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DEMONSTRATION OF GAS-POWERED DRILLING OPERATIONS FOR ECONOMICALLY CHALLENGED WELLHEAD GAS AND EVALUATION OF COMPLEMENTARY PLATFORMS

Revised Final Report

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DEMONSTRATION OF GAS-POWERED DRILLING OPERATIONS FOR ECONOMICALLY CHALLENGED WELLHEAD GAS AND EVALUATION OF COMPLEMENTARY PLATFORMS

PROJECT SUMMARY

The Energy & Environmental Research Center (EERC) in partnership with the North Dakota Industrial Commission Oil and Gas Research Council; Continental Resources, Inc.; the U.S. Department of Energy National Energy Technology Laboratory; ECO-Alternative Fuel Systems; Altronic; and Butler Caterpillar conducted a project to demonstrate and evaluate utilization of wellhead gas for fueling diesel engines used to power a drilling rig in North Dakota. This evaluation consisted of two phases. Preliminary testing was conducted at the EERC using a leased Caterpillar engine and a mixture of diesel and simulated wellhead gas in a dual-fuel application. Results from these tests were reported previously and have been included as an appendix to this report. Phase II of the project consisted of field-testing engines using a mixture of diesel and wellhead gas on a drilling rig during the drilling of two wells. This report summarizes the results of the demonstration project, including an assessment of engine performance, diesel fuel savings, and the impact on engine emissions.

The results of the 47-day demonstration project illustrated that utilizing wellhead gas in bi-fuel applications to power a drilling rig can lead to an overall decrease in diesel fuel use, fuel cost, and truck transport of liquid fuel, without adversely impacting drilling operations. The specific results from this project included fuel-related cost savings of nearly $60,000 due to the lower value of wellhead gas relative to diesel. If implemented broadly across the Williston Basin, bi-fuel operation of nearly 200 drilling rigs using otherwise flared wellhead gas could result in:

1) 1,800,000 Mcf wellhead gas used to power drilling rigs in 1 year (2% of currently flared wellhead gas).

2) 18,000,000 gallons of diesel fuel saved in 1 year.

3) $72,000,000 diesel fuel costs saved in 1 year.

4) 3600 fuel delivery trucks (5000-gallon tanker) avoided in 1 year.

5) Air emission reduction can be achieved using commercially available diesel engine exhaust gas treatment (catalytic conversion). These technologies are capable of reducing CO and nonmethane hydrocarbon emissions in bi-fuel-operated engines to levels similar to 100% diesel-only operation.

TABLE OF CONTENTS

LIST OF FIGURES

Continued. . .

LIST OF FIGURES (continued)

LIST OF TABLES

NOMENCLATURE

BTDC	before top dead center
BHP	break horse power
CARB	California Air Resources Board
CFR	Cooperative Fuel Research
CN	cetane number
ECO-AFS	ECO-Alternative Fuel Systems
EERC	Energy & Environmental Research Center
EGT	exhaust gas temperature
EPA	U.S. Environmental Protection Agency
GSP	gas supply pressure
HHV	higher heating value
LPG	liquefied petroleum gas
MAP	manifold air pressure
MAT	manifold air temperature
NDIC	North Dakota Industrial Commission
NETL	National Energy Technology Laboratory
NGL	natural gas liquid
NMHC	nonmethane hydrocarbons
OEM	original equipment manufacturer
OGRC	Oil and Gas Research Council
rpm	revolutions per minute
TDC	top dead center
VAC	air filter vacuum
VIB	engine vibration
VOC	volatile organic compound

DEMONSTRATION OF GAS-POWERED DRILLING OPERATIONS FOR ECONOMICALLY CHALLENGED WELLHEAD GAS AND EVALUATION OF COMPLEMENTARY PLATFORMS

EXECUTIVE SUMMARY

The Energy & Environmental Research Center (EERC), in partnership with the North Dakota Industrial Commission (NDIC) Oil and Gas Research Council (OGRC); Continental Resources, Inc.; and the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) conducted a project evaluating the use of wellhead gas to fuel diesel engines powering a drilling rig in North Dakota.

Natural gas production in North Dakota has more than tripled since 2010, and nearly 30% of the gas produced is being flared. Currently, gas infrastructure projects valued at over $8 billion are at various stages of development. These projects include building processing plants, pipelines, and compression facilities to increase associated wellhead gas capture. In the meantime, a near-term opportunity is available to use associated gas, cofired with diesel, in diesel generators powering drilling rigs.

This project consisted of two phases. Preliminary testing was conducted at the EERC using a Caterpillar engine and a mixture of diesel and simulated wellhead gas. Results from these tests were reported previously and are included in Appendix A of this report. Phase II consisted of field-testing engines using a mixture of diesel and untreated wellhead gas, or bi-fuel, on a drilling rig during the drilling of two wells. A bi-fuel system operates by fumigating natural gas into the air intake of the diesel engine, reducing the amount of diesel fuel required to meet load. The bi-fuel system used for this project was provided by Altronic and is marketed as GTI Bi-Fuel®. Continental Resources, Inc., along with its drilling contractor Cyclone Drilling, provided access to a drilling rig for this demonstration project. Cyclone Rig No. 28 is powered by three 3512C Caterpillar diesel engines which were modified by ECO-Alternative Fuel Systems (ECO-AFS) with STEPCON® Bi-Fuel systems, manufactured by Altronic.

The results of the 47-day demonstration project illustrated that utilizing wellhead gas in bi-fuel applications to power a drilling rig can lead to an overall decrease in diesel fuel use, fuel cost, truck transport of liquid fuel, and emissions, without adversely impacting drilling operations. The specific results from this project included:

1) Reduced diesel fuel use by 16,000–18,500 gallons and associated fuel delivery truck traffic.

2) Fuel-related cost savings of nearly $60,000 because of the lower value of wellhead gas relative to diesel.

3) Beneficial use of wellhead gas at the point of production.

4) Reduction in overall air emissions compared to diesel-only engine operation plus flaring an equivalent amount of wellhead gas. However, operating engines in bi-fuel mode does result in increased carbon monoxide and nonmethane hydrocarbons when compared to diesel-only engine operation.

5) Seamless operation of the GTI Bi-Fuel system with no impact on drilling operations.

6) Additional fuel savings possible by minimizing diesel-only operation with optimized process control and/or operational oversight of the GTI Bi-Fuel system.

7) Bi-fuel systems operated efficiently with routine engine maintenance.

Although bi-fuel operation of drilling rigs is beginning to be recognized as a viable option for producers, the majority of drilling rigs in North Dakota are still fueled by diesel only. Logistical and contractual issues can complicate the availability of wellhead gas for drilling operation. However, the results from this study highlight the benefit to working through these issues and expanding implementation of bi-fuel systems. Based on the results from this project, the project team estimated the overall effect of utilizing otherwise flared wellhead gas to power drilling operations of nearly 200 drilling rigs in North Dakota. The result of such broad implementation would include:

1) 1,800,000 Mcf wellhead gas used to power drilling rigs in 1 year (2% of currently flared wellhead gas).

2) 18,000,000 gallons of diesel fuel saved in 1 year.

3) $72,000,000 diesel fuel costs saved in 1 year.

4) 3600 fuel delivery trucks (5,000 gallon tanker) avoided in 1 year.

5) 68% reduction in overall air emissions compared to diesel-only operation plus flaring an equivalent amount of gas.

6) Additional air emission reduction can be achieved using commercially available diesel engine exhaust gas treatment (catalytic conversion). These technologies are capable of reducing CO and nonmethane hydrocarbon emissions in bi-fuel-operated engines to levels similar to 100% diesel-only operation.

DEMONSTRATION OF GAS-POWERED DRILLING OPERATIONS FOR ECONOMICALLY CHALLENGED WELLHEAD GAS AND EVALUATION OF COMPLEMENTARY PLATFORMS

INTRODUCTION

Natural gas production in North Dakota has more than tripled since 2010, but the development of the Bakken oil play has progressed at a rate that has outpaced the development of gas-gathering infrastructure to handle all of the associated gas produced alongside oil. This has resulted in nearly 30% of the natural gas produced being flared. However, infrastructure is being developed to move the natural gas to market, and projects worth $8 billion are under various stages of development to add processing plants, pipelines, and compression facilities. In the meantime, there is a use for the flared natural gas. With nearly 200 diesel-powered drilling rigs in operation in the state at any given time, there is a high demand for diesel fuel to run them. A solution to reduce the amount of diesel use and the associated fuel costs is to convert the diesel engines used on the drilling rigs to burn natural gas or wellhead gas to replace some of the diesel fuel. The cofiring of natural gas in a diesel engine is not new technology. However, using wellhead gas which contains significant quantities of higher hydrocarbons compared to pipeline gas has not been fully explored. The potential problem with wellhead gas, especially in the Bakken shale, is the relatively high concentration of higher hydrocarbons. The presence of ethane, propane, butane, pentane, and heptane at concentrations of up to 50% (North Dakota Department of Mineral Resources, 2010) can lead to increased engine knock, which can severely damage the engines. The vast majority of bi-fuel systems operate using pipeline natural gas; consequently, more data and experience are available for fuels with greater methane purity.

The Energy & Environmental Research Center (EERC), in conjunction with the North Dakota Industrial Commission Oil and Gas Research Council; the U.S. Department of Energy National Energy Technology Lab (NETL); Continental Resources, Inc.; ECO-Alternative Fuel Systems (ECO-AFS); Altronic; and Butler Caterpillar, has completed the current project to demonstrate and evaluate utilization of wellhead gas for fueling diesel engines used to power drilling rigs in North Dakota. Phase I of the project was conducted at EERC pilot facilities and evaluated diesel engine performance while simultaneously firing diesel fuel and a simulated Bakken formation wellhead gas. The final report for Phase I testing is included in Appendix A. Phase II of the project was to demonstrate and evaluate the performance of the diesel engines, outfitted with bi-fuel systems, used to power a drilling rig while firing a blend of diesel fuel and untreated rich wellhead gas under actual drilling operation.

BACKGROUND

Modification of diesel engines to operate on a mixture of diesel and natural gas is known as dual-fuel or bi-fuel technology. The terminology is used interchangeably and is intended to refer to the firing of diesel fuel and natural gas simultaneously in a diesel engine. The International Association for Natural Gas Vehicles defines the terms differently from the U.S. Environmental Protection Agency (EPA) and the California Air Resources Board (CARB). In the United States, dual fuel (simultaneous firing) is marketed as a "bi-fuel" system because of the EPA and CARB definitions, which define a dual-fuel vehicle as having the option to fire only one fuel at a time.

A bi-fuel system operates by fumigating natural gas into the air intake of the diesel engine. Combustion of the natural gas is initiated from the pilot ignition of diesel fuel injected in the combustion cylinder. A bi-fuel system has the ability to switch fuel modes without interruption in engine power output and can be automatically switched to 100% diesel mode during operations above the programmed power limit, thus avoiding the necessity to derate the engine. The various components of a bi-fuel system are installed external to the engine, and no engine disassembly or modification is required. All original equipment manufacturer (OEM) engine specifications for injection timing, valve timing, and compression ratio remain unchanged after installation. Typical bi-fuel control systems monitor natural gas pressure, manifold pressure, temperatures, and engine vibration to control fumigated gas injection.

Diesel engine systems are designed based on internal combustion properties of the fuel. Although cetane is the fuel property of interest in diesel engines, the octane number is important when gaseous fuels are combusted in combustion ignition engines. Gaseous fuels with lower octane numbers like hexane can contribute to engine knock. Table 1 provides the composition of a pipeline-quality natural gas and a typical wellhead gas found in the Bakken Formation (Caterpiller, 1997; Energy Conversions Inc., 2011; Ferguson, 1986). The combustion characteristics for the individual gases are also presented. Notice that the natural gas liquids (NGLs) of higher carbon numbers have a lower octane rating, which means they have less knock resistance and, therefore, a lower critical compression ratio relative to autoignition. Mixing NGLs with methane lowers the fuel's resistance to knock and, therefore, requires greater understanding to better tune an engine for Bakken Formation gas applications in bi-fuel systems.

Table 1. Composition and Combustion Characteristics of Pipeline and Bakken Formation Gases

	Dry Pipeline Gas	Sample Bakken Gas	Octane Number (motor)	Critical Compression Ratio	Autoignition Temperature, °F
Methane, CH_4	92.2%	55%	120	12.6	1076–1200
Ethane, C_2H_6	5.5%	22%	99	12.4	959
Propane, C_3H_8	0.3%	13%	97	12.2	896
Butane, C_4H_{10}		5%	90	5.5	788–932
Pentane, C_5H_{12}		1%	63	4.0	500–788
Hexane, C_6H_{14}		0.25%	26	3.3	437–451
Heptane, C_7H_{16}		0.1%	0		
Nitrogen, N_2	1.6%	3%			
Carbon Dioxide, CO_2	0.4%	0.5%			
Diesel Fuel	NA	NA	NA	NA	410–750
HHV,[1] Btu/scf	1041	1495			

[1] Higher heating value.

Normal diesel fuel combustion produces a pressure rise inside the engine cylinder at a predictable rate and peak. The combustion in a diesel engine is controlled by the injection rate of diesel fuel into the cylinder. Critical to diesel engine design is the compression ratio and the appropriate ignition delay period for the fuel. Ignition delay is the period between the start of injection and autoignition of the fuel. A designer strives for the appropriate ignition delay, for once the mixture of fuel and air autoignites, all of the fuel already injected burns very quickly. Too much fuel charge or too high of a compression ratio can result in intolerable knocking in a diesel engine. Engine knock is the noise generated from autoignition of the fuel in the engine cylinder, where the fuel burns quickly and will rattle the engine parts. This form of combustion within the cylinder is referred to as detonation and involves a supersonic flame front that propagates through the fuel gas mixture. During audible knock, the pressure produced inside the cylinder is erratic and creates forces that lead to catastrophic engine damage such as piston pitting and physical cylinder head failure. In a bi-fuel engine, autoignition of the fumigated gas is unlikely to result from piston compression. Natural gas ignites at a much higher temperature (1076°–1200°F) compared to diesel fuel (410°–750°F) (Generac Power Systems, 2003); however, a significantly larger amount of fuel is precharged in the cylinder prior to injection of diesel. The injection of diesel is the source for ignition of the gaseous fuel; therefore, careful consideration is required to ensure the fuel charge does not burn uncontrollably upon ignition.

Fuels have been commonly characterized relative to their performance in piston engines. Spark-ignited engines are normally used to fire gaseous fuels and gasoline-based vapors. The ignition timing and compression ratio of spark-ignited engines are critical variables relative to proper fuel combustion. Octane rating or octane number is a standard measure of the performance of spark-ignition fuels. The octane rating of gasoline is measured in a test engine and is defined by comparison with the mixture of 2,2,4-trimethylpentane (isooctane) and heptane that would have the same antiknocking capacity as the fuel under test: the percentage, by volume, of 2,2,4-trimethylpentane in that mixture is the octane number of the fuel. A fuel with a rating of 90 octane means that the fuel has the same detonation resistance as 90% isooctane with 10% heptane. Octane ratings of over 100 are possible because some fuels are more knock-resistant than isooctane; methane is a good example, with an octane rating of 120.

Cetane number or (CN) is a measurement of the combustion quality of diesel fuel during compression ignition. It is a significant expression of the quality of a diesel fuel. CN is a measure of a fuel's ignition delay, which is the time period between the start of injection and the first identifiable pressure increase during combustion of the fuel. CN is measured by burning the fuel in a Cooperative Fuel Research (CFR™) engine, under standard test conditions. The compression ratio of the CFR engine is increased until the time between fuel injection and ignition is 2.407ms. The resulting CN is then calculated by determining which mixture of cetane (hexadecane) and isocetane (2,2,4,4,6,8,8-heptamethylnonane) will result in the same ignition delay. In a particular diesel engine, higher cetane fuels will have shorter ignition delay periods than lower cetane fuels. CNs are only used for diesel fuels and do not apply to gaseous fuels. In short, the higher the CN, the more easily the fuels will combust in a compression setting such as a diesel engine.

In a spark-ignition engine, the higher the octane number, the more compression the fuel can withstand before detonating. Fuels with a higher octane rating are used in high-compression engines that generally have higher performance. In contrast, fuels with low octane numbers (but high CNs) are ideal for diesel engines. However, fuels rated for high knock resistance in spark-ignition engines should not be confused with the performance of compression ignition fuels that are used in diesel engines which have significantly higher compression ratios than spark-ignited engines.

It is important to understand the fuel characteristics relative to both knock and compression ignition characteristics for bi-fuel operations. A diesel engine fitted with a bi-fuel system relies on compression to ignite diesel fuel, which, in turn, provides the spark to ignite the gaseous fuel. It is in this sense that both octane (knock) and cetane (ignition delay) performance are relevant characteristics of the subject fuels. Previous work relative to fuel performance in bi-fuel engines has provided considerable insight to the current study.

Performance of gaseous fuels fired in diesel engines is primarily measured by recording the pressure rise in the cylinder versus the crank angle. Such data can indicate extreme pressure rise due to detonation of the fuel and provide the characteristics of ignition delay. Generally, long ignition delay results in unburned hydrocarbons and lower efficiency. Ignition that is too advanced can result in knock.

Papagiannakis and others (2008) measured the performance of a single-cylinder Lister LV1 direct injection diesel engine fitted with a natural gas supply to the engine air intake. The compression ratio of the engine was 17.6:1, and injection timing was set to 26 degrees before top dead center (BTDC). The power output of the engine was 6.7 kW at 3000 revolutions per minute (rpm). Figure 1 demonstrates the decrease in cylinder pressure and ignition lag as greater amounts of diesel fuel were displaced with natural gas at constant load, engine speed, and brake mean effective pressure. The peak pressure difference between diesel fuel operation and 86% replacement of diesel fuel with natural gas is about 3–4 degrees of crank angle. It can generally be concluded that adding methane only to a diesel engine presents a low risk for engine knock.

Propane or liquefied petroleum gas (LPG), normally a mix of propane and butane, has also been studied in dual-fuel diesel engines. Bakken gas propane composition can be greater than 13%. Propane can have a higher likelihood for knock because of the higher energy density (2.5×) and lower octane rating (97 vs. 120) relative to methane. At 40% diesel replacement and full load, the optimum blend of propane and butane for firing in a diesel engine was found to be 70% propane and 30% butane (Le and Nguyen, 2011). AVL research engines are commonly used to study piston engine combustion phenomenon. An AVL 5402 research engine was converted by Le and Nguyen (Saleh, 2008) to operate as a dual-fuel diesel with LPG supplied to the engine air intake. The compression ratio for this engine was 17.3:1 and rated for 9 kW at 3200 rpm. Pressure versus crank angle data was collected for various amounts of LPG used to replace diesel fuel, Figure 2. As LPG was added to the engine, the peak pressure increased, the ignition lag decreased, and the knocking tendency increased. During combustion, propane or LPG has the exact opposite effect of methane. Le and Nguyen (2011) also experimented with advancing the injection timing in the range of 14–24 degrees BTDC, Figure 3. Advancing the timing produced higher cylinder pressure rise at 20% replacement and full load operation at 2000 rpm. Experiments with changing the amount of diesel pilot produced little effect on the pressure rise or ignition lag.

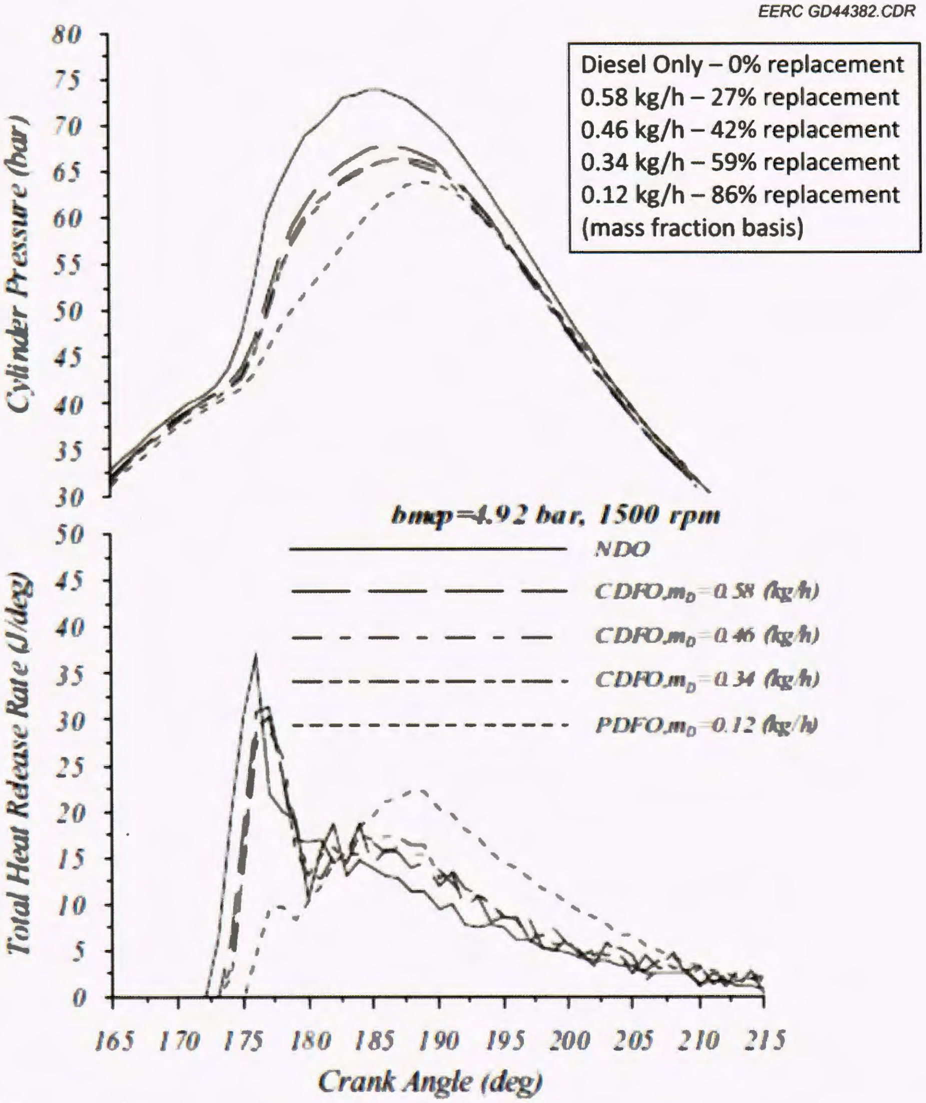

Figure 1. Effect of increased natural gas (diesel replacement) on cylinder pressure versus crank angle (modified from Papagiannakis and others [2008]) at 80% full-load operation.

An investigation of ignition delay was performed by Karim and Burn (1980) for gaseous fuels at varied inlet air temperatures. The ignition of fuel is delayed as temperature decreases. Figure 4 indicates about a 6 degree lag from 20° to –10°C. Ignition delay for the various fuels is more noticeable at colder temperatures. Gaseous fuels such as methane, propane, and hydrogen initially create a delayed ignition. This delay reaches a maximum, and as more diesel fuel is replaced, the delay time is shortened. Propane appears to have a limited acceptable mole % of the intake mixture relative to other gases as ignition delay is decreased, likely leading toward knock.

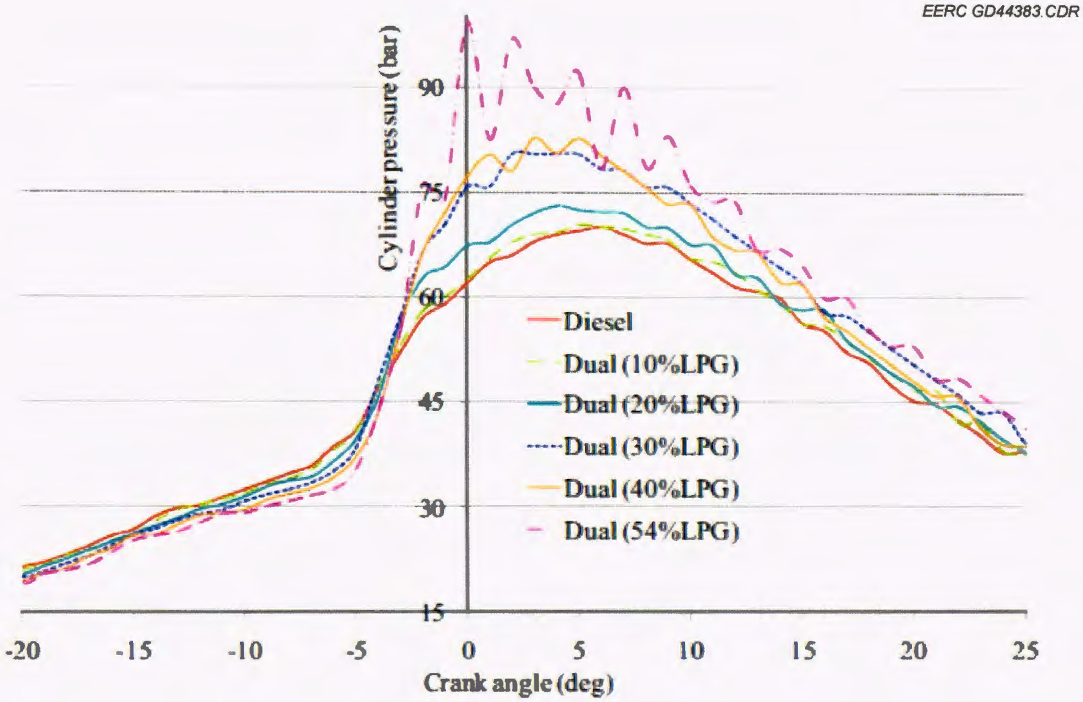

Figure 2. Pressure versus crank angle data for LPG fired with diesel fuel mass fraction basis (Le and Nguyen [2011]).

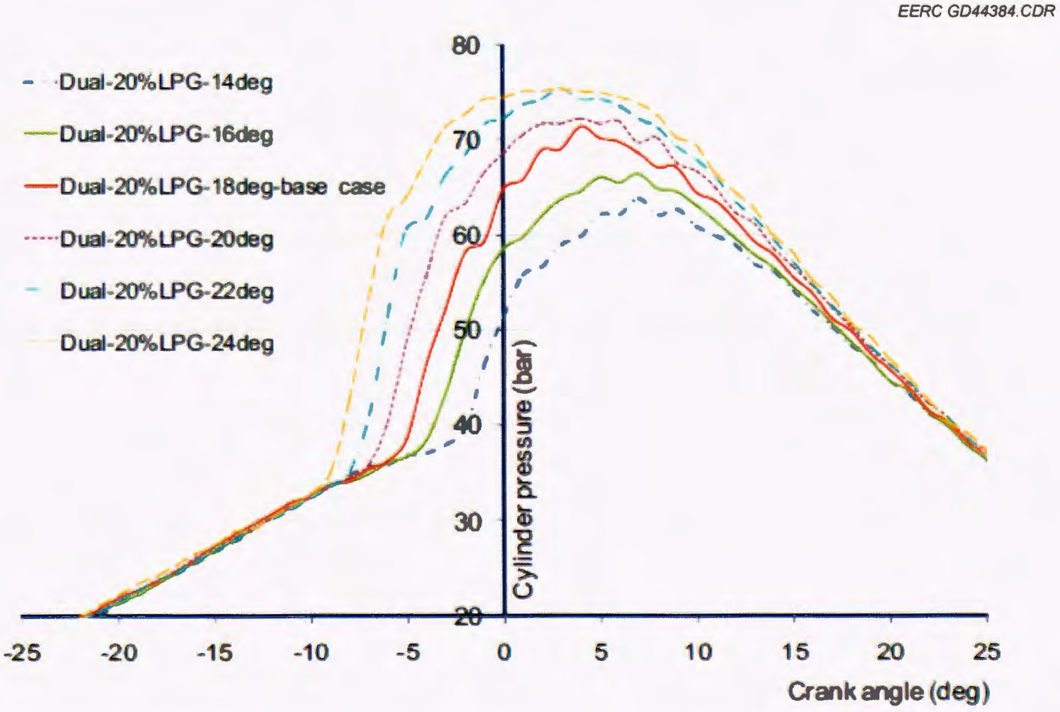

Figure 3. Effect of advancing diesel injection timing (Le and Nguyen [2011]).

The heaviest hydrocarbons in Bakken gas include hexane and heptane. These gases are normally less than 1% of the total gas composition. However, the heavier gases have less knock resistance. The performance of these gases was considered by Alperstein and others (1957) using a 17:1 single cylinder diesel engine with ignition timing at 20 degrees BTDC. Figure 5 shows that additions of these heavier hydrocarbons in quantities of near 20% produce a substantial pressure rise as compared to the baseline pressure profile for firing of diesel fuel. Small quantities (<5%) should produce minimal appreciable cylinder pressure increase. Ignition delay appeared to be minimal.

A simplified heat release model was used by Patro (1994) to evaluate the effects of hydrogen on combustion in a diesel-fueled engine. Patro showed that the first and second derivatives of the pressure versus crank angle curve (P/θ) could be used to determine the start of injection, the start of ignition, and the maximum rate of pressure rise. These values could be used to determine the effect of fuel composition on ignition delay.

In summary, literature review indicates that Bakken gas is likely to have a higher propensity for knock than pipeline natural gas. Methane, which comprises the majority of Bakken gas, when fired alone with diesel fuel produces an ignition delay and lower cylinder pressures. This performance is likely offset to a degree by the composition of propane and heavier hydrocarbons in Bakken gas. Performance for ethane fired in a diesel engine did not seem to be available in the literature. Ethane is greater than 20% composition in Bakken gas, and its performance, although unknown, could have some influence on combustion properties.

OBJECTIVES

This project was designed to evaluate the performance of diesel engines used to power drilling operations using Bakken Formation gas in bi-fuel applications. The project consisted of three major activities. The first activity consisted of testing the operational limits of a diesel engine using rich gas in a bi-fuel application. These tests were completed at the EERC using a simulated Bakken gas. Results from those tests were previously reported and are included as Appendix A.

Following completion of testing at the EERC, a field demonstration was completed to evaluate diesel engine performance using wellhead gas during actual drilling operations. Data collected from this field activity included engine performance data, fuel savings, and emission measurements. The results from this demonstration activity form the basis of this report.

In addition to the activities focused on bi-fuel operation, a study was conducted to look at alternative gas use opportunities in the Williston Basin. This report entitled "End-Use Technology Study – An Assessment of Alternative Uses for Associated Gas" was submitted to NDIC in September 2012.

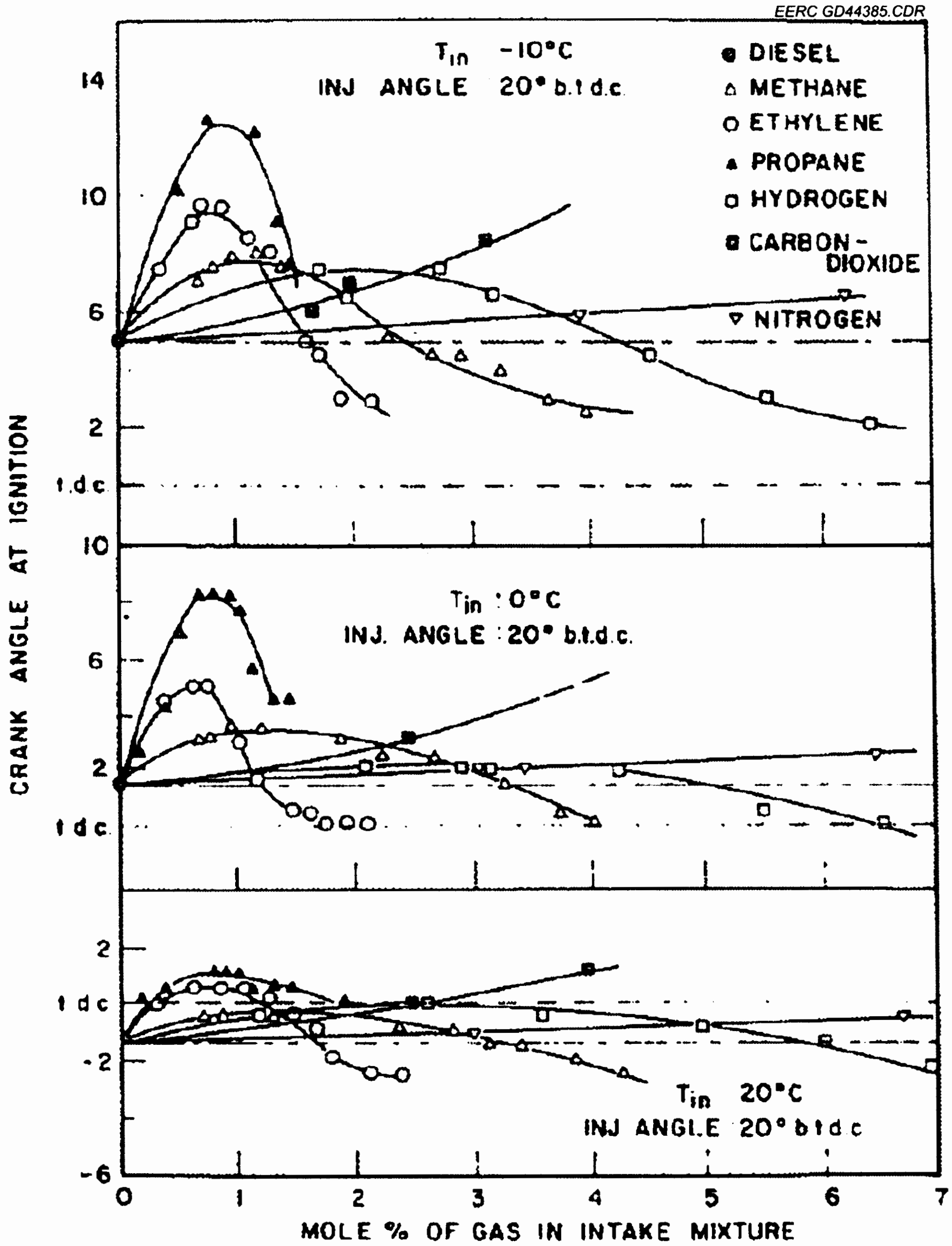

Figure 4. Performance of various fuels given increasing diesel fuel replacement (modified from Karim and Burn [1980]).

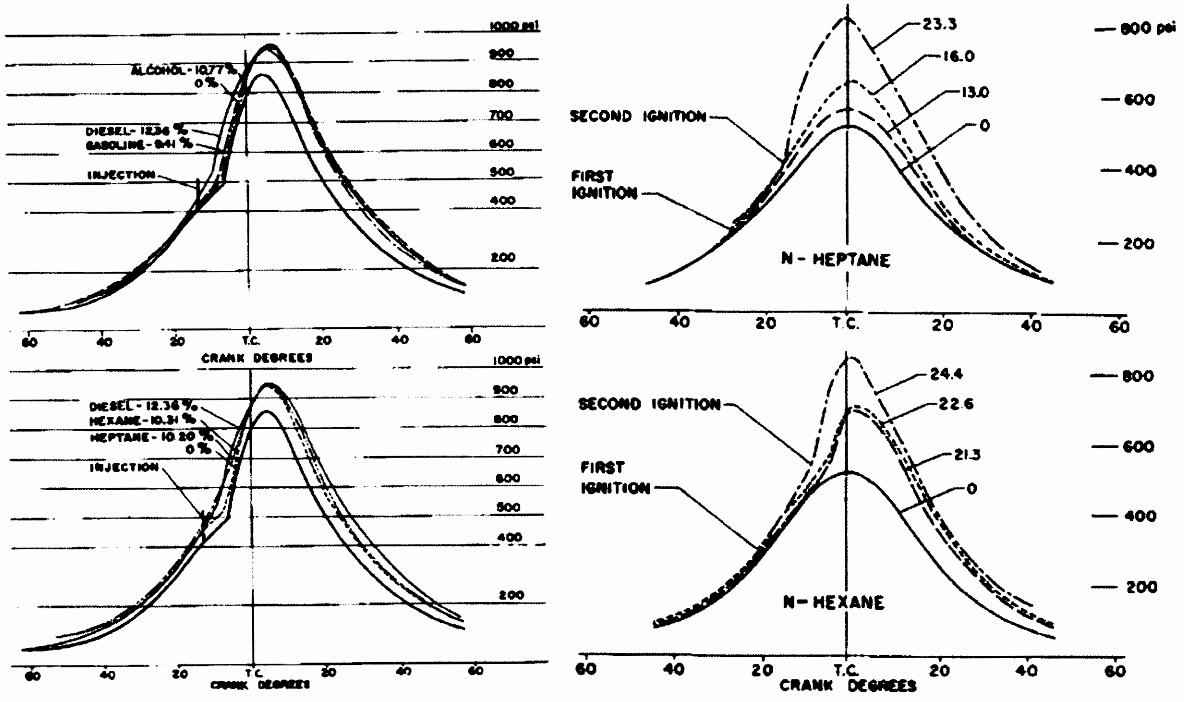

Figure 5. Effect of heptane and hexane fired in a dual-fuel diesel (modified from Alperstein and others [1957]).

EXPERIMENTAL SETUP

Continental Resources, Inc., along with its drilling contractor, Cyclone Drilling, provided access to a drill rig for this demonstration project. Cyclone Drilling Rig No. 28 was moved to a location roughly three miles north of Killdeer, North Dakota, in August of 2012. The site was a two-well pad designated Test Well 1 and Test Well 2. One well was drilled into the Bakken Formation, and the other was drilled into the Three Forks Formation. Cyclone Rig No. 28 is powered by three 3512C Caterpillar diesel engines. The specifications for the diesel engines are presented in Table 2. Drilling of two wells on a single pad occurred over 47 days from August 17 to October 2, 2012.

GTI Bi-Fuel systems manufactured by Altronic are currently being used in the oil and gas industry in drilling operations, and Caterpillar engines are common prime movers for drilling rigs. Therefore, this project utilized equipment from these manufacturers to demonstrate the viability of using wellhead gas to power a drilling rig.

During the rig move, ECO-AFS installed STEPCON® Bi-Fuel systems, manufactured by Altronic for GTI, on the three Caterpillar diesel engines used to power the rig. The GTI systems utilize a fumigation gas delivery method whereby natural gas is delivered to the cylinders via the standard engine air-intake system. Gaseous fuel is ignited by a diesel "pilot" which acts as an ignition source for the air–gas mixture. The STEPCON systems are an enhancement

Table 1. Diesel Engine Specifications

Engine	Caterpillar 3512C (four-stroke cycle)
Cylinders	12
Aspiration	Turbo-charged, after-cooled
Compression Ratio	14.7:1
Speed, rpm	1200
Engine Power, BHP	1476
Engine Certification	EPA TIER-2 2006

to the basic GTI Bi-Fuel system and a schematic of the system is shown in Figure 6. The system uses individual solenoid valves to control the natural gas flow to the engines and allow for the greatest substitution rates over a wider load range. The GTI controller monitors the following bi-fuel system and engine parameters:

- Natural gas supply pressure (GSP)
- Manifold air pressure (MAP)
- Manifold air temperature (MAT)
- Air filter vacuum (VAC)
- Engine exhaust gas temperature (EGT)
- Engine vibration (VIB)
- Engine load

The GTI controller uses preset safety and control levels for each system parameter to activate or deactivate the Bi-Fuel system. If a parameter exceeds the control level, the Bi-Fuel system will stop natural gas flow for a period of time (5 seconds for this application), the controller will then check all of the parameters, and if all are below the control limit, the natural gas supply will be turned on again. During operation, if any of the parameters exceed the safety level, the GTI system will turn off the natural gas and require a manual reset to initiate restart of natural gas flow. The vibration parameter has the added feature that the vibration signal must exceed the control or safety threshold for a specified period of time before the control is activated. For this set up, the “vibration time” was set to 3 seconds. The STEPCON system is very flexible, allowing different amounts of natural gas to be supplied to the engine under different load conditions. This feature allows the engine to operate with the greatest amount of natural gas possible at different load, resulting in more efficient operation and the greatest substitution of diesel. At low load (0% to 12%), natural gas flow is stopped because it becomes difficult for the engine governor to maintain a constant engine speed if bi-fuel is being used. The STEPCON systems used on this drilling rig were set up with the following valve arrangement:

- 0%–12% engine load – natural gas supply valves closed, no diesel substitution.

- 12%–20% load – primary power valve open (roughly 20% diesel substitution at 13% load).

- 20%–30% load – primary power valve and first solenoid valve open (roughly 30% diesel substitution at 20% load).

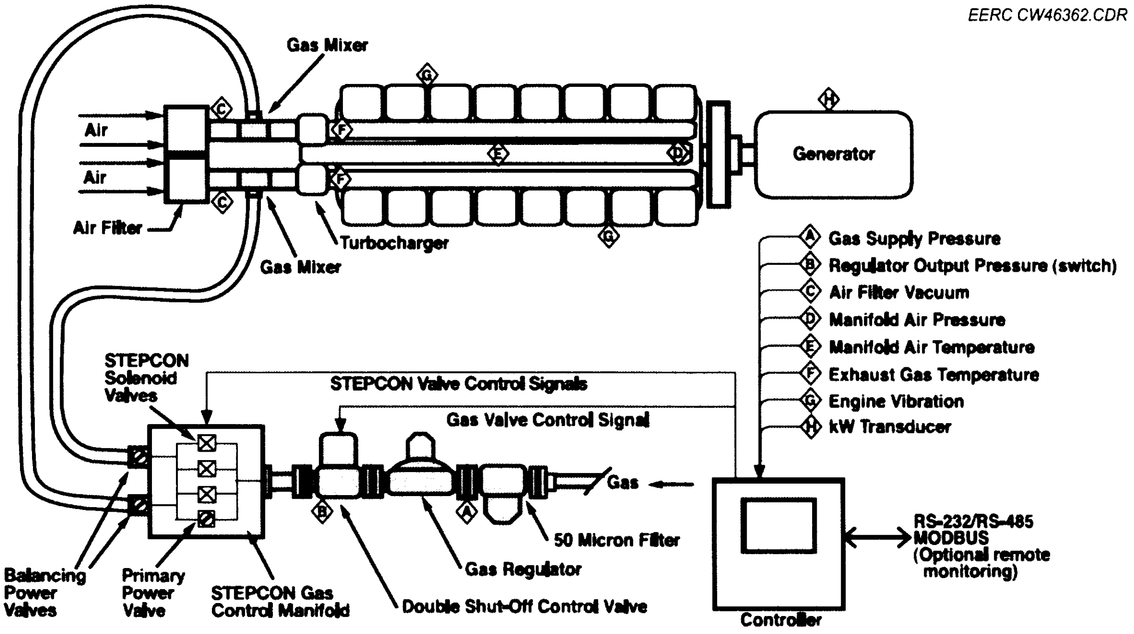

Figure 6. Schematic of GTI Altronic's STEPCON Bi-Fuel system (from Altronic).

- 30%–40% load – primary power valve and first two solenoid valves open (roughly 43% diesel substitution at 32% load).
- 40%–60% load – primary power valve and all three solenoid valves open (roughly 54% diesel substitution at 41% load).
- 60%–70% load – primary power valve and first two solenoid valves open (roughly 50% diesel substitution at 60% load).
- 70%–100% load – natural gas supply valves closed, no diesel substitution.

A system to remove liquids from the wellhead gas was also supplied by ECO-AFS. The system was equipped with an ABB gas meter to measure the total wellhead gas flow to the three engines. A 400-gallon VanGas vessel with gas-dry desiccant beads was used to remove moisture from the incoming wellhead gas. A collection tank was used to remove any NGLs that may have gotten through the desiccant. Murphy safety shutdown valves were installed to prevent wellhead gas from reaching the engines in the event of high liquids in the collection tank. The entire unit is self-contained inside an 8′×10′ steel shipping container that is heated and weatherproof and can be transported during rig move.

In addition to the Bi-Fuel system, the EERC had high-speed pressure transducers manufactured by Optrand, Inc., installed in the heads of two cylinders on Engine No. 1. The transducers are capable of measuring pressures up to 3000 psig at frequencies of 20 kHz. Optrand sensors are not based on piezoelectric sensors, but optically measure the deflection of a diaphragm. This technique minimizes the effects of thermal shock and temperature-induced drift.

To measure crank angle and rpm, a BEI Sensors H25 incremental optical encoder with a 1/4° resolution was attached to the end of the generator shaft which is directly coupled to the engine crank shaft. The encoder was indexed to top dead center (TDC) of the No. 1 cylinder. Diesel fuel flow was measured with FloScan diesel flowmeters that were installed on each engine.

LabView was used along with National Instruments CompactRIO components, to create a data acquisition system. The system was set up to log data collected by the GTI system, high-speed pressure data, rpm, and fuel consumption data. Each of the GTI systems was hard-wired to the logging computer, but the high-speed pressure data and fuel flow rate data were transmitted over a wireless router. Initial communication issues prevented access to all of the GTI data. Data were collected at 15-second intervals for each engine. The cylinder pressure and rpm data acquisition system were programmed to capture pressure data for four complete revolutions of the engine and log it to a file only when selected. This kept the data logged for each test condition to a manageable size. A Testo 350 M/XL portable flue gas analyzer were used to measure the stack temperature and concentrations of NO_x, SO_2, O_2, CO, and C_xH_y. The data from the analyzer were logged manually. Hourly wellhead gas flow data were downloaded daily from the ABB flowmeter in the gas-conditioning skid.

Analysis of the wellhead gas collected at the inlet and outlet of the conditioning skid are presented in Table 3. Results show the composition is consistent over time and very little change in gas composition across the conditioning skid. The hydrocarbon composition of the wellhead gas was very similar to that used for the parametric study performed at the EERC (see Appendix A). The HHV of the wellhead gas was approximately 1450 Btu/ft^3 compared to methane at 1008 Btu/ft^3.

PROCEDURE

Data were downloaded daily and compiled into a report provided to Continental Resources, Inc., and Cyclone Drilling. The reports included diesel and wellhead gas consumption for the previous day along with estimated diesel savings. Data available from the GTI systems included the following:

- % engine load for each engine
- Exhaust gas temperature
- Turbocharger inlet pressure
- Vibration from two sensors
- Bi-Fuel on/off signal
- Manifold air pressure

These data, along with the fuel consumption data, were enough to calculate fuel savings for each engine. The percent load, diesel rate, exhaust gas temperature, and vibration data were plotted each day as a function of time.

Table 2. Analysis of Unconditioned and Conditioned Gas

Date	8/17/2012	8/17/2012	9/6/2012	9/6/2012	9/12/2012
Location	Inlet	Outlet	Inlet	Outlet	Outlet
Component	mol%	mol%	mol%	mol%	mol%
Carbon Dioxide	0.75	0.75	0.71	0.71	0.73
Propane	12.23	12.27	11.76	11.90	11.97
iso-Butane	1.23	1.23	1.15	1.17	1.17
n-Butane	3.63	3.64	3.36	3.41	3.43
Hydrogen Sulfide	0.00	0.00	0.00	0.00	0.00
iso-Pentane	0.57	0.57	0.50	0.52	0.51
c-2-Butene	0.01	0.01	0.00	0.00	0.01
n-Pentane	0.73	0.74	0.60	0.62	0.64
1,3-Butadiene	0.00	0.01	0.00	0.00	0.00
Ethane	22.36	22.44	21.75	21.95	22.32
Oxygen/Argon	0.10	0.07	0.71	0.51	0.25
Nitrogen	3.31	3.24	5.25	4.60	3.75
Methane	55.07	55.02	54.20	54.61	55.23
Carbon Monoxide	0.01	0.01	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00	100.00

Stack emissions were periodically measured for each engine. In addition to the data from the Testo gas meter, gas bag samples were collected from each stack and at the inlet and outlet of the gas conditioning skid. The Testo data were converted to a g/BHP*hr (gram/brake horsepower hour) for comparison on a common basis. The gas bag samples were analyzed using a gas chromatograph–mass spectrometer at the EERC. Hydrocarbons species through pentane (C5) were identified. These data were used to determine the NMHC present in the stack exhaust.

RESULTS

During the 47-day demonstration, engine performance was observed by EERC researchers and Cyclone Drilling operators. Drilling operations and engine use were not altered to accommodate the use of the GTI Bi-Fuel system. In general, all three engines alternated from bi-fuel operation to diesel only and back to bi-fuel mode according to normal operational protocol without any perceivable effect.

To evaluate the true effect of bi-fuel operation on drilling rig operations and engine performance and issues of interest to stokeholders, EERC personnel collected a variety of data. Results are organized into the following categories:

1) Engine Performance Summary
2) Fuel Savings Estimates
3) Opportunities for System Optimization
4) Engine Exhaust Emission Measurement
5) Ignition Delay and Engine Knock

Engine Performance Summary

Engine performance data were obtained from two sources; operational data were collected from the GTI control system on each engine, and diesel fuel flow data were obtained from meters installed on each of the three engines. Operational data collected from the GTI control system which provided the most relevant information about engine performance included engine vibration, engine load measured as percentage of full scale (% load), and exhaust gas temperature. Overall, engine performance appeared to be unaffected by the addition of gaseous fuel, and representative data have been provided in this report to illustrate what was observed over the course of the two-well demonstration.

During normal drilling operations, engine loads tend to remain high, in the range of 30%–60% load. At these load conditions, the engines can operate with the highest rate of natural gas addition and greatest diesel fuel savings. Under low load and idle conditions, natural gas supply is stopped and the engines operate exclusively on diesel fuel. An illustration of engine load during steady-state drilling operation is provided in Figure 7. Typically, two of the three engines are operated and synchronized to provide power to the drill rig. The third engine is typically turned off since sufficient power is achievable from operating two engines. Operation of the three engines is sequenced to ensure that the hours of operation are the same for each engine. In Figure 7, Engine No. 1 and Engine No. 2 operated for the majority of the 24-hour period, with the majority of the time spent between 30% and 50% load. The intermittent spike and drop in load from 10% load to nearly 80% load correspond with drilling operations and the addition of a new piece of drill pipe.

Diesel flow to each engine was measured continuously and provided an indication of when gaseous fuel was supplied to the engines. An illustration of the diesel flowmeter data for the same time period of steady-state drilling operation is provided in Figure 8. Over the 24-hr period, Engine No. 1 operated with a diesel consumption rate of about 18 gph, with additional fuel being supplied by wellhead gas through the GTI system. The plot for Engine No. 2 illustrates the change in diesel fuel consumption when operating in bi-fuel mode. Diesel fuel consumption was approximately 22 gph while operating with wellhead gas supply through the GTI system. At around 5 p.m., the wellhead gas supply was stopped, and the diesel fuel rate immediately increased to 40 gph to provide the necessary fuel to meet the steady load demand. During this period, diesel flowmeter data indicate that approximately 45% of the diesel fuel demand was provided by wellhead gas.

Engine exhaust gas temperature is one of several parameters the GTI system monitors to ensure proper engine performance when supplying gaseous fuel to the engine. Figure 9 plots the EGT for all three engines during the same 24-hr period presented in Figures 7 and 8. These data were collected early in the drilling cycle when the daytime ambient temperature exceeded 90°F (see Appendix B). The high ambient temperatures resulted in elevated operating temperature and EGT in the engines. When the EGT increased to 1200°F, the GTI system turned off gas flow as illustrated previously in Figure 8 by the increase in Engine No. 2 diesel fuel use between 17:00 and 24:00. Stopping gaseous fuel supply to Engine No. 2 did not result in a decrease in the EGT, and it is believed that the high ambient temperature was the cause of the elevated EGT.

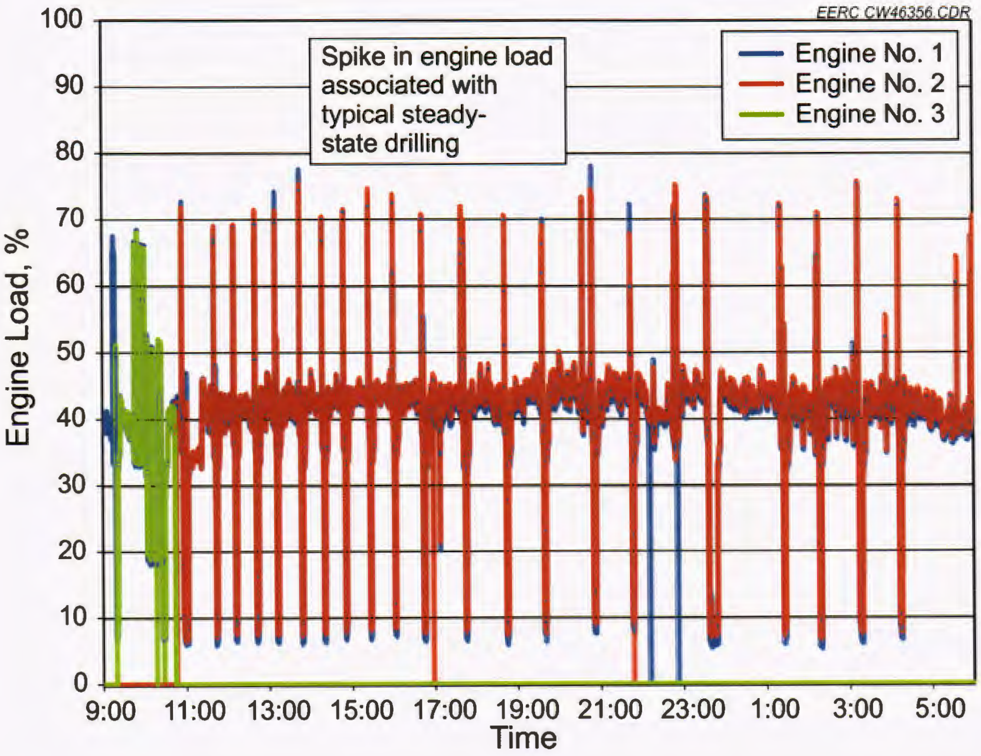

Figure 7. Engine load as a function of time during steady-state drilling operation.

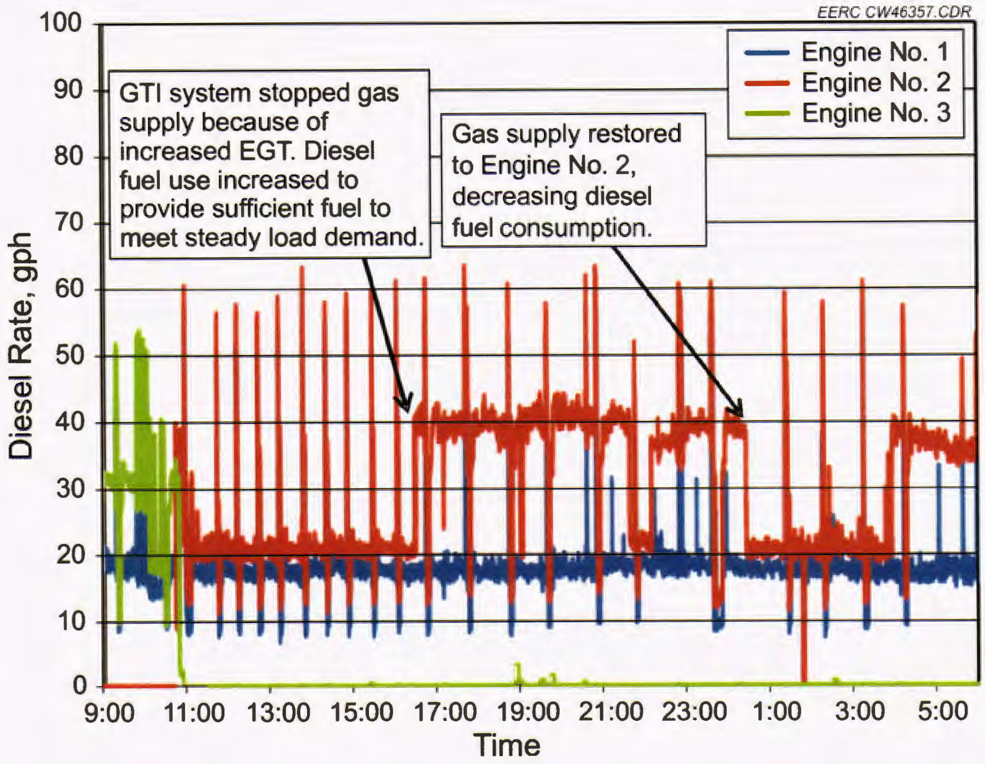

Figure 8. Diesel consumption rate as a function of time during steady-state drilling operation.

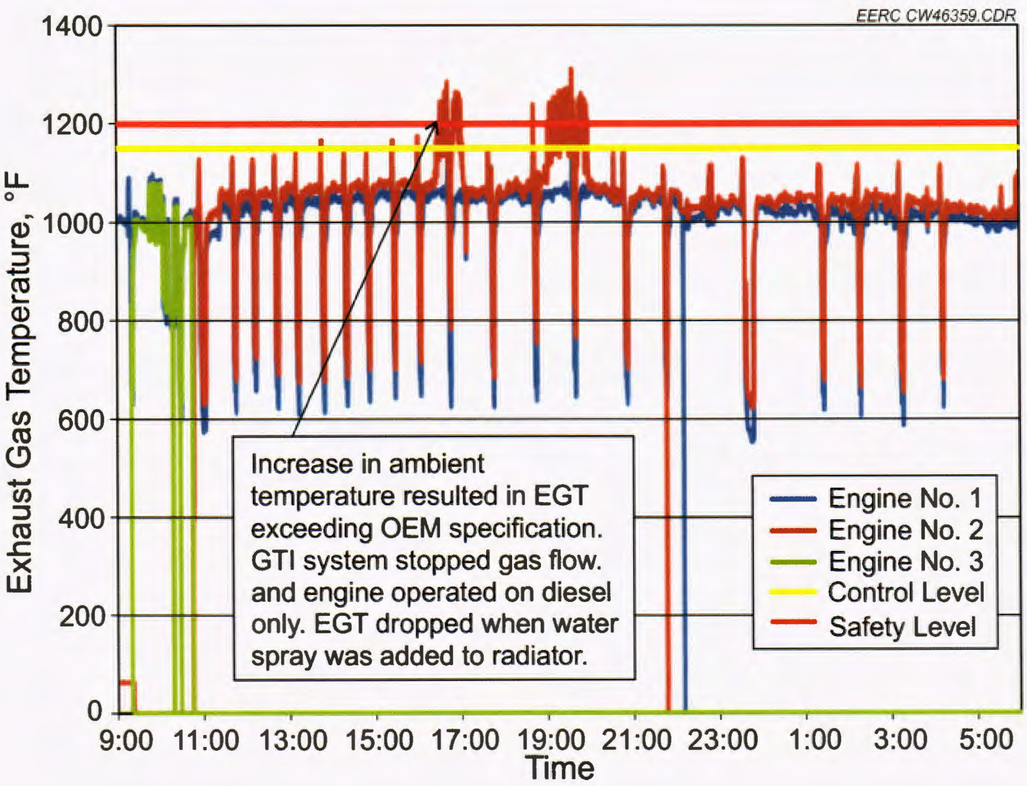

Figure 9. Engine exhaust gas temperature as a function of time.

However, these data do illustrate the effective control mechanism of the GTI system which prevents bi-fuel operation when operational parameters are outside the recommended OEM specifications. The EGT for Engine No. 2 did not decrease when bi-fuel was turned off. However, EGT did drop to below the 1200°F limit after Cyclone Drilling operators applied water spray to the engine radiator to improve cooling capacity.

Engine vibration was monitored on each engine to ensure bi-fuel operation did not adversely impact engine performance. The supply of methane and other gaseous hydrocarbon fuels can alter combustion properties and lead to uncontrolled fuel detonation, engine knock, and excessive vibration. The GTI system is designed to ensure that this does not occur by monitoring engine vibration and stopping gas flow if vibration is detected. A plot of vibration data from each of the three engines is provided in Figure 10. Evident are fairly regular spikes in vibration, consistent with rapid changes in load. Over the course of the steady-state drilling period plotted, vibration never approached the control level of 1 ips. Further, looking at the vibration data for Engine No. 2, there is no evidence that switching from bi-fuel mode to diesel only at 1700 hr resulted in a change in engine vibration. These data are consistent with that collected throughout the demonstration period, suggesting that the diesel replacement rates established during commissioning were sufficient to provide significant diesel fuel savings while also ensuring proper engine operation.

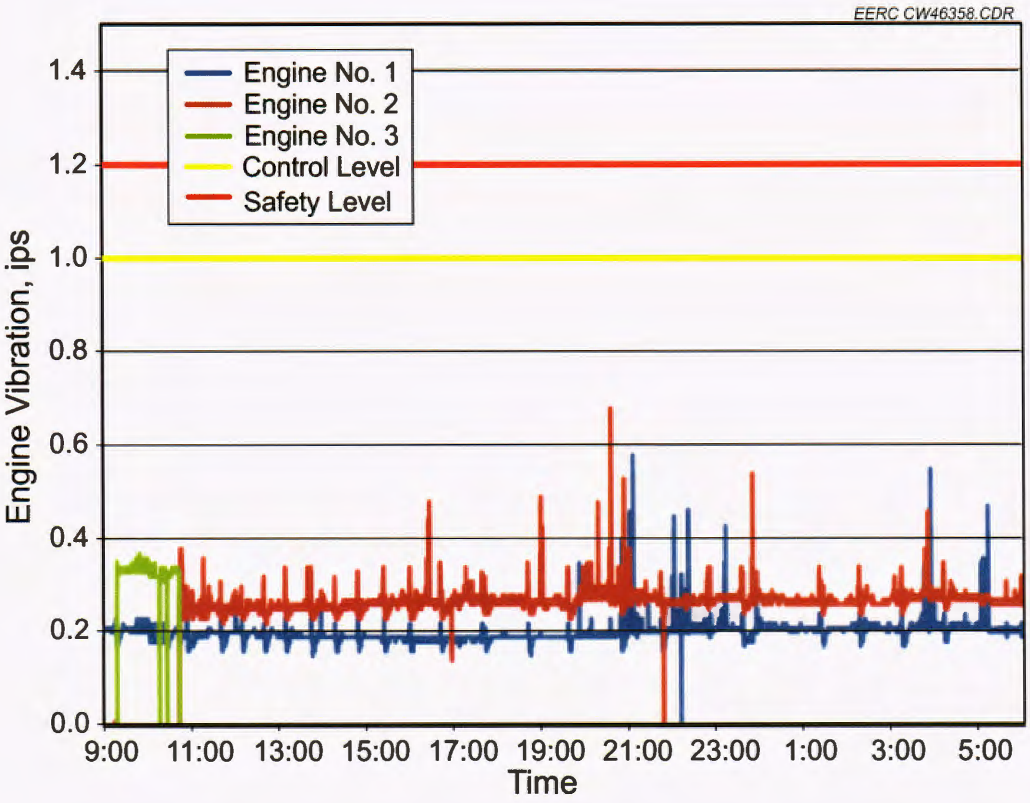

Figure 10. Engine vibration as a function of time during steady-state drilling operation.

Although steady-state drilling operation results in the highest engine load and provides opportunity for the greatest diesel fuel replacement with wellhead gas, a significant amount of time during well drilling is dedicated to tripping: the process of returning the drill pipe to or removing the drill pipe from the wellbore. Engine operation during tripping is significantly different from drilling operations and consists of large amounts of time when the engines are idling along with frequent spikes in load associated with raising or lowering the drill pipe. The engine load profile during a representative period of time during dripping is plotted in Figure 11. Engines Nos. 1 and 3 were operating throughout the 24-hr period. During the first part of the day (6:00–14:00), the rig was drilling, and the load profile matches that presented earlier in Figure 7. For the remainder of the day, the rig was tripping. During drilling, the engine loads were fairly stable, and the only time excessive engine vibration was recorded was when another joint (section of drill pipe) was added. A plot showing engine vibration data for the same period of time is provided in Figure 12. During tripping, the engine loads fluctuate from low to high as the drill string is raised or lowered and additional joints are added or removed. This caused significant vibration in all three engines. These load and vibration profiles are typical of those for the entire drilling cycle and were not affected by wellhead gas flow being on or off.

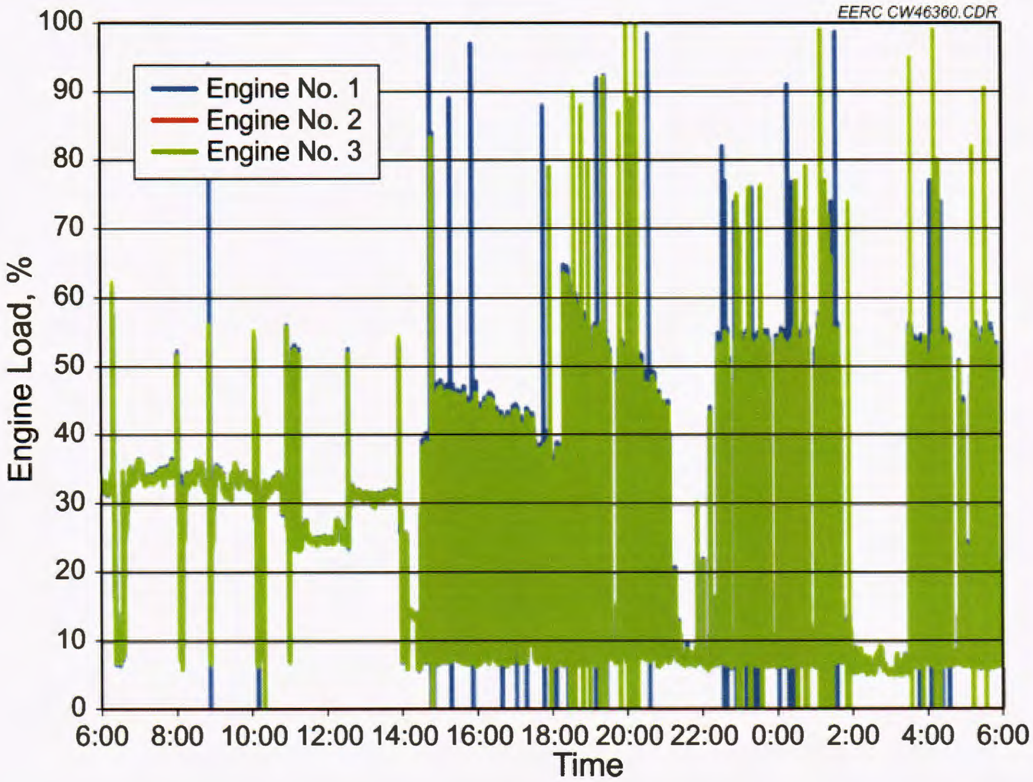

Figure 11. Engine load as a function of time during drilling and tripping activity.

Over the course of the demonstration, there was one period of time when vibration exceeded the control or safety limits for more than 3 seconds resulting in the GTI system stopping wellhead gas flow. On August 18, 2012, excessive vibration was measured, and wellhead gas supply was stopped. After several attempts to restart the GTI systems, it was determined that gas from Gas Supply Well 1 had been added to the wellhead gas previously coming from only one well, Gas Supply Well 2. It was theorized that a change in gas quality led to the high vibration measured at the engines. Wellhead gas analysis collected by the EERC on Friday, August 17, 2012 (Gas Supply Well 2 only) and Continental Resources, Inc., on Saturday, August 18, 2012 (after Gas Supply Well 1 had been added to the gas supply) shows very little difference between gas samples. Results from these analyses are provided in Table 4. Although not evident in these data, it is possible that when the wellhead gas from Gas Supply Well 1 was initially added to the supply line feeding the engines, a slug of heavier hydrocarbons was introduced to the system, causing the observed engine vibration. Once flow from the well stabilized, wellhead gas quality returned to typical values, and gas analyses failed to show any appreciable difference.

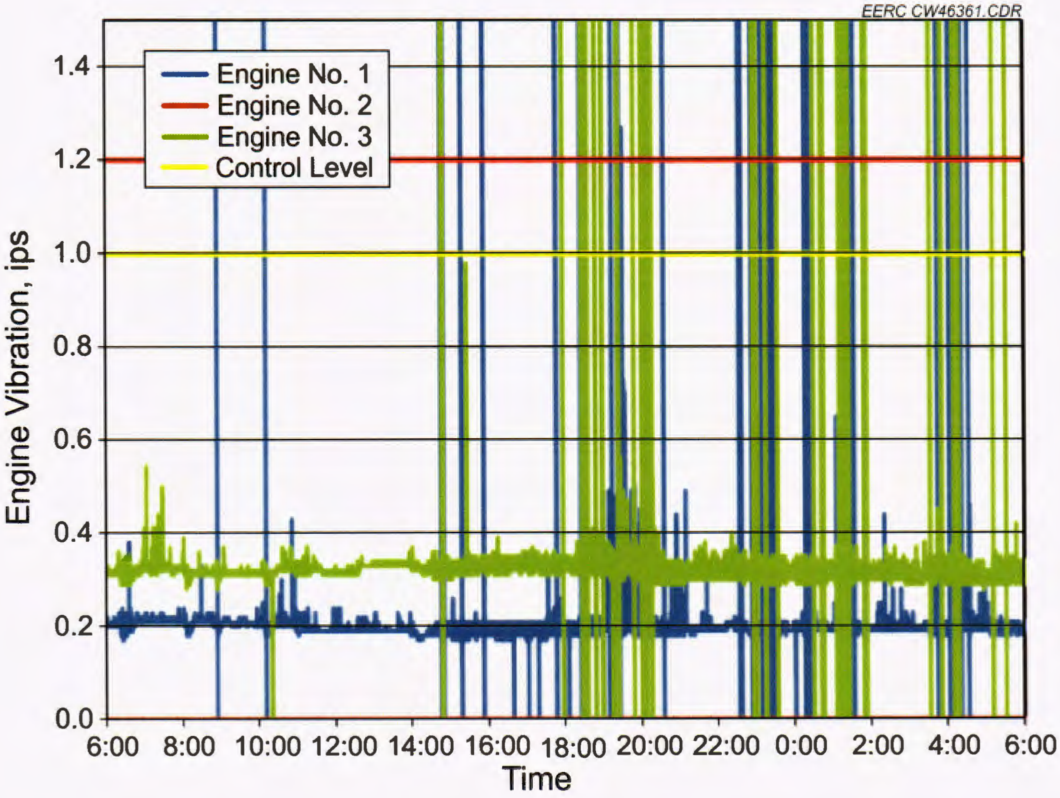

Figure 12. Engine vibration as a function of time during drilling and tripping activity.

Table 3. Gas Quality Summary Table

	mol% Gas Supply Well 1 8/17/2012	mol% Gas Supply Well 2 8/18/2012
Carbon Dioxide	0.73	0.57
Propane	12.03	12.39
iso-Butane	1.21	1.24
n-Butane	3.57	3.78
iso-Pentane	0.56	0.60
c-2-Butene	0.01	
n-Pentane	0.72	0.83
Ethane	21.99	21.76
Oxygen/Argon	0.10	
Nitrogen	3.26	3.08
Methane	54.16	54.52
Carbon Monoxide	0.01	
Total	98.34	98.77

Fuel Savings Estimates

The fuel savings were determined two different ways. The first method relied on diesel fuel meter data and theoretical "diesel-only" data to estimate fuel savings. ECO-AFS commissioning data were used to generate fuel consumption versus load curves for diesel-only operation for each of the three engines. When engines were operating in bi-fuel mode, the actual diesel consumption was measured. The diesel-only curves were used, along with the measured engine load, to calculate what the theoretical diesel-only consumption rate would have been if wellhead gas supply had been off. The fuel savings were determined by calculating the difference between the calculated "diesel-only" fuel rate and the measured fuel rate under bi-fuel operation. Figure 13 plots the calculated daily cumulative diesel fuel savings for each engine and the total for all three engines. Diesel fuel savings data were obtained beginning on August 22 after diesel flowmeters were installed and calibrated. It is clear from the plot that the wellhead gas supply rate for Engine No. 3 was lower than the other two engines. ECO-AFS had set the gas injection rate lower because of higher engine vibration measured during commissioning of the GTI systems.

In addition to diesel fuel measurements, a second method was used to calculate fuel savings. The ABB gas meter measured total wellhead gas supplied to the three engines over the course of the field demonstration. This method does not provide engine specific savings, but it did provide a total wellhead gas consumption value. The wellhead gas consumption rate was converted to an equivalent diesel rate based on 1450 Btu/scf for the gas and 140,000 Btu/gal for the diesel fuel. Figure 14 plots the total calculated daily cumulative diesel fuel savings along with the cumulative wellhead gas consumption (converted to an equivalent diesel rate). Since no diesel consumption data were available before August 22, the diesel data were adjusted to match the gas data on that date. The two methods yield similar results. The increasing difference near the end of the test period may be caused by drift in the diesel or gas flowmeters. Based on these results and a diesel price of $3.80/gal, the savings in diesel fuel over the duration of the two well demonstrations was between $64,000 and $70,000. This fuel savings estimate assumes a conservative $5.00/Mcf wellhead gas value (taking into account the value of high NGL associated gas), resulting in approximately $8900 for the cost of wellhead gas over the duration of the demonstration.

The diesel savings that can be achieved using a bi-fuel system is highly dependent upon the rig activity. Figure 15 plots the combined daily diesel replacement rate for all three engines. The highest replacement rates occurred when the rig was drilling steady, with limited tripping or idle time. These operations are consistent with engine loads between 30% and 50% maximum and result in the greatest diesel replacement with wellhead gas. The average replacement rates for each activity are presented in Table 5. Typically, when the rig was idle, the engines were at less than 12% load, and the wellhead gas flow was off. Figures 16 and 17 plot the load profiles for each engine in terms of hours at load or percentage of time at load. The load ranges are broken down to match the control levels of the GTI STEPCON system. At less than 12% load, the wellhead gas flow is turned off. Figures 18 and 19 plot the diesel fuel used and the diesel fuel saved for each STEPCON control range. The figures show there is a large amount of time where the engines are operating between 0% and 12% load and wellhead gas flow is off, therefore, no fuel savings.

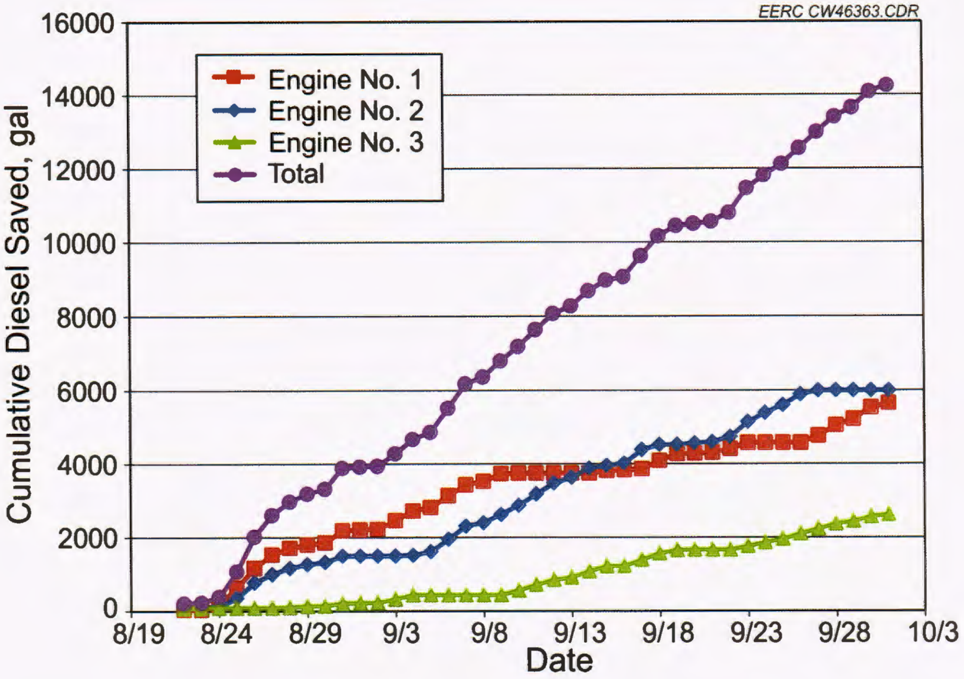

Figure 13. Cumulative diesel savings based on fuel flowmeter measurements.

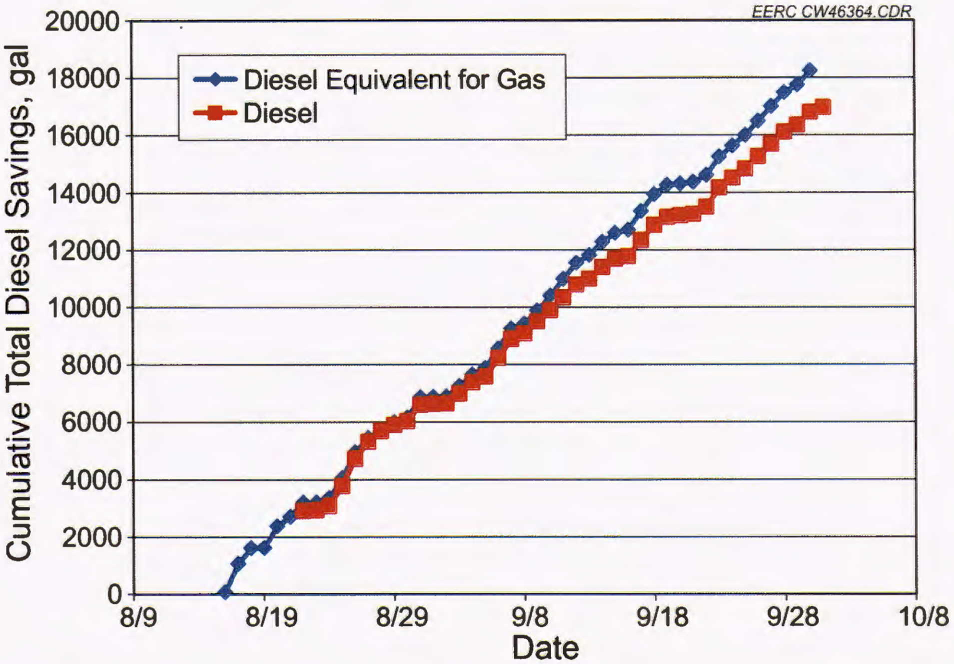

Figure 14. Comparison of diesel fuel savings based on diesel flowmeters and gas flowmeter readings.

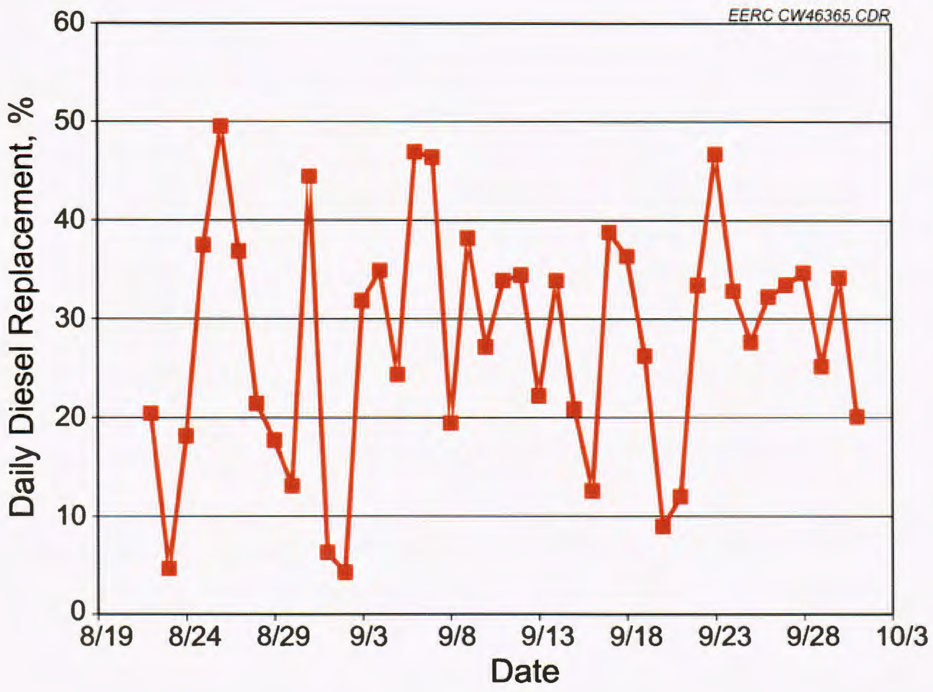

Figure 15. Daily total diesel displacement.

Opportunities for System Optimization

The GTI Bi-Fuel system is designed to be operated with minimal operator intervention and to provide fail-safe operation to prevent unnecessary wear on the engines and downtime or interruption to drilling activities. Under normal operation, the GTI control system will stop natural gas flow to the engine in the event any engine operating parameter is outside OEM specification. In some cases, the control system restarts natural gas flow after engine conditions return to specified limits; in other cases, a manual reset is required by an operator. During the demonstration period, engine operation was monitored closely by the EERC, Continental Resources, Inc., and Cyclone Drilling personnel; therefore, system upsets or faults were identified, and the necessary manual reset occurred after minimal downtime. Monitoring GTI Bi-Fuel performance over the test period resulted in the identification of several opportunities for

Table 4. Average Diesel Replacement Based on Rig Activity

Rig Activity	Average % Replacement
Drilling	38
Drilling and Tripping	30
Drilling and Idle	34
Tripping and Idle	10
Drilling, Tripping, and Idle	25

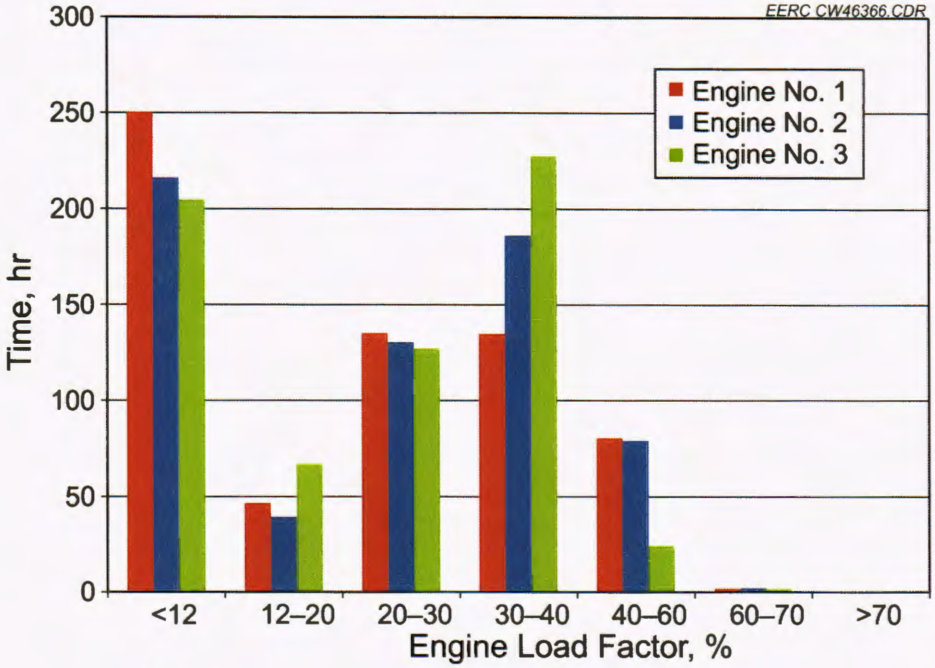

Figure 16. Engine load profiles on an hourly basis.

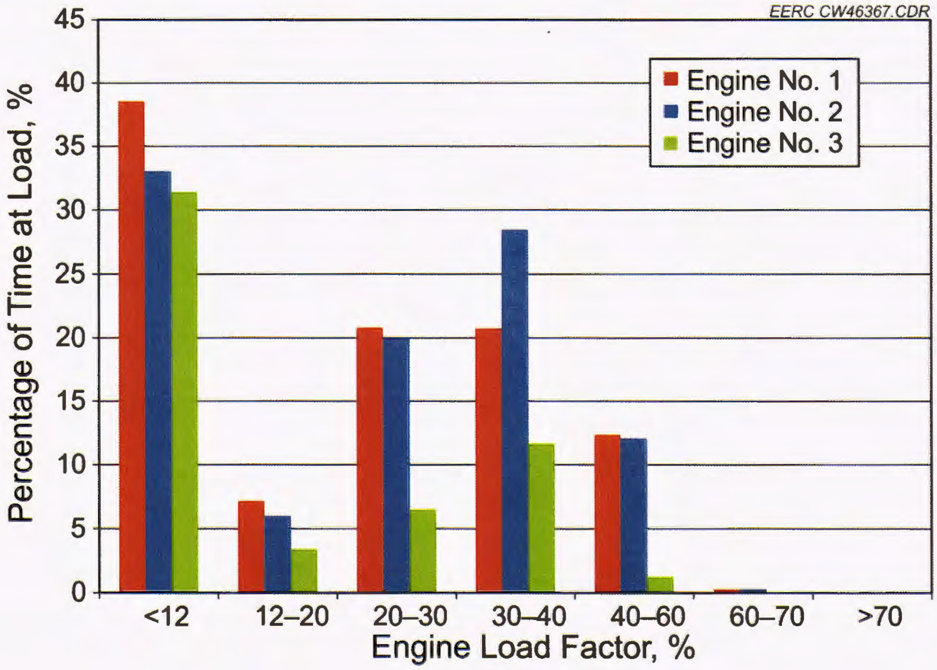

Figure 17. Engine load profiles on a percentage basis.

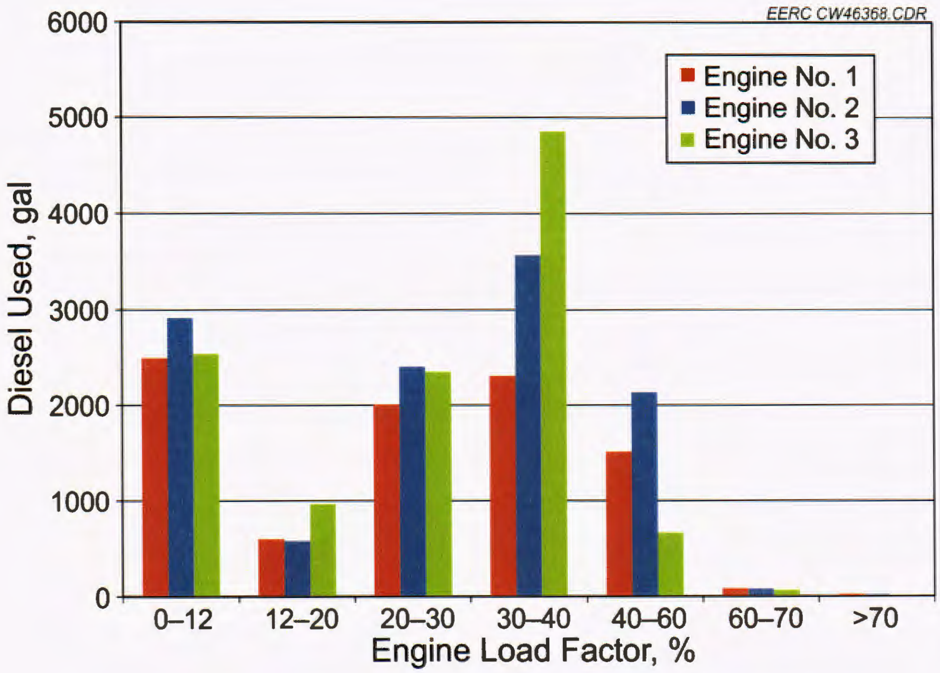

Figure 18. Total diesel consumed for each STEPCON load level.

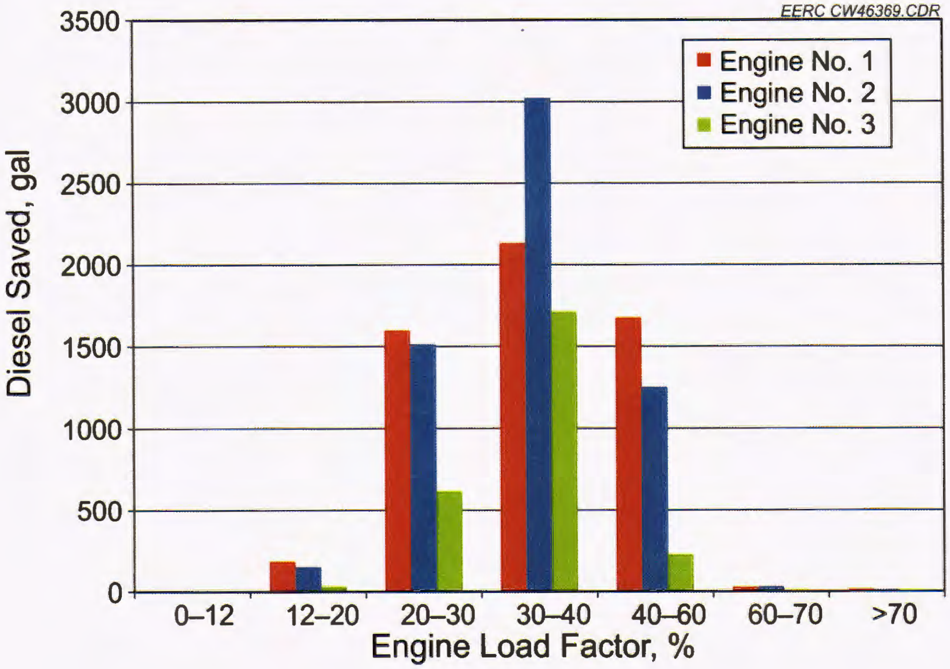

Figure 19. Total diesel saved for each STEPCON load level.

additional system up-time and associated diesel fuel savings. These observations and associated recommendations primarily require changes in the philosophy and operation of the Bi-Fuel system and do not represent shortcomings in the GTI Bi-Fuel system or control strategy.

Engine condition and maintenance are important factors in ensuring the maximum benefit from any bi-fuel system. The GTI Bi-Fuel system is designed and configured to provide safe reliable gaseous fuel supply to the diesel engine while maintaining operation within the OEM specifications. In some ways, use of the Bi-Fuel system can lead to improved engine operation because of the presence of a live/real-time display providing input on engine metrics. These data can help engine operators quickly assess engine performance to provide some diagnostic capabilities to the user. As mentioned previously, there were days during the drilling cycles where the ambient temperature was high, causing the GTI system to stop wellhead gas flow. During these times, EERC personnel monitored engine parameters and notified Cyclone Drilling personnel that engine temperatures were exceeding control or safety limits, and measures were taken to bring engine temperature back within an acceptable range. During these periods, an additional 2000 gallons of diesel fuel could have been replaced by wellhead gas if the engine-cooling systems had been working properly. As such, cooling system maintenance was added to the list of tasks to be completed during regularly scheduled maintenance. If engine performance had not been monitored, the diesel-only periods could have been much longer, resulting in less fuel savings.

Another opportunity for improved fuel savings was illustrated by the difference observed in higher diesel fuel use measured from Engine No. 3 relative to the others as shown in Figure 13. If Engine No. 3 had run similar to the other two engines, an additional 3000 gallons of diesel fuel could have been replaced. ECO-AFS personnel derated the bi-fuel system because of excessive vibration. If mechanics were aware of this, they may have been able to work with ECO-AFS to minimize the vibration and increase the diesel replacement rate. In order to take advantage of these opportunities in the future, the performance of the engines and diesel consumption will need to be monitored. Having someone available to remotely reset the GTI controller when a safety fault occurs could reduce bi-fuel down time and increase diesel replacement. Monitoring engine parameters and diesel fuel consumption will help identify engines that require maintenance or adjustments that may need to be made to the GTI system. Other possibilities for cost saving would involve load leveling during tripping activity or operating fewer engines at higher loads during low-demand periods. Figures 16 and 17 show that during more than 30% of the time the engines are running below 12% load. It may be beneficial to conduct routine bi-fuel system tuning to ensure the best possible diesel fuel replacement.

Engine Exhaust Emission Measurement

Operating a diesel generator with a mixture of wellhead gas and diesel fuel can change the combustion properties of the engine and thereby alter exhaust emissions. Over the course of the field demonstration, a series of exhaust gas measurements were obtained to evaluate the effect of bi-fuel operation on air emissions. Sample ports were installed on the stack of each engine to provide access for emission sampling of the stack gases. All sampling occurred at a nominal engine load of 30%, and measurements were collected under both diesel-only and bi-fuel operation. A Testo analyzer was used to measure CO, NO_x, and SO_2 concentrations, and analysis of the gas bag samples provided the NMHC values. All concentrations were converted to a g/BHP*hr basis for comparison. The emission data, summarized in Table 6, show that operating the engines in bifuel mode results in an increase in CO and NMHC emissions and a decrease in NO when compared to diesel-only operation. Mansour and others (2001) investigated the emissions and performance of a bifueled diesel engine and modeled the gas–diesel combustion reactions using chemical kinetic reaction mechanisms. They determined that the CO emission increase when running in a bifuel mode was caused by nonoptimized pilot timing, flame quenching and partial burning. Engine manufacturers may be able to address these issues with designs tailored to specific fuel mixes, but little can be done to address these combustion properties in existing engines with aftermarket bifuel systems like GTI's. One solution to address the increase in CO and NMHC emissions is the use of oxidation catalysts which are commercially available and have been demonstrated to significantly reduce these emissions. The average concentrations of NMHCs and NO_x also increased when on bifuel. Results from the Testo analyzer showed high levels of unburned hydrocarbon in the stack gas when on bifuel, but the NO_x concentration was unaffected. Analysis of gas bag samples showed that the hydrocarbon species present in the stack were in nearly the same proportions as in the feed wellhead gas. This is indicative of "slip" which is caused by the overlap in timing of the intake and exhaust valves that allows some of the incoming wellhead gas to pass through the cylinder without combusting. Under normal diesel-only operation, this slip is just air. However, during bifuel operation, the combustion air, mixed with natural gas, can pass through the engine unburned during this valve overlap. The SO_2 concentration measured at the engine exhaust was below the detection limit and consistent with wellhead gas analysis which showed no sulfur compounds were present.

During preparations for the demonstration project, ECO-AFS installed and commissioned the GTI Bi-Fuel systems. At that time, ECO-AFS determined that Engine No. 1 was operating at a temperature higher than recommended by OEM. After working with Cyclone Drilling mechanics, ECO-AFS diagnosed a bad fuel injector, replaced it, and adjusted the valve timing. Following these maintenance items, the GTI Bi-Fuel system was commissioned, and the engine operated normally. Shortly after the start of the demonstration, exhaust gas samples were collected from each engine and analyzed. The results from this first set of samples are summarized in Table 7 and demonstrate a fairly significant difference in emissions among the three engines, especially for CO and NMHC. Because maintenance on Engine No. 1 had been recently completed, it was theorized that improved valve timing may have contributed to the relatively lower CO and NMHC emissions compared to Engine Nos. 2 and 3.

Table 5. Summary of Engine Emission Data

	Average CO, g/BHP*hr	Average NMHC + NO_x, g/BHP*hr	Average NO_x, g/BHP*hr	Average NO, g/BHP*hr	Average SO_2, g/BHP*hr
Bi-Fuel On					
Engine No. 1	9.8	7.8	3.3	1.7	<0.005
Engine No. 2	13.8	14.8	2.4	1.4	<0.005
Engine No. 3	9.1	7.7	2.7	1.4	<0.005
Bi-Fuel Off					
Engine No. 1	1.7	3.1	2.9	2.5	<0.005
Engine No. 2	2.2	3.3	3.1	2.8	<0.005
Engine No. 3	1.2	3.0	2.8	2.5	<0.005

In an effort to test the theory and improve emissions, Cyclone Drilling mechanics adjusted the valve timing on Engine Nos. 2 and 3 and exhaust gas samples were collected and analyzed. The maintenance conducted on Engine No. 2 did not appear to impact CO or NMHC emissions as illustrated in emission data provided in Table 8. Initial data collected from Engine No. 3 suggested that valve adjustment had reduced emissions as indicated by Sample Set 2 data presented in Table 9. Following the collection of the second set of samples, mechanics replaced the injectors on Engine No. 3 (Table 9), and two additional exhaust gas samples were collected and analyzed. Although initial analysis suggested an improvement in emissions, subsequent Samples 3 and 4 illustrate sufficient variability to prevent conclusive indications of emission improvement.

Table 6. Initial Engine Emission Comparison

	Engine No. 1 Sample 1 Bi-Fuel	Engine No. 2 Sample 1 Bi-Fuel	Engine No. 3 Sample 1 Bi-Fuel
CO, g/BHP*hr	9.6	13.9	10.7
NMHC + NO_x, g/BHP*hr	8.5	15.0	7.9
NO_x, g/BHP*hr	3.4	2.6	2.8
NO, g/BHP*hr	2.0	1.3	1.4
SO_x, g/BHP*hr	<0.005	<0.005	<0.005

Table 7. Engine No. 2 Emission Measurement Data

	Sample 1 Bi-Fuel	Sample 2 Bi-Fuel	Average Bi-Fuel	Average Diesel-Only
CO, g/BHP*hr	13.9	13.7	13.8	2.3
NMHC + NO_x,g/BHP*hr	15.0	14.6	14.8	3.4
NO_x, g/BHP*hr	2.6	2.3	2.5	3.1
NO, g/BHP*hr	1.3	1.4	1.4	2.8
SO_x, g/BHP*hr	<0.005	<0.005	<0.005	<0.005
	Baseline measurement	Measured after valve adjustment		

Table 8. Engine No. 3 Emission Measurement Data

	Sample 1 Bi-Fuel	Sample 2 Bi-Fuel	Sample 3 Bi-Fuel	Sample 4 Bi-Fuel	Average Bi-Fuel	Average Diesel-Only
CO, g/BHP*hr	10.7	8.5	7.4	9.9	9.1	1.2
NMHC + NO_x, g/BHP*hr	7.9	6.6	6.5	9.8	7.7	3.0
NO_x, g/BHP*hr	2.8	2.8	2.7	2.5	2.7	2.8
NO, g/BHP*hr	1.4	1.3	1.5	1.3	1.4	2.5
SO_x, g/BHP*hr	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
	Baseline measurement	Measured after valve adjustment	Measured after fuel injector replacement	Replicate measurement		

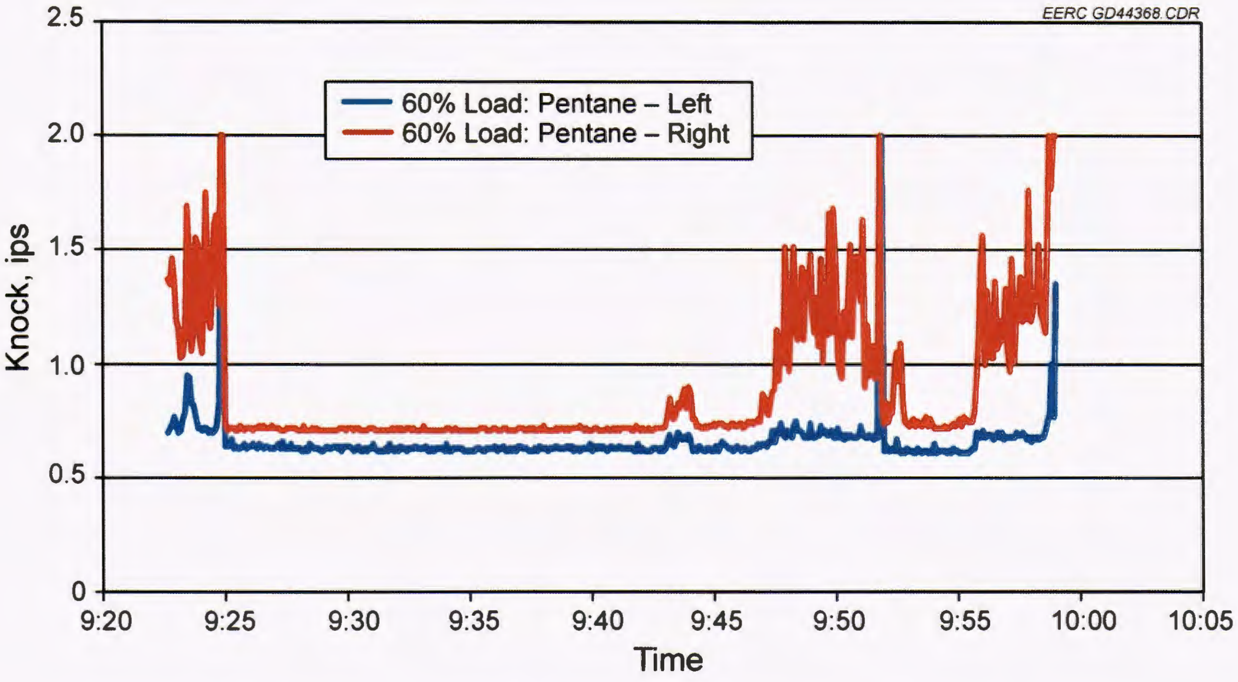

Figure 32. 60% load knock data at 70% replacement with up to 4% pentane and balance methane.

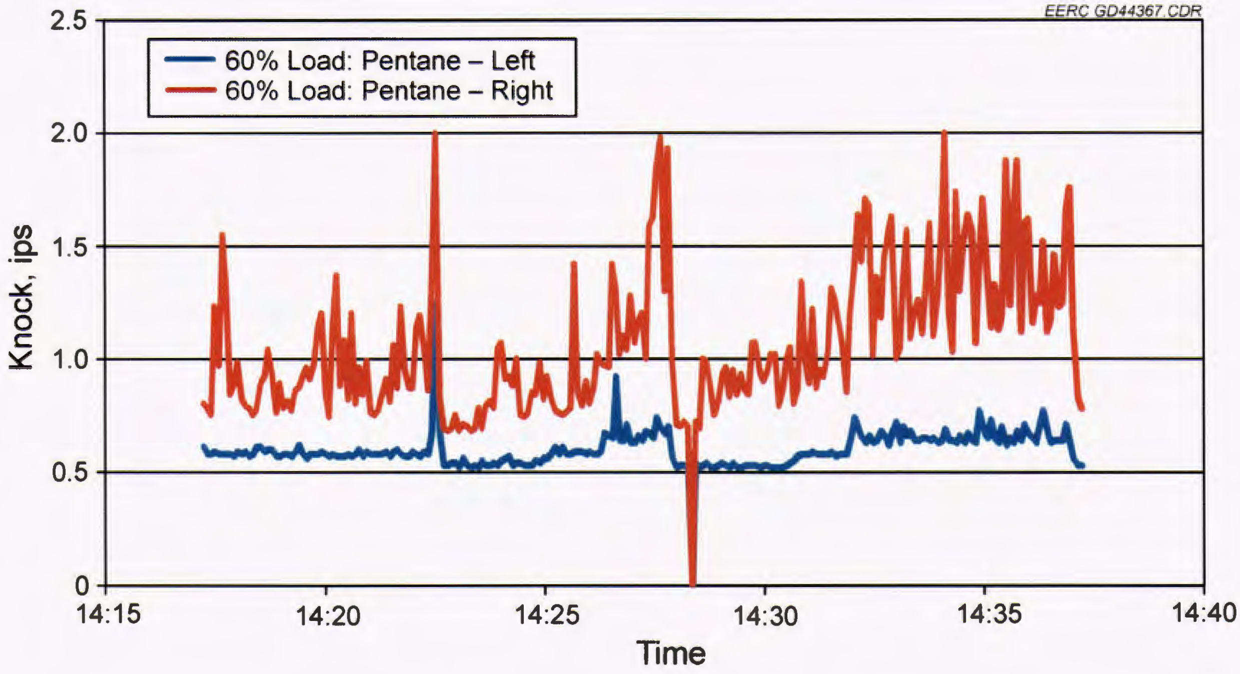

Figure 33. 60% load knock data at 60% replacement with up to 4% pentane and balance methane.

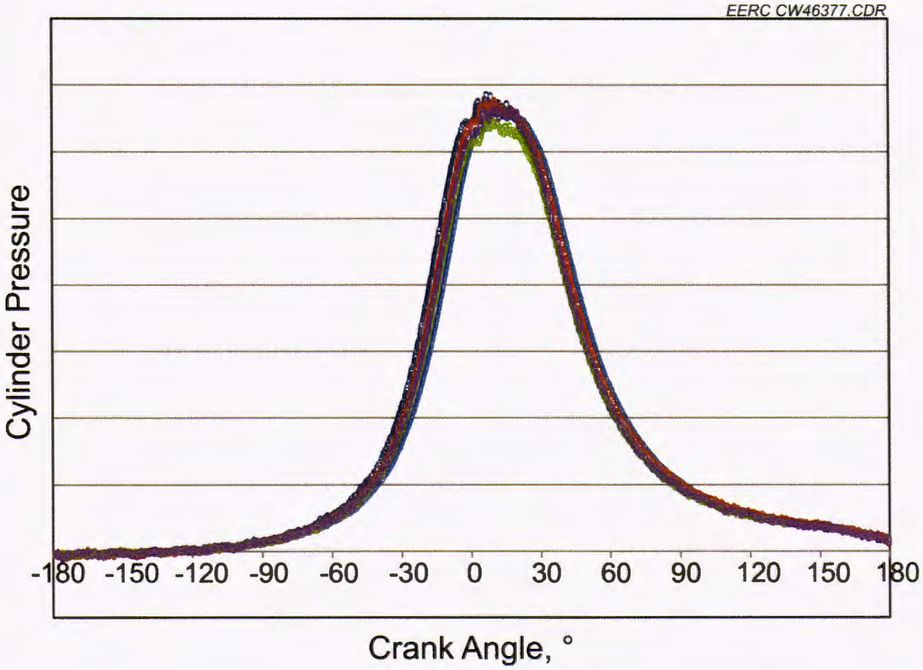

Figure 21. Pressure versus crank angle for Engine No. 1 at high load on diesel only.

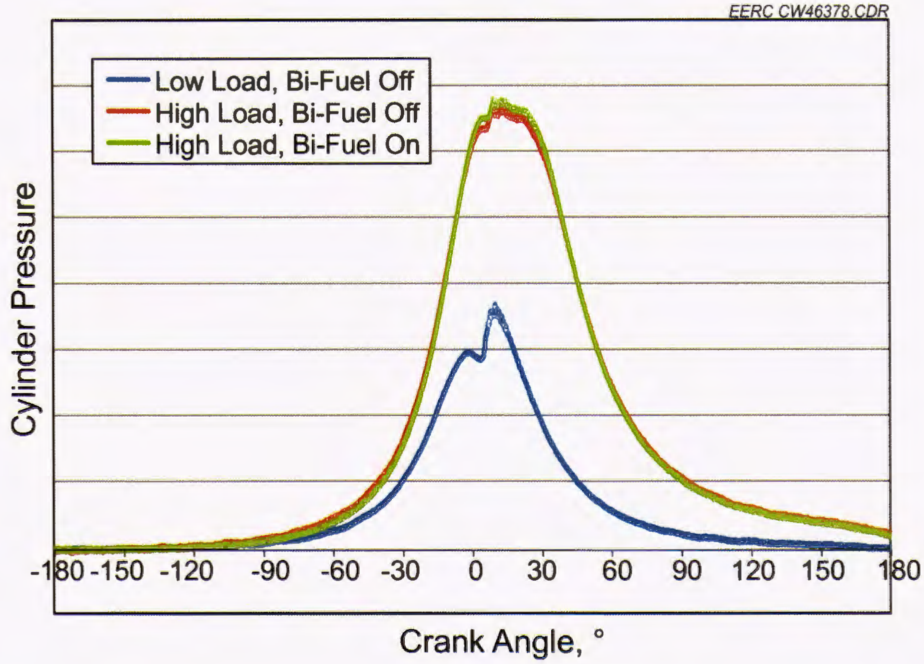

Figure 22. Average pressure versus crank angle plot for Cylinder No. 9.

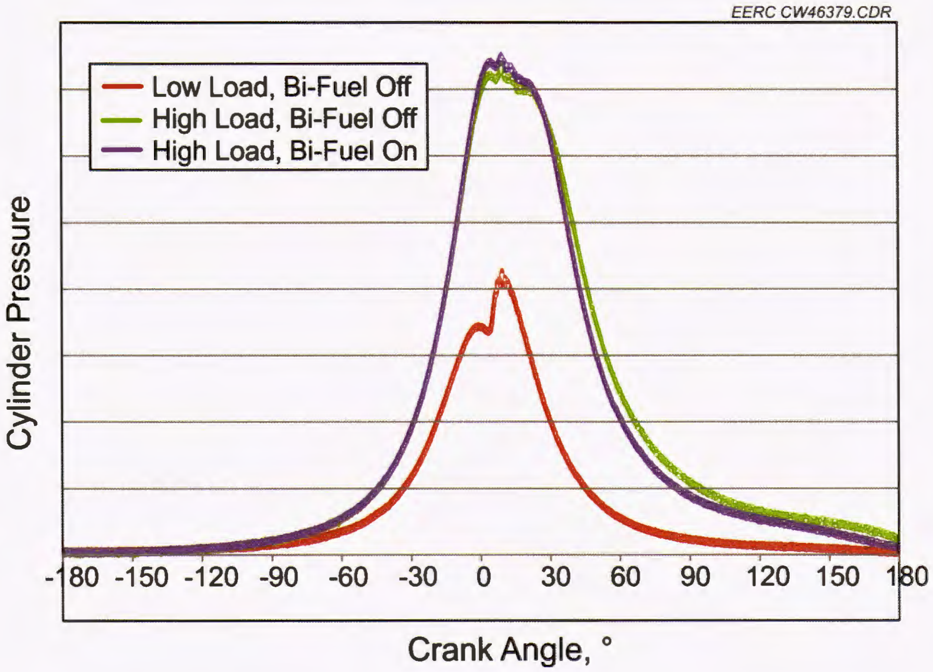

Figure 23. Average pressure versus crank angle plot for Cylinder No. 10.

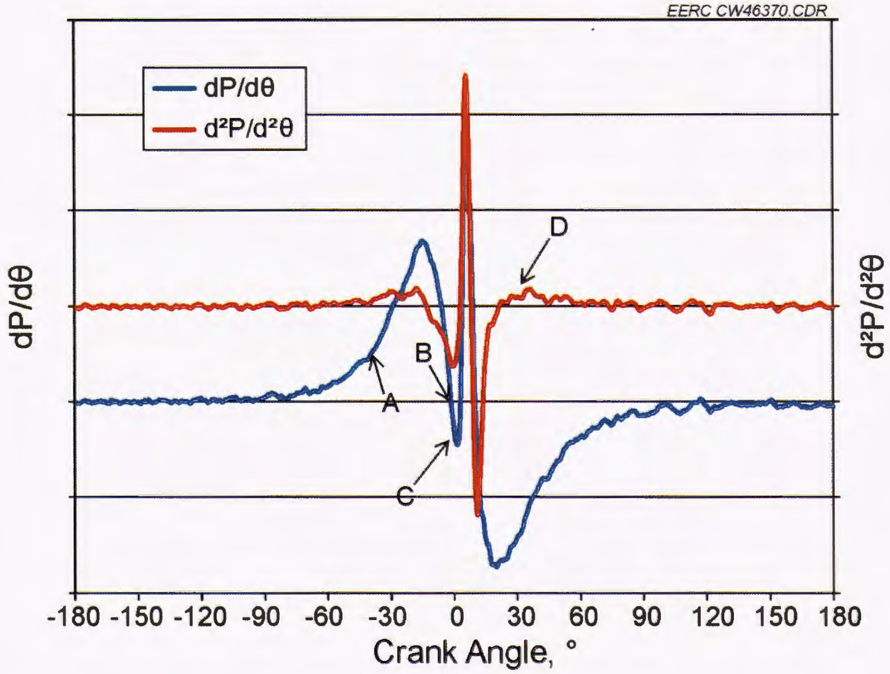

Figure 24. First and second derivatives of the P/θ curve for Cylinder No. 9 with bi-fuel off at low load.

corresponds to the start of pilot fuel (diesel) injection. Point "B," the point where the second derivative curve crosses the x-axis, is the start of pilot fuel ignition, and the time between Points A and B (fuel injection to fuel ignition) is the ignition delay. Point "C" is TDC, and Point "D" is the end of primary fuel combustion. Based on these points, we can compare plots and evaluate the effect of gaseous fuel addition to the diesel engine. For reference, Figure 25 plots the same first-derivative data with the corresponding pressure data (P/θ curve). Figures 26 and 27 compare the first derivatives of the P/θ curves for each cylinder with bi-fuel on and off, while Figures 28 and 29 do the same with the second-derivative plots of the P/θ curves. From these plots, it is clear that bi-fueling this engine had little to no effect on ignition delay or combustion. As mentioned earlier, the presence of methane tends to decrease cylinder pressure and increase the lag in ignition, while propane has the opposite effect on fuel combustion in a compression ignition engine. It appears, based on these data, that the larger fuel molecules (propane, butane, pentane, and heptane) present in the wellhead gas are mitigating the ignition delay caused by methane, similar to what was observed during the parametric testing at the EERC (see Appendix A).

CONCLUSIONS

The EERC successfully completed a 47-day two-well demonstration of diesel engines, used to power drilling rigs in North Dakota, running on a mixture of diesel fuel and wellhead gas. A commercially available GTI Bi-Fuel system manufactured by Altronic and installed by

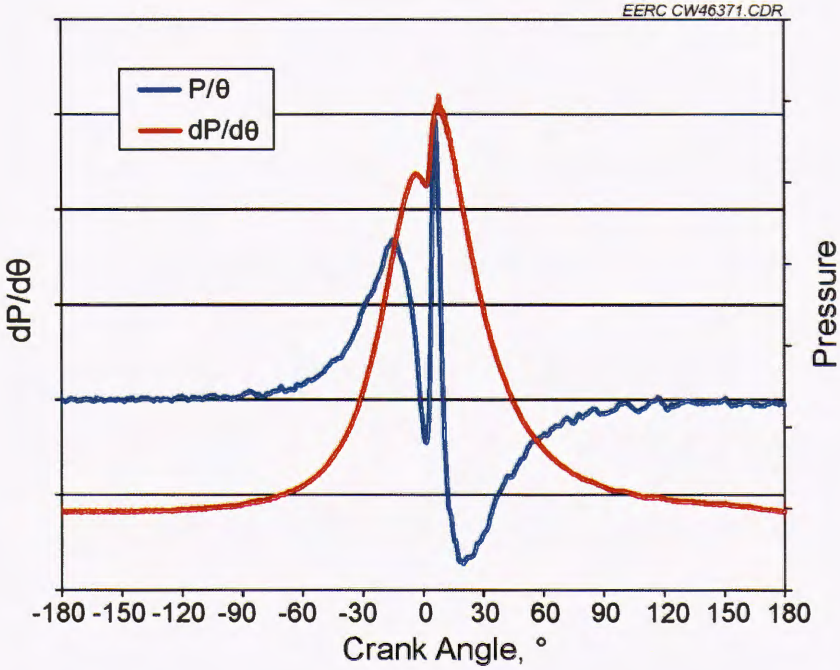

Figure 25. P/θ and first derivative of the P/θ curve for Cylinder No. 9 with bi-fuel off at low load.

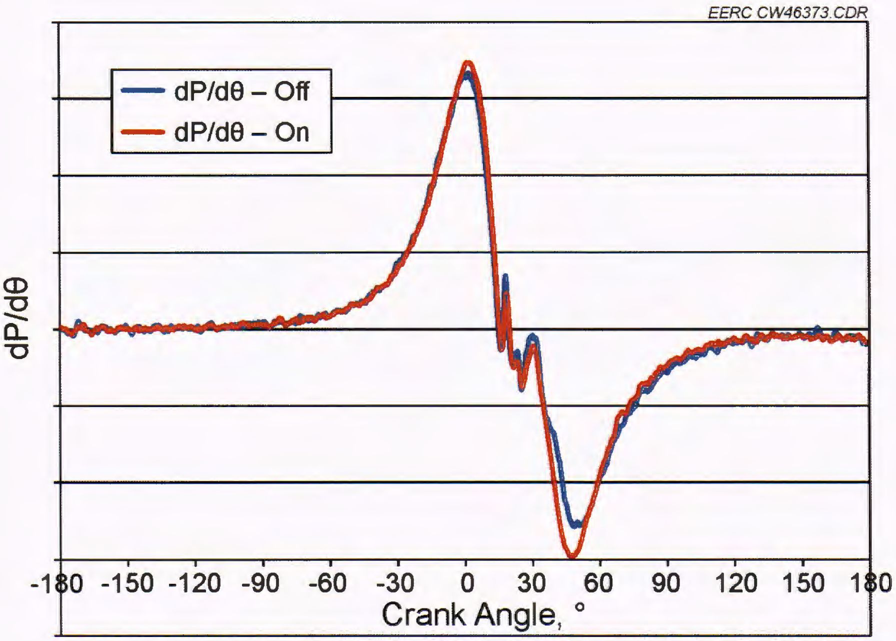

Figure 26. First derivative of the P/θ curve for Cylinder No. 9 at high load with bi-fuel off and on.

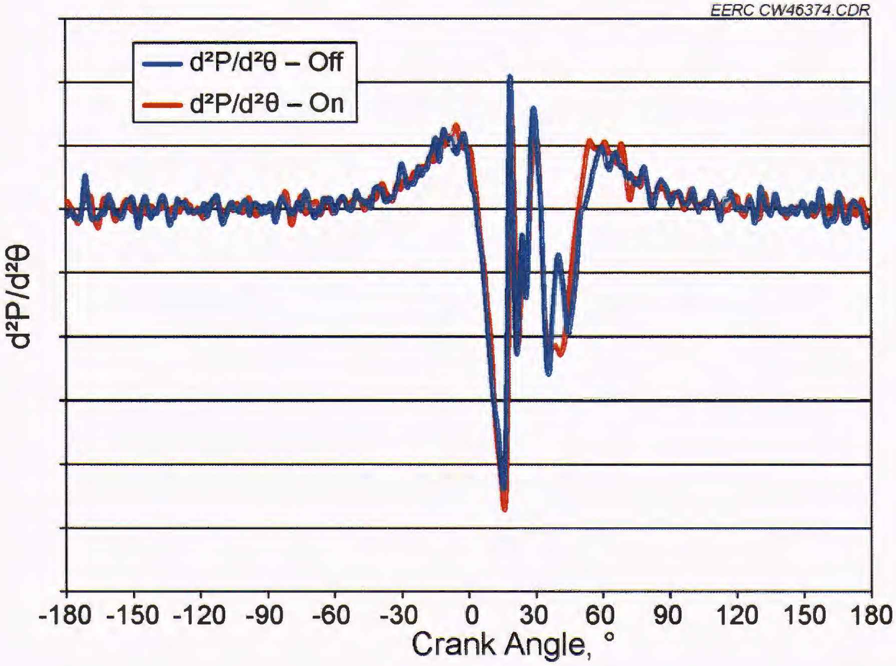

Figure 27. Second derivative of the P/θ curve for Cylinder No. 9 at high load with bi-fuel off and on.

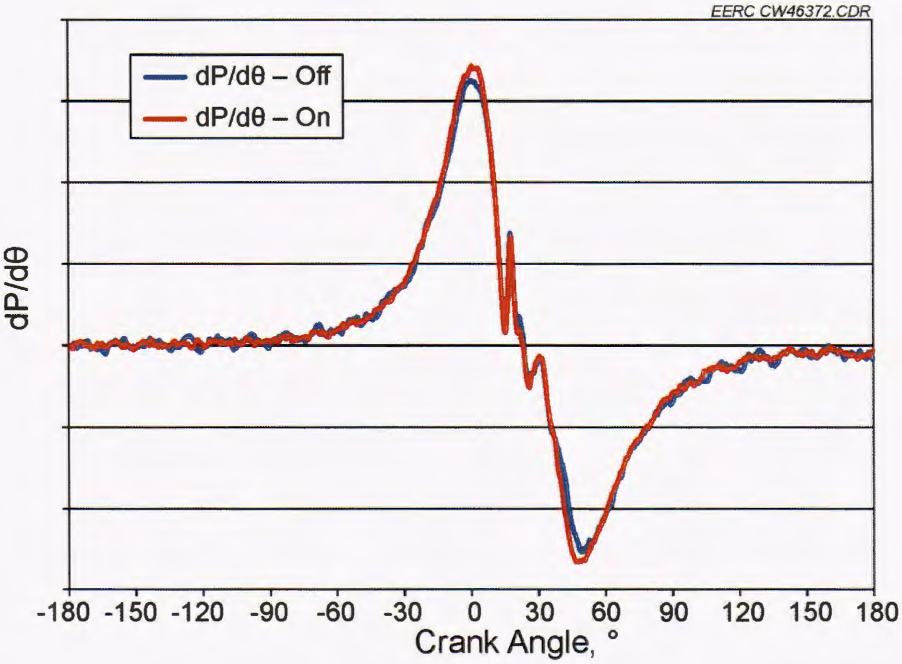

Figure 28. First derivative of the P/θ curve for Cylinder No. 10 at high load with bi-fuel off and on.

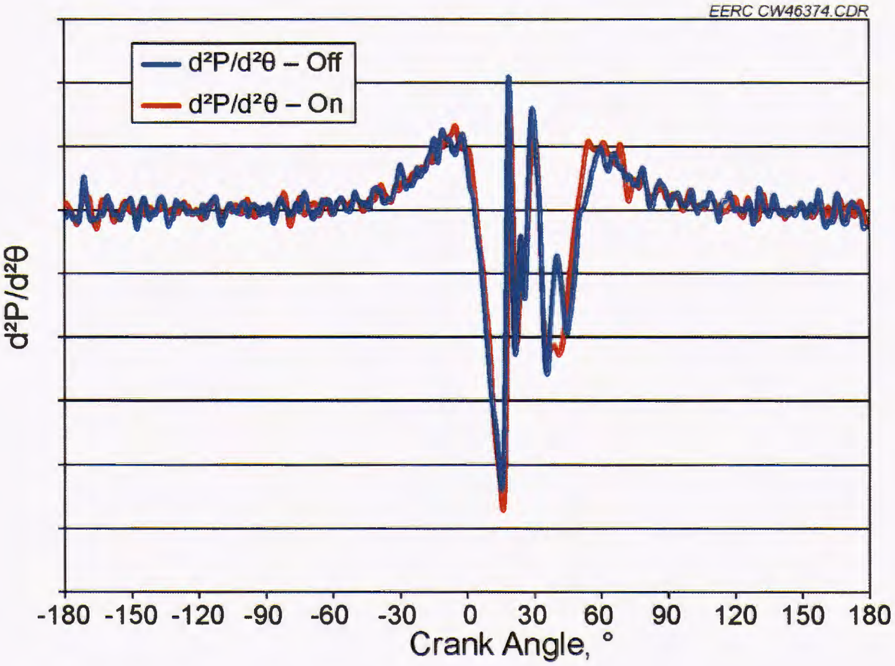

Figure 29. Second derivative of the P/θ curve for Cylinder No. 10 at high load with bi-fuel off and on.

ECO-AFS was installed on the three diesel engines of Cyclone Drilling Rig No. 28. Wellhead gas was supplied via pipeline from a producing well 1600 feet from the drilling location. Results showed there were no adverse effects of running on wellhead gas in terms of operability or engine operating parameters such as exhaust gas temperature, engine vibration, or ignition delay.

Specific results from this project included:

1) Reduced diesel fuel use by 16,000–18,500 gallons and associated fuel delivery truck traffic.

2) Fuel-related cost savings of nearly $60,000 due to the lower value of wellhead gas relative to diesel.

3) Beneficial use of wellhead gas at the point of production.

4) Reduction in overall air emissions compared to diesel-only engine operation plus flaring an equivalent amount of wellhead gas. However, operating engines in bi-fuel mode does result in increased carbon monoxide and NMHCs when compared to diesel-only engine operation.

5) Seamless operation of the GTI Bi-Fuel system with no impact on drilling operations.

6) Additional fuel savings possible by minimizing diesel-only operation with optimized process control and/or operational oversight of the GTI Bi-Fuel system.
7) Bi-fuel systems operated efficiently with routine engine maintenance.

Based on the results from this project, the project team estimated the overall effect of utilizing otherwise flared wellhead gas to power drilling operations of nearly 200 drilling rigs in North Dakota. The result of such broad implementation would include:

1) 1,800,000 Mcf wellhead gas used to power drilling rigs in 1 year (2% of currently flared wellhead gas).

2) 18,000,000 gallons of diesel fuel saved in 1 year.

3) $72,000,000 diesel fuel costs saved in 1 year.

4) 3600 fuel delivery trucks (5000-gallon tanker) avoided in 1 year.

5) 68% reduction in overall air emissions compared to diesel-only operation plus flaring an equivalent amount of gas.

6) Additional air emission reduction can be achieved using commercially available diesel engine exhaust gas treatment (catalytic conversion). These technologies are capable of reducing CO and NMHC emissions in bi-fuel-operated engines to levels similar to 100% diesel-only operation.

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