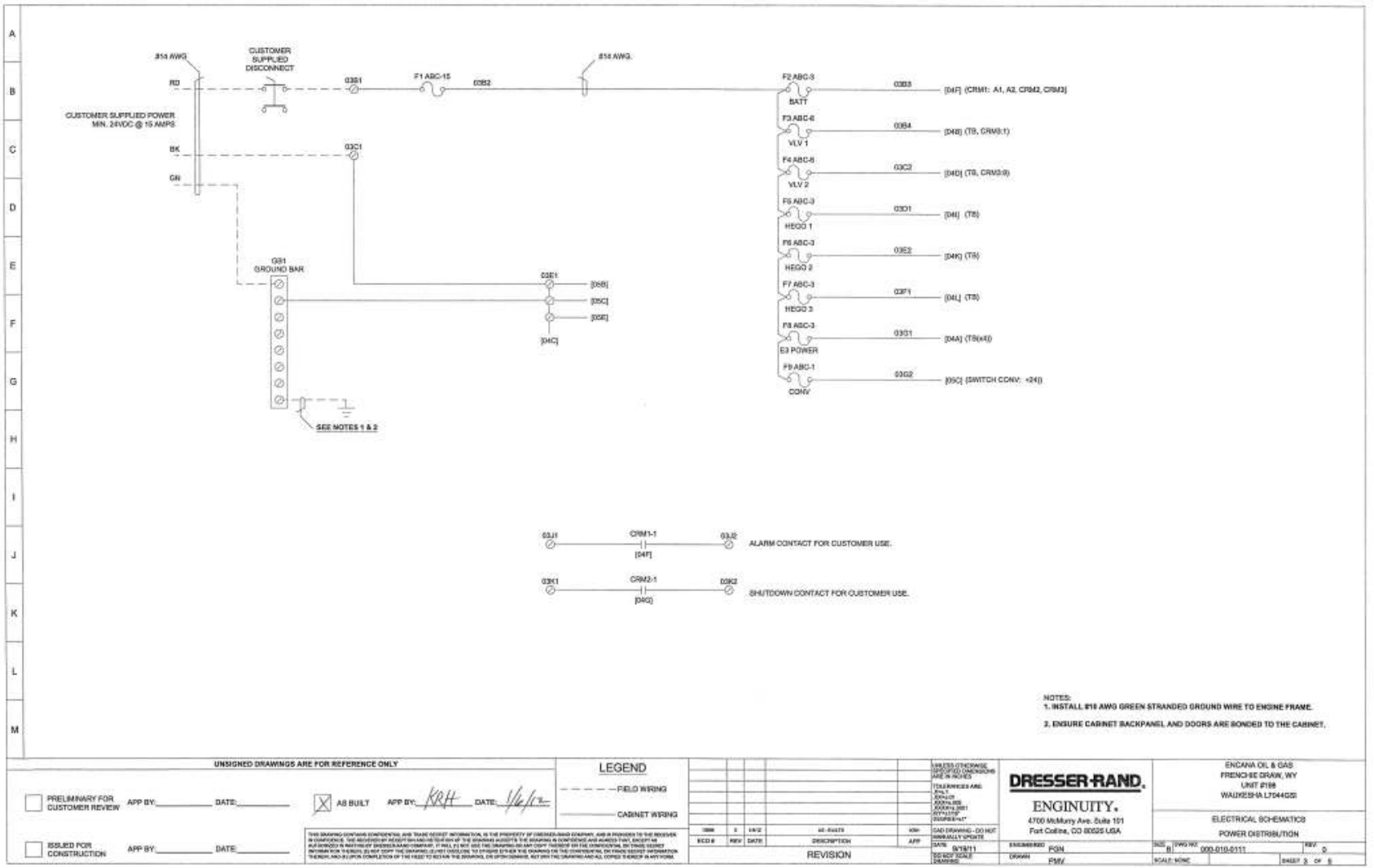
ELECTRICAL SCHEMATICS
COVERSHEET AND INDEX

SIZE B DWG NO 000-010-0111 REV 0

SCALE NONE SHEET 1 OF 5



GENERAL DRAWING NOTES:
1. THIS DESIGN AND INSTALLATION IS FOR A CLASS 1 DIVISION 2 GROUP D ELECTRICAL CLASSIFICATION.
2. SINGLE CONDUCTOR PANEL WIRING SHALL BE 18 AWG MTW EXCEPT AS NOTED.
3. GROUND WIRE SHALL BE GREEN 14 AWG MTW EXCEPT AS NOTED.
4. ALLOW AT LEAST 36" LENGTH FOR UNUSED CONDUCTORS IN A MULTI-CONDUCTOR CABLE. BUNDLE AND LAY SPARE CONDUCTORS NEATLY IN WIRE DUCT. AVOID COILING WHEN POSSIBLE.
5. USE HEAT SHRINK LABLES FOR ALL CONDUCTOR AND CABLE IDENTIFICATION.
6. ALL 18/2 SHIELDED CABLE SHALL BE BELDEN 9318 UNLESS OTHERWISE NOTED.
7. ALL DIODES IN4007 UNLESS OTHERWISE NOTED.
HOW TO READ THESE SCHEMATICS
1. WIRE NUMBERS ARE SHOWN IN THE FORMAT PPRC WHERE PP REFERS TO THE PAGE NUMBER, R REFERS TO THE ROW LETTER AND C IS THE POSITION ACROSS THE PAGE FROM LEFT TO RIGHT.
2. CROSS REFERECES ARE SHOWN IN THE FORMAT [PPR] WHERE PP REFERS TO THE PAGE AND R REFERS TO THE ROW WHERE THE REFERENCED ITEM MAY BE FOUND.
CB-03B1
12/2 TC BELDEN 27641A
03B1
03C1
03D1
[05A]
CABINET WIRING
FIELD WIRING
DIODE
RESISTOR
SCREW TERMINAL
THERMOCOUPLE
RTD
GROUND
FUSE
LIGHT
RED
N.O. RELAY CONTACT
N.C. RELAY CONTACT
RELAY COIL
SOLENOID
FLUORESCENT LAMP
120 VAC RECEPTACLE
N.C. VIBRATION SWITCH
MUSHROOM HEAD PUSHBUTTON
N.O. PUSHBUTTON CONTACT
N.C. PUSHBUTTON CONTACT
N.O. FLOAT SWITCH
N.O. LIMIT SWITCH
N.O. FLOAT SWITCH
N.C. FLOAT SWITCH
N.C. LIMIT SWITCH
N.C. PRESSURE SWITCH
ROTATIONAL TRANSDUCER
MAG PICKUP
VIBRATION TRANSMITTER
UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY
PRELIMINARY FOR CUSTOMER REVIEW APP BY: DATE:
ISSUED FOR CONSTRUCTION APP BY: DATE:
AS BUILT APP BY: KRH DATE: 1/6/12
LEGEND
FIELD WIRING
CABINET WIRING
ECO# REV DATE DESCRIPTION APP
REVISION
DRESSER-RAND.
ENGINUITY.
4700 McMurry Ave. Suite 101
Fort Collins, CO 80525 USA
ENGINEERED FGN
DRAWN PMV
DATE 8/19/11
ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #199
WAUKESHA L7044GSI
ELECTRICAL SCHEMATICS
GENERAL NOTES AND SYMBOLS
DWG NO 000-010-0111
REV D
SCALE NONE
SHEET 2 OF 6



NOTES:
1. INSTALL #10 AWG GREEN STRANDED GROUND WIRE TO ENGINE FRAME.
2. ENSURE CABINET BACKPANEL AND DOORS ARE BONDED TO THE CABINET.

UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY

☐ PRELIMINARY FOR CUSTOMER REVIEW APP BY:_____ DATE:_____

☒ AS BUILT APP BY: KRH DATE: 1/6/12

☐ ISSUED FOR CONSTRUCTION APP BY:_____ DATE:_____

LEGEND
- - - - - FIELD WIRING
——— CABINET WIRING

ECO #	REV	DATE	DESCRIPTION	APP
1888	3	9/8/11	AS - BUILTS	KRH

REVISION

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES ARE:
.X=±1
.XX=±0.05
.XXX=±0.005
.XXXX=±.0001
ANGLES=±1°
SURFACES=63

CAD DRAWING - DO NOT MANUALLY UPDATE
DATE: 9/28/11
DO NOT SCALE DRAWING

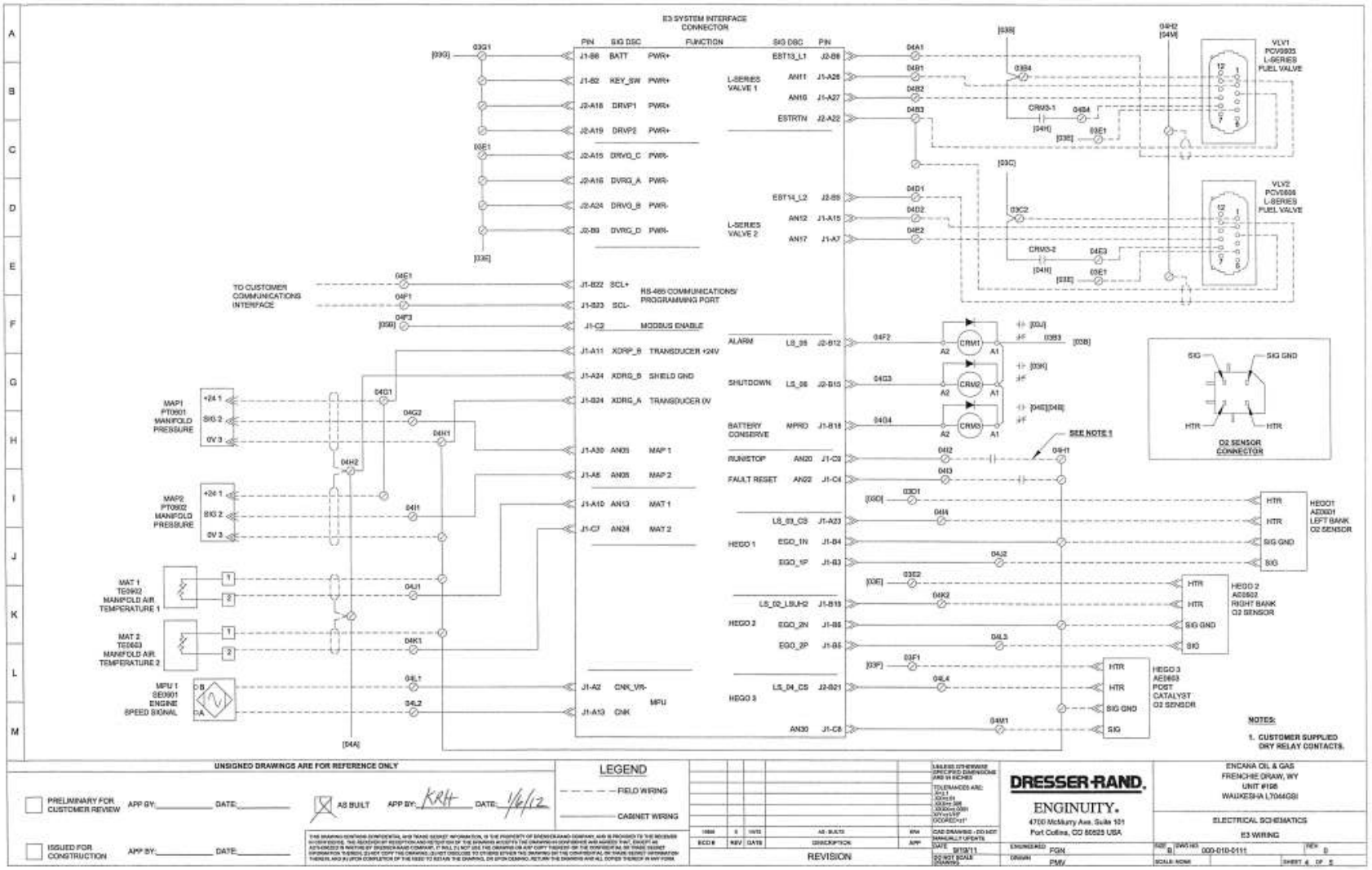
DRESSER-RAND.
ENGINUITY.
4700 McMurry Ave, Suite 101
Fort Collins, CO 80525 USA

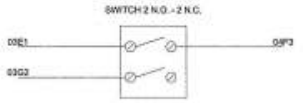
ENGINEER: PSN
DRAWN: PMV

ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #198
WAUKESHA L7044GSI

ELECTRICAL SCHEMATICS
POWER DISTRIBUTION

SIZE: B | DWG NO: 000-010-0111 | REV: 0
SCALE: NONE | SHEET 3 OF 5


E3 SYSTEM INTERFACE CONNECTOR
PIN SIG DSC FUNCTION
J1-B8 BATT PWR+
J1-B2 KEY_SW PWR+
J2-A18 DRVP1 PWR+
J2-A19 DRVP2 PWR+
J2-A15 DRVG_C PWR-
J2-A16 DVRG_A PWR-
J2-A24 DRVG_B PWR-
J2-B9 DVRG_D PWR-
J1-B22 SCL+
J1-B23 SCL-
RS-485 COMMUNICATIONS/ PROGRAMMING PORT
J1-C2 MODBUS ENABLE
J1-A11 XDRP_B TRANSDUCER +24V
J1-A24 XDRG_B SHIELD GND
J1-B24 XDRG_A TRANSDUCER 0V
J1-A30 AN05 MAP 1
J1-A5 AN08 MAP 2
J1-A10 AN13 MAT 1
J1-C7 AN28 MAT 2
J1-A2 CNK_VR- MPU
J1-A13 CNK
SIG DSC PIN
EST13_L1 J2-B8
L-SERIES VALVE 1
AN11 J1-A26
AN16 J1-A27
ESTRTN J2-A22
EST14_L2 J2-B9
L-SERIES VALVE 2
AN12 J1-A15
AN17 J1-A7
ALARM LS_05 J2-B12
SHUTDOWN LS_06 J2-B15
BATTERY CONSERVE MPRO J1-B18
RUNSTOP AN20 J1-C3
FAULT RESET AN22 J1-C4
LS_03_CS J1-A23
HEGO 1
EGO_1N J1-B4
EGO_1P J1-B3
LS_02_LSUH2 J1-B13
HEGO 2
EGO_2N J1-B6
EGO_2P J1-B5
LS_04_CS J2-B21
HEGO 3
AN30 J1-C8
TO CUSTOMER COMMUNICATIONS INTERFACE
MAP1 PT0901 MANIFOLD PRESSURE
MAP2 PT0902 MANIFOLD PRESSURE
MAT 1 TE0902 MANIFOLD AIR TEMPERATURE 1
MAT 2 TE0903 MANIFOLD AIR TEMPERATURE 2
MPU 1 SE0901 ENGINE SPEED SIGNAL
VLV1 PCV0805 L-SERIES FUEL VALVE
VLV2 PCV0806 L-SERIES FUEL VALVE
CRM1
CRM2
CRM3
CRM3-1
CRM3-2
O2 SENSOR CONNECTOR
SIG
SIG GND
HTR
HEGO1 AE0901 LEFT BANK O2 SENSOR
HEGO 2 AE0902 RIGHT BANK O2 SENSOR
HEGO 3 AE0903 POST CATALYST O2 SENSOR
SEE NOTE 1
NOTES:
1. CUSTOMER SUPPLIED DRY RELAY CONTACTS.
UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY
PRELIMINARY FOR CUSTOMER REVIEW
AS BUILT
ISSUED FOR CONSTRUCTION
LEGEND
FIELD WIRING
CABINET WIRING
REVISION
DRESSER-RAND.
ENGINUITY.
4700 McMurry Ave, Suite 101
Port Collins, CO 80525 USA
ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #198
WAUKESHA L7044GSI
ELECTRICAL SCHEMATICS
E3 WIRING
ENGINEERED FGN
DRAWN PMV
DWG NO. 000-010-0111
SCALE: NONE



UNSIGNED DRAWINGS ARE FOR REFERENCE ONLY

☐ PRELIMINARY FOR CUSTOMER REVIEW APP BY:_____ DATE:_____

☐ ISSUED FOR CONSTRUCTION APP BY:_____ DATE:_____

☒ AS-SUILT APP BY: KRH DATE: 1/6/12

LEGEND

- - - - - FIELD WIRING

——— CABINET WIRING

ECO #	REV	DATE	DESCRIPTION	APP

REVISION

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

TOLERANCES ARE:
2 PL ±.1
3 PL ±.01
2 DEC ±.005
3 DEC ±.000
FRACTIONS ±1/16"
ANGLES ±1°

DO NOT MANUALLY UPDATE

DRESSER-RAND.

ENGINUITY.

4700 McMurry Ave, Suite 101
Fort Collins, CO 80525 USA

ENCANA OIL & GAS
FRENCHIE DRAW, WY
UNIT #198
WAUKESHA L7044GSI

ELECTRICAL SCHEMATICS
COMMUNICATION ISOLATION / CONVERSION

DATE 1/6/12
ENGINEERED FGN
DRAWN PMV
SIZE B | DWG NO 000-010-0111 | REV 0
SCALE NONE | SHEET 5 OF 5

DO NOT SCALE DRAWING

REVISION HISTORY			
REV	DESCRIPTION	DATE	APPROVED
0	PRELIMARY FOR REVIEW	8/19/2011	CDEFOOR

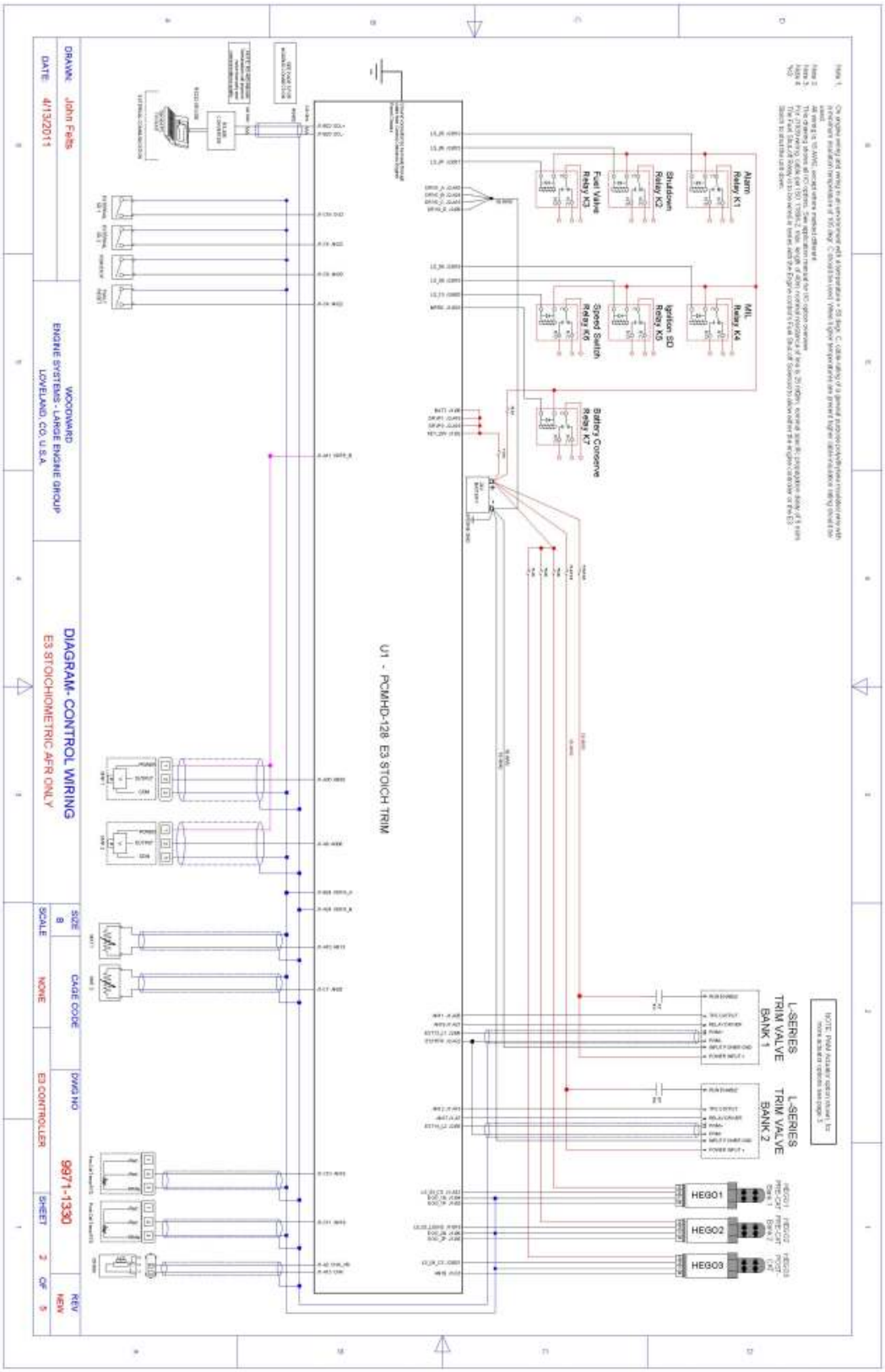
WOODWARD

E3 STOICHIOMETRIC CONTROL SYSTEM WITH CATALYST AND ENGINE PROTECTION SYSTEM

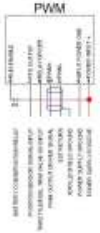
Encana Gram Central #5 Unit 198
Waukesha L7044GSI SN C-15011/1
E3 Stoichiometric AFR Only
Woodward PN 8280-1104

CONTROL WIRING DIAGRAM

DRAWN: Chris DeFoor	WOODWARD, INC. LARGE ENGINE SYSTEMS LOVELAND, COLORADO, USA	DIAGRAM- CONTROL WIRING	SIZE B	CAGE CODE	DWG NO XXXX-XXXX		REV 0
DATE: 8/19/2011		E3 STOICHIOMETRIC AFR ONLY	SCALE NONE		TITLE	SHEET 1	OF 5


DRAWN: John Fellis
DATE: 4/13/2011
WOODWARD
ENGINE SYSTEMS - LARGE ENGINE GROUP
LOVELAND, CO, U.S.A.
DIAGRAM- CONTROL WIRING
E3 STOICHIOMETRIC AFR ONLY
SIZE B
CAGE CODE
DWG NO 9971-1330
REV NEW
SCALE NONE
E3 CONTROLLER
SHEET 2 OF 5
U1 - PCMHD-128 E3 STOICH TRIM
Alarm Relay K1
Shutdown Relay K2
Fuel Valve Relay K3
MIL Relay K4
Ignition SD Relay K5
Speed Switch Relay K6
Battery Conserve Relay K7
L-SERIES TRIM VALVE BANK 1
L-SERIES TRIM VALVE BANK 2
HEGO1
HEGO2
HEGO3

ACTUATOR OPTIONS

	F-Series	L-Series			ProAct ISC
PWM OPTION		L-SERIES PWM 			
CAN OPTION	F-SERIES CAN 	NO CAN OPTION			

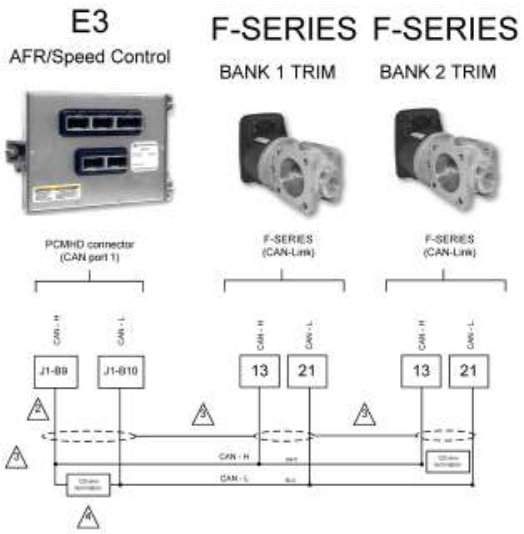
DRAWN: John Felts	WOODWARD ENGINE SYSTEMS - LARGE ENGINE GROUP LOVELAND, CO, U.S.A.	DIAGRAM- CONTROL WIRING E3 STOICHIOMETRIC AFR ONLY	SIZE B	CAGE CODE	DWG NO 9971-1330	REV NEW
DATE: 4/13/2011			SCALE NONE	ACTUATOR OPTIONS	SHEET 3 OF 5	

1. Cable per ISO 11898-2:
Maximum length of 40 m For the J1939 on 250 Kbps.
Ends of the network need to be terminated with 120 ohm resistors
Nominal resistance of line is 70 mohm/m
Nominal specific propagation delay of 5 ns/m.

2. Maximum length of drop line length of 1 m at 250 Kbps

3. The shielding needs to be continued through.

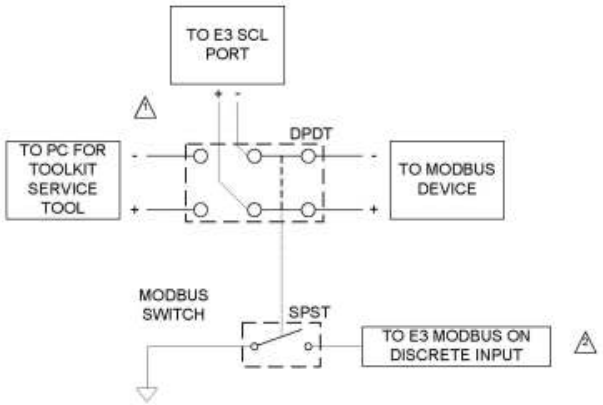
4. Termination resistor on needed on each end of network.



DRAWN: John Felts	WOODWARD ENGINE SYSTEMS - LARGE ENGINE GROUP LOVELAND, CO, U.S.A.	DIAGRAM- CONTROL WIRING E3 STOICHIOMETRIC AFR ONLY	SIZE B	CAGE CODE	DWG NO 9971-1330	REV NEW
DATE: 4/13/2011			SCALE NONE	CAN J1939	SHEET 4 OF 5	

1. When the E3 Modbus Switch is closed to activate the E3 Serial Port for Modbus, the source must also be switched to avoid line contention. A Double-Pole Double-Throw Relay is normally used.

2. The E3 Modbus switch input is not configured as defaulted from the factory, use the Toolkit Service Tool to configure a spare Discrete input as the Modbus ON function.



DRAWN: John Felts	WOODWARD	DIAGRAM- CONTROL WIRING	SIZE B	CAGE CODE	DWG NO 9971-1330	REV NEW
DATE: 4/13/2011	ENGINE SYSTEMS - LARGE ENGINE GROUP LOVELAND, CO, U.S.A.	E3 STOICHIOMETRIC AFR ONLY	SCALE NONE	MODBUS	SHEET 5 OF 5	

LIST OF ABBREVIATIONS

AFR – Air Fuel Ratio

BHP – Brake Horsepower

BSE – Brake Specific Emissions

CeO_2 – Ceria

CH_4 – Methane

CH_2O – Formaldehyde

CO_2 – Carbon Dioxide

CO – Carbon Monoxide

CSU – Colorado State University

EECL – Engines and Energy Conversion Laboratory

GC – Gas Chromatograph

H_2 – Hydrogen

HC – Hydrocarbons

HEGO – Heated Exhaust Gas Oxygen (sensor)

ICE – Internal Combustion Engine

LB – Lean Burn (engine)

MAP – Manifold Absolute Pressure

MAT – Manifold Air Temperature

MPU – Magnetic Pickup

N_2 – Nitrogen

NO – Nitric Oxide

NO_2 – Nitrogen Dioxide

NOx – Oxides of Nitrogen

NSCR – Non-Selective Catalytic Reduction

O_2 – Oxygen

P&ID – Piping and Instrumentation Diagram

RB – Rich Burn (engine)

SI – Spark Ignited

STP – Standard Temperature and Pressure

THC – Total Hydrocarbons

TWC – Three-Way Catalyst

UHC – Unburnt Hydrocarbons

VOC – Volatile Organic Compound