THE FEASIBILITY OF NATURAL GAS AS A FUEL SOURCE FOR MODERN LAND-BASED DRILLING RIGS

A Thesis

by

ANDREW HOWARD NUNN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2011

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee,	F.E. Beck
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ABSTRACT

The Feasibility of Natural Gas as a Fuel Source for Modern Land-Based Drilling Rigs.

(December 2011)

Andrew Howard Nunn, B.S., Oregon Institute of Technology

Chair of Advisory Committee: Dr. Gene Beck

The purpose of this study is to determine the feasibility of replacing diesel with natural gas as a fuel source for modern drilling rigs. More specifically, this thesis (1) establishes a control baseline by examining operational characteristics (response, fuel usage, and cost) of an existing diesel-powered land rig during the drilling of a well in the Haynesville Shale; (2) estimates operational characteristics of a natural gas engine under identical conditions; and (3) draws a comparison between diesel and natural gas engines, determining the advantages and disadvantages of those fuel sources in drilling applications. Results suggest that diesel engines respond to transient loads very effectively because of their inherently higher torque, especially when compared with natural gas engines of a similar power rating. Regarding fuel consumption, the engines running on diesel for this study were more efficient than on natural gas. On a per-Btu basis, the natural gas engines consumed nearly twice as much energy in drilling the same well. However, because of the low price of natural gas, the total cost of fuel to drill the well was lowered by approximately 54%, or 37,000 USD. Based on the results, it is possible to infer that the use of natural gas engines in drilling environments is feasible,

and in most cases, an economical and environmental advantage. First, when compared with diesel, natural gas is a cleaner fuel with less negative impact on the environment. Second, fuel cost can be reduced by approximately half with a natural gas engine. On the other hand, natural gas as a fuel becomes less practical because of challenges associated with transporting and storing a gas. In fact, this difficulty is the main obstacle for the use of natural gas in drilling environments. In conclusion, because of its minimal drawback on operations, it is recommended that in situations where natural gas is readily available near current market prices, natural gas engines should be utilized because of the cost savings and reduced environmental impact. In all other cases, particularly where transport and storage costs encroach on the cost benefit, it may still be advantageous to continue powering rigs with diesel because of its ease of use.

DEDICATION

To my friend Priscila, for her persistence, help, guidance, and patience

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This thesis would not have been possible without the help of my committee members and the faculty of the Texas A&M Department of Petroleum Engineering. I would like to whole heartedly thank them for their help and guidance.

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CHAPTER I

INTRODUCTION

A natural gas (NG) engine is a mechanical machine that consumes NG as a fuel source and converts it into mechanical work. Most are spark-ignited (SI) reciprocating internal combustion engines (RICEs); however, gas-fired turbines are another common device that can also fall under the above definition. They can vary in output from a fraction of an hp to many thousands.

NG engines, both RICEs and turbine engines, are commonplace throughout both the upstream and downstream oil and gas industry; however, they are typically installed and operated in specific applications. This is primarily because of how well the engine's physical and performance characteristics match with the application, but the fuel source may also become a factor during specification (Caterpillar 2006a).

Historically, the use of NG as a fuel source to power prime movers in land drilling rigs has not been common. The vast majority of drilling rigs worldwide have their power supplied by diesel engines (Hill et al. 2011). While NG applications can and have been implemented, the operational characteristics of an NG engine are not ideal for the conditions imposed in drilling applications. When compared with traditional diesel-fueled engines, the operational limitations make them uneconomical and difficult to use (Caterpillar 2010a).

This dissertation follows the style of *SPE Journal of Petroleum Technology*.

Recently, the rising cost of diesel fuel and the tightening of emissions regulations have forced the drilling industry to take another look at this application. The relative lower cost of NG could save the industry money, and NG also burns cleaner than diesel, lowering harmful emissions and making it easier and cheaper to meet emission requirements (Caterpillar 2010a).

With advances in technology both on the drilling rigs themselves and in the distribution and storage of NG, the operational disadvantages of the past can either be managed or eliminated altogether. The repowering of the land drilling rig fleet to NG engines could have a substantial impact in lowering the overall cost of drilling a well.

Therefore, the purpose of this study is to examine and identify the critical operational characteristics required of a modern diesel-fueled drilling rig and then determine the operational drawbacks, if any, of using NG solutions. Changes in rig performance characteristics and the impact on operation are presented, in addition to an economic analysis on the overall cost of drilling a well with the presented solution.

In order to accomplish this, this thesis (1) investigates specific regulations for different types of rig engines; (2) examines the operational characteristics (response, fuel usage, and cost) of an existing diesel-powered land rig to establish a control baseline; (3) estimates operational characteristics (fuel usage and cost) of an NG engine in a drilling environment; and (4) establishes a comparison of diesel and NG engines, indicating the feasibility of using an NG engine.

Chapter II provides an overview of drilling rigs as well as the various engine types used in the oil and gas industry and their common applications. Past, current, and future emission legislation is also presented.

Chapter III examines a well drilled in the Haynesville Shale play of northern Louisiana using a modern variable-frequency-drive (VFD) diesel-powered land drilling rig to establish a baseline of existing operations. The engine load, fuel consumption, and time are analyzed and related to various rig operations.

Chapter IV discusses the various NG solutions and how they are implemented. The performance characteristics of each solution are predicted and compared with the existing data presented in Chapter III.

Chapter V provides a general discussion of the findings, comparing the various NG solutions, and discusses operational pros and cons when compared with traditional diesel-fueled rigs. A total cost of ownership for various NG solutions is calculated based on equipment and operational cost, including fuel and regular maintenance. This cost is presented alongside economic data, indicating the feasibility of using NG engines in drilling applications and supporting a recommendation.

CHAPTER II

OVERVIEW

Chapter II presents an overview and history of drilling rigs, engine types used in the oil and gas industry, their common oil and gas applications, and emissions regulations for these engine types.

Drilling Rigs

Drilling rigs are used to drill a well into the earth from which oil and gas can be extracted. All rigs are portable, but vary greatly in size, mobility, and capability. Drilling rigs can be based either on land or offshore. An example of a land-based rig is shown in **Fig. 1.**

Drilling rigs are characterized as either mechanical or electric. Older rigs were mechanically driven, with the engine powering rig equipment through a transmission comprising either a clutch or a torque converter. While mechanical rigs are still in use today, most modern drilling rigs are electrically powered. Electric drilling rig engines are coupled to electric generators, in what is called a generator set, or genset, which creates electricity that powers electric motors driving the rig equipment. Because electric motors can be controlled electronically, these rigs do not require the use of transmissions.

Fig. 1—View of a land-based drilling rig.

The major rig components are the drillstring, draw-works, rotary table/top drive, and mud pumps. The drillstring is the length of pipe on which the bit and other downhole tools are mounted. It is composed of individual sections of approximately 30 ft in length called joints. It is often stacked on the rig in 90-ft lengths of three joints each called stands. The draw-works comprises the cable reel and winch; it serves as the lifting mechanism for the drillstring. It can also be used as an accessory to connect makeup or disconnect breakout joints or stands; however, on many modern rigs, there is now dedicated equipment, known commonly as iron roughnecks, to perform this task. The rotary table has been used as the traditional means of rotating the drillstring. The table is located in the rig floor and, using a special rectangular pipe called a kelly attached to the drillstring, it rotates the drillstring while allowing for vertical movement as the wellbore deepens. On modern rigs, the rotary table and kelly have been replaced with a top drive, which provides rotation while moving vertically with the drillstring. The mud pumps are piston-type, high-pressure, positive displacement pumps used to circulate drilling fluid or drilling mud down the drillstring and back to surface (Caterpillar 2006a).

Electric drilling rigs can be categorized into either direct current (DC) or alternating current (AC), depending on the type of electricity the rig generators produce. Electric motors power the draw-works, top drive, mud pumps, and other systems with electricity provided by the rig generators. The electric motors used for these operations must be capable of producing high torque at zero rpm, as well as at variable speeds (Caterpillar 2006a).

DC rigs are the oldest type of electric drilling rigs. The generators on DC rigs produce DC that powers DC motors. These DC motors provide the desirable characteristics required for hoisting, drilling, and pumping. The speed of motors is controlled by varying the voltage the motor receives. This variance is accomplished through the use of variable resistors placed directly in line between the generator and motor. As the load on the motor increases, the motor will draw more current. To maintain its speed, the supplied voltage will also need to be increased (Caterpillar 2006a).

DC generators regulate voltage and current by varying the current through the field windings and increasing the strength of the magnetic field. A commentator and carbon brushes are integral parts of the DC generator and are subject to wear. They also produce voltage fluctuations that may require additional components for voltage regulation. While DC drilling rigs are still common, the problems associated with the technology have led to the DC rig being phased out (Caterpillar 2006a).

The next generation of the electric drilling rig came with the introduction of the AC rig. AC generators have less moving parts and therefore require less maintenance than their DC counterparts. They also produce more constant electric voltage because AC voltage fluctuates by nature (Caterpillar 2006a).

These AC rigs are able to take advantage of the more desirable characteristics of AC generators while maintaining the benefits of DC motors. This is done by converting the AC to DC through the use of a silicon-controlled rectifier (SCR) (Caterpillar 2006a).

Currently, most electric drilling rigs are the AC SCR type. The generators are usually 600-V AC rectified to 800-V DC for use with the variable speed DC motors. SCR drives require special oversized generators that allow for fluctuation in the power factor (PF), which is caused by the modulation of the DC motors. DC motors operating at low speeds cause a low PF where DC motors operating at high speeds cause a high PF. Generators used in an SCR application are typically oversized to a 0.6 or 0.7 PF and have a higher kV amperage (KVA) rating than should be required (Caterpillar 2006a).

Simply oversizing the generator to compensate for a variable PF is not enough. The generator needs to be mechanically reinforced to compensate for the increased forces exerted on the winding due to the SCR operation. SCR operation also increases heat generated in the winding, which needs to be compensated for. If the generators are improperly sized or not designed for use with an SCR, their use may result in circuit breaker tripping and short generator life (Caterpillar 2006b).

The newest technology in electric drilling rigs utilizes both AC generators and AC motors. This is accomplished through the use of VFDs. With an AC VFD rig, 600-V AC or 690-V AC is rectified to 800-V DC using front-end diode technology, which reduces voltage fluctuation caused by SCR systems. This DC is then made available to a VFD, which converts it back to AC and feeds it to variable speed AC motors. AC motor speed is controlled by the VFD, varying the frequency of the AC rather than varying voltage as on a DC motor (Caterpillar 2006a).

The use of the VFD greatly reduces the amount of stress on the generator associated with the SCR and results in increased generator life; however, PF fluctuation is still present, requiring the same special AC generators that are used on an SCR rig (Caterpillar 2006b).

Engine Types

While the RICEs described below exist in both two-stroke and four-stroke configurations, two-stroke engines are not used in large industrial applications, such as drilling, and are therefore outside the scope of this study. All RICEs discussed are four-stroke.

Diesel Engines

Diesel engines, or compression-ignited (CI) engines, are RICEs that use the heat of compressed air to ignite and burn fuel. They operate on what is known as the diesel cycle. Diesels are four-stroke engines that operate by drawing air into the combustion chamber and compressing it to high pressures. This compression causes the air temperature within the combustion chamber to rise above the ignition point for diesel fuel. Injectors introduce fuel to the air in a fine mist that distributes evenly throughout the combustion chamber. As the fuel vaporizes and burns, the rapidly expanding exhaust forces the piston down and delivers power to the crankshaft.

Because diesel fuel is introduced directly into the combustion chamber (and not into an intake manifold), it is very responsive to rapid changes in load. Also, the relatively slow burn rate of the atomized diesel fuel gives diesel engines flat torque curves that extend through most of the engine's range of rotations per minute (Busch et al. 1913).

Natural Gas Engines

NG engines are a type of SI RICE that runs specifically on NG. The NG engine operates according to the Otto Cycle, as do other SI RICEs that utilize similar fuel sources such as gasoline or alcohol. Unlike a diesel engine, air and fuel is premixed and delivered to the engine cylinder together via an intake manifold. The air/fuel mixture is then compressed by a piston, but because fuel is already present, the heat of compression cannot exceed the fuel's ignition point. A spark is introduced into the combustion chamber to ignite the fuel. As in all RICEs, the rapidly expanding exhaust forces the piston down and delivers power to the crankshaft.

Because the air and fuel are mixed upstream of the cylinder, a small amount of time is required for the fuel to reach the cylinder once a change in fuel delivery is required for a change in load. For this reason, an NG engine does not react as quickly to load changes as a diesel. Also, NG burns much more rapidly than diesel fuel; therefore, engine torque peaks at a narrow band high in the rpm range (Caterpillar 2010a).

Turbines

Turbines are internal combustion engines (ICEs) that use rotation rather than reciprocation to generate power. Gas turbines operate on the Brayton Cycle. A turbine consists of three main parts: the compressor, the combustor, and the turbine sections. Air is drawn into the inlet and compressed. Fuel is then continuously injected and burned in the combustor. The rapidly expanding exhaust gas is passed over blades in the turbine and converted to rotating power.

Turbines display performance properties specific to this type of engine. They possess a very high power-to-weight ratio, but do not respond as quickly to varying loads as a RICE. Turbines have the ability to run on various fuel types, and their performance characteristics change as a result. Typically, however, torque peaks at low rpm and drop off in a linear fashion with increasing rotational speed.

A turbine's main advantage in most applications is its light weight and portability. However, unless used in a combined cycle configuration, where the waste heat is used to make steam, they are typically not as efficient as a RICE. Turbine efficiency is also directly related to inlet air temperature (Solar Turbine 2009). As the ambient temperature rises, the efficiency falls sharply (Witherspoon 2011). This fall may make the use of turbines much more attractive in arctic conditions; however, they become much less desirable for use in the southern United States.

The emissions of a turbine are also difficult to control. They can produce higher levels of hazardous emissions than a RICE, and emission warranties are not typically offered (Witherspoon 2008). There are also currently no specific regulations pertaining to the emissions of a turbine in a nonroad application such as on a drilling rig. Only regulations for stationary sources are available, which may make permitting difficult. For these reasons, the use of turbines as a power source in drilling applications will not be further pursued in this thesis; however, it may warrant further research.

Performance Characteristics

Regardless of type, an engine must be properly sized to deliver the power required by the specific application. The load response characteristics of the engine must meet the load demands of the equipment being driven. In power generation applications, load acceptance, stability, and response are crucial to sustained operation. As generators are constant speed applications, torque rise and acceleration capabilities are not required. However, the ability of an engine to maintain constant rpm is vital to the proper operation of the generators and any associated electronics (Caterpillar 2006b).

When load is applied or removed from a genset operating at a steady-state condition, the speed of the engine is temporally changed. This change in speed has a knock-on effect on the voltage and frequency of the electricity being produced. The engine is forced to recover, or respond, to the change in load returning to a new steady-state condition. This response is known as transient response (Caterpillar 2006a).

When a significant load is applied to a genset, both the engine and generator speeds are reduced, causing a drop in both frequency and voltage. This drop is known as frequency and voltage dip. The opposite is true when a load is removed, causing what is known as frequency and voltage overshoot. An example of this dip and overshoot due to transient load is show in **Fig. 2**. The associated electrical equipment has a tolerance for accepting fluctuations; however, if the dip or overshoot is too great, it can result in damage to the equipment or cause it to trip offline (Caterpillar 2006a).

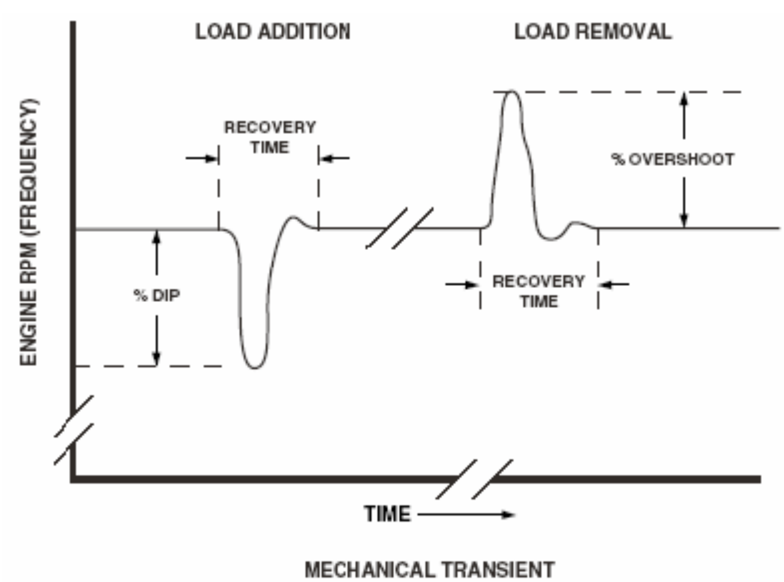

Fig. 2—Dip and overshoot due to transient loads (Caterpillar 2006a).

When selecting a motor to power a generator, three application-specific criteria must be addressed:

1) What is the acceptable percent of frequency and voltage dip?
2) How long can the dip last?
3) What are the load steps and how quickly are they applied?

The acceptable tolerances for the above criteria will be dependent on the application, and the suitable motor and generator must be able to react to transient loads effectively enough to stay within these set parameters (Caterpillar 2006b).

Common Applications

Both diesel and NG engines are commonplace in the petroleum industry; however, they are typically installed and operated in specific applications. Diesel engines are typically installed for drilling, well servicing, and emergency power applications. NG engines, on the other hand, are often utilized for gas compression drive, production power, and production pumping. The use of diesel versus NG is dependent on many factors, including the availability of the fuel source and the performance characteristics of the engine itself.

Before selecting an engine for a particular application, it is important to understand the specific demands and requirements imparted on these engines under each application.

Gas Compressors

Compressor plants compress low-pressure NG for field gas/liquid separation and transportation before being pumped down a pipeline to a processing facility. Depending on the distance between the wellhead and the refinery, there may be several compressor stations placed along a pipeline. The loads placed on the engines are relatively consistent, and NG can be directly extracted from the pipeline to fuel the engine. Both NG RICEs and gas turbines are readily used in this application.

Production Power and Pumping

Production facilities require electricity to run anything from electric motors to controls to appliances. If production facilities are required to produce their own electric power, then engine power is often utilized to drive electric generators. Often, this electric power is used to turn electric motors on mechanical pumps used throughout the production facility; however, direct drive pumps are also common. Similar to the compressors, the loads placed on the engines are relatively consistent. Because these are stationary applications, permanent NG lines can be installed to provide fuel; therefore, both NG RICEs and gas turbines are readily used in this application as well.

Service Rigs

Service rigs often use large engines to power equipment used in the underground maintenance or repair of a well. Typically, these engines are used to power pumping operations such as cementing, acidizing, or hydraulic fracturing. Workover and intervention with coiled tubing operations are other examples of well servicing operations. Service rigs are often truck-mounted portable units where a single engine may be used as primary source of mobility, as well as to power the well servicing equipment. A transmission is utilized to transfer power from the wheels to the various equipment mounted on the rig. Because of its mobile nature, diesel-fueled RICEs are common in this application.

Drilling Equipment

Electric drilling rigs are generally powered by skid-mounted generator packages utilizing engines to drive the generators. Typical generator package configurations consist of banks of two to four generator sets, each mounted on individual skids. These skids also house a radiator and controls and are almost exclusively diesel powered.

Regulation

Code of Federal Regulation

As is the case with nearly every industry, the oil and gas exploration and production (E&P) industry, including the drilling industry, is required to follow a specific set of rules set by government regulators. According to the National Archives and Records Administration, the Code of Federal Regulations (CFR) is the codification of these rules published in the Federal Register by the executive departments and agencies of the federal government. It is divided into 50 titles that cover the areas subject to federal regulation and is updated on an annual basis (National Archives and Records Administration 1999).

Each title is divided into numbered chapters (Chapters I, II, III…), which are further divided into numbered parts (Parts 1, 2, 3…). Many of these parts are further divided into alphabetically labeled subparts (Subparts A, B, C…) (National Archives and Records Administration 1999).

The section is the basic unit of the CFR. Sections are numbered beginning with the corresponding part number and separated by a period (Sections 1.1, 1.2, 1.3…). Please note that the sections are numbered low to high within each part, with independent grouping under each subpart. Each title, part, and subpart bears its own title, which describes the specific regulatory area covered. Each section is further divided using a descending level of units referred to as paragraphs, which are noted using a range of letters, numbers, roman numerals, and italics. Please see **Table 1** for an illustration of the CFR numbering system. As an example, CFR, Title 40, Part 89, Subpart A, Section 1, Paragraph B, Subsection 3, Sub-Subsection ii would be noted as 40 CFR 89.1(b)(3)(ii) (National Archives and Records Administration 1999).

TABLE 1— CFR NUMBERING SYSTEM

Name	Title	Chapter	Part	Subpart	Section	Paragraph
Designation	1-50	I - VII	1 - 1799	A, B, C, etc.	Part 1, 2, 3, etc.	See below

	Paragraph					
Name	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
Designation	(a), (b), (c), etc.	(1), (2), (3), etc.	(i), (ii), (iii), etc.	(A), (B), (C), etc.	(1), (2), (3), etc.	(i), (ii), (iii), etc.

Title 40. Title 40 (40 CFR) is the set of regulations created by the United States Environmental Protection Agency (EPA) to protect the environment. According to the organization's website, it is a department in the executive branch of government that has been delegated authority by the legislative branch (congress) to write and enforce regulations necessary to implement pertaining laws (EPA 2011a). The Clean Air Act is one such law. Passed by congress with its subsequent amendments and extensions, it authorizes the EPA to create national ambient air quality standards (NAAQs) "and to regulate emissions of hazardous air pollutants" (HAPs) (EPA 2011b).

Under 40 CFR are the performance and emissions standards regulating the various prime movers used in the gensets that are part of this study. RICEs are categorized in the CFR as CI engines or SI engines. For the purpose of this study, the only CI engines examined are diesel-fired engines, the only SI engines examined are

NG-fired engines, and all RICEs are considered to be nonroad engines. The final genset prime mover type to be discussed in this study is combustion turbines.

Definitions. For the purpose of this study, the following definitions apply:

- Nonroad engine means an internal combustion engine that, by itself or in or on a piece of equipment, is portable or transportable, meaning designed to be and capable of being carried or moved from one location to another. Indicia of transportability include, but are not limited to, wheels, skids, carrying handles, dolly, trailer, or platform.
- SI means relating to a gasoline-fueled engine or other engines with a spark plug (or other sparking device) and with operating characteristics significantly similar to the theoretical Otto combustion cycle. SI engines usually use a throttle to regulate intake air flow to control power during normal operation.
- CI means relating to a type of reciprocating, internal combustion engine that is not an SI engine, with operating characteristics that are significantly similar to the theoretical diesel cycle.

Title 40 specifies specific emissions criteria for engines by type and size. Drilling rigs vary in size; however, this study will focus on modern triples with high power ratings. These triples are very large pieces of equipment that require immense amounts of power to operate. Because of this, the gensets used are well above the highest power rating outlined in Title 40, greater than 560 kW. All emission values shown in **Tables 2 to 4** are not-to-exceed (NTE) standards.

Nonroad Compression-Ignited Engines (Diesel Engines)

Tiers 1 to 3. Emission regulations in Tiers 1 to 3 began in January 1996 with the first implementation. Beginning with Tier 1 regulations, the regulations introduced stringent emission requirements phased-in over time, with Tier 2 following Tier 1 and finally Tier 3, which came into full effect for all power categories in 2008. For the power rating category relating to drilling rig gensets greater than 560 kW, there is no Tier 3. Tier 2 is the most stringent standard and came into effect in 2006. Please see Table 2 for the Tiers 1 to 3 emissions standards (National Archives and Records Administration 2011).

TABLE 2—NONROAD CI RICE TIERS 1 TO 3 EMISSION STANDARDS (g/kW-hr)

Rated power (kW)	Tier	Model year	Oxides of nitrogen (NO_x)	Hyrdocarbon (HC)	Nonmethane hydrocarbon (NMHC) + NO_x	Carbon monoxide (CO)	Particulate matter (PM)
kW > 560	Tier 1	2000	9.2	1.3	-	11.4	0.54
	Tier 2	2006	-	-	6.4	3.5	0.2

Tier 4. The final piece of emissions regulation to be implemented is Tier 4. The Tier 4 legislation itself is phased-in over time in two steps: Tier 4 Interim and Tier 4 Final. Tier 4 creates an additional power category for engines greater than 900 kW and makes a distinction in between engines that are part of a genset and those that are not.

This distinction is in contrast to Tiers 1 to 3, which make no distinction. Tier 4 is significant because where Tiers 1 to 3 emission standards were achievable with improvements in engine design and control, meeting Tier 4 standards requires exhaust after-treatment, similar to today's modern on-road engines (National Archives and Records Administration 2011).

Tier 4 Interim takes the place of the nonexistent Tier 3 for the greater-than-560-kW category. Beginning in 2011, engines in this category must comply with the emissions criteria, shown in Table 3 (National Archives and Records Administration 2011).

TABLE 3—NONROAD CI RICE TIER 4 INTERIM EMISSION STANDARDS (g/kW-hr)

Model years	**Maximum engine power**	**Application**	**PM**	**NO_x**	**NMHC**	**CO**
2011 to 2014	560 < kW < 900	All	0.1	0.5	0.4	0.5
	kW > 900	Gensets	0.1	0.67	0.4	0.5
		All except gensets	0.1	0.5	0.4	0.5

Tier 4 Final is currently the most stringent emissions regulation in the United States for nonroad CI engines and is effective 1 January 2014. Please see Table 4 for the criteria (National Archives and Records Administration 2011).

TABLE 4 —NONROAD CI RICE TIER 4 EXHAUST EMISSION STANDARDS (g/kW-hr)					
Maximum engine power	**Application**	**PM**	**NO_x**	**NMHC**	**CO**
kW > 560	Gensets	0.03	0.67	0.19	0.5
	All except gensets	0.04	0.5	0.19	0.5

Manufacturer Flexibility Program. The Tier 4 Interim was written to allow manufacturers of large equipment, above 560 kW, to phase-in the Tier 4 Final performance standards in a similar way to manufacturers of smaller engines falling under Tier 3. The added cost associated with research and development (R&D) and testing, however, has led most the major engine manufacturers to skip Tier 4 Interim and work directly toward meeting Tier 4 Final in 2014. With previous greater-than-560-kW engines being only Tier 2–compliant and Tier 4 Interim effective in 2011, a void has been left. Tier 2 engines can no longer be manufactured and sold under Tier 4 Interim legislation, so sales of greater-than-560-kW engines will cease under Tier 4 Interim until the Tier 4 Final engines enter production nearer to 2014 (National Archives and Records Administration 2011).

The only exception to Tier 4 Interim is the Equipment Manufacturers Flexibility Program. This program is an exemption option intended to provide flexibility and relief in the Tier 4 Interim legislation to equipment manufacturers who purchase and install nonroad compression engines in the equipment they manufacture. For a timeframe exceeding Tier 4 Interim and extending into Tier 4 Final, equipment manufacturers will be able to purchase limited quantities of non-Tier 4 Interim engines from engine manufacturers. These quantities can either represent a percentage of total production or can fall under the small-volume allowance. The small-volume allowance is either 350 units, NTE 100 units per year, or 700 units, NTE 200 per year (National Archives and Records Administration 2011).

For most drilling rig manufacturers, the small-volume allowance for engines greater than 560 kW will equal 700 total units. See **Table 5** for timelines of the Equipment Manufacturers Flexibility Program by power category (National Archives and Records Administration 2011).

TABLE 5—MANUFACTURERS FLEXIBILITY PROGRAM GENERAL AVAILABILITY OF ALLOWANCES

Power category	Calendar year
kW > 560	2011 to 2017

Each engine manufactured, sold, and purchased under this program will need to be properly labeled, and the equipment manufacturer will need to notify the EPA of its intent to take part in the program. In addition to notifying the EPA, the equipment manufacturer must keep a record of the quantities of non-Tier 4 engines purchased and report to the EPA on an annual basis (National Archives and Records Administration 2011).

Nonroad Large Spark-Ignited Engines (Natural Gas Engines)

Emissions regulations for nonroad large SI engines came into effect 1 January 2004. Although different variations of these engines exist using different fuel sources, such as alcohol or ethanol, this type of engine typically refers to gasoline- or NG-driven engines. Gasoline- or alternative fuel–powered engines are out of the scope of this study and therefore, for the purpose of this thesis, all nonroad large SI engines will be NG engines (National Archives and Records Administration 2011).

Tier 1 standards for NG engines originally required steady-state testing only. Tier 1 steady-state testing exhaust emission standards are shown in **Table 6.** Tier 2 came into effect with the 2007 model year and currently requires further transient and field testing (National Archives and Records Administration 2011).

TABLE 6—NONROAD SI ICE TIER 1 EMISSION STANDARDS (g/kW-hr)

Testing	**HC + NO_x**	**CO**
Certification and production-line testing	4	50
In-use testing	5.4	50

Tier 2 emission standards for both steady-state and transient testing require the same numerical emission standards; however, the transient test is not required for engines greater than 560 kW. Tier 2 field testing requirements are determined using either the standard or alternative method referenced in **Table 7** (National Archives and Records Administration 2011).

Because NG is composed of primarily methane, NMHC emissions are virtually zero from NG engines. Furthermore, because NG burns nearly completely, total hydrocarbon (THC) emissions are very low as well. It is for this reason that, for NG engines, the HC component of the numerical formulas can be assumed to be zero. The Tier 2 emission standards are shown below in Table 7 (National Archives and Records Administration 2011).

TABLE 7—NONROAD SI ICE TIER 2 EMISSION STANDARDS (g/kW-hr)

Testing	**General emission standards**		**Alternate emission standards**		
	$HC + NO_x$	CO	$(HC + NO_x) \times (0.791)$ CO	$HC + NO_x$	CO
Steady-state / Transient testing	2.7	4.4	Not applicable	Not applicable	Not applicable
Field testing	3.8	6.5	16.78	3.8	31

In addition to the emission standards described above, a provision exists for exempting large NG engines. In order to qualify for this exemption, the engine must operate solely on NG and have an engine power at or above 250 kW. Additionally, the engine must be part of an engine family that complies with Tiers 1 to 4 for diesel engines as previously described. If these criteria are met, the engine may be exempted from the NG requirements and may be certified under Tiers 1 to 4 standards. This could be an advantage if the NG engine is able to meet the Tiers 1 to 4 diesel requirements (National Archives and Records Administration 2011).

Many major manufacturers are not compliant with the Tier 4 Interim standards currently in effect and have instead chosen to direct their efforts toward Tier 4 Final compliance. Consequently, this had led to these manufacturers currently offering noncompliant large diesel engines under the Manufacturers Flexibility Program. Therefore, the current offering of non-Tier-4-compliant engine families fails the criteria for the NG engine exemption and will continue to do so until the Tier 4 Final–compliant engines are offered in the future (National Archives and Records Administration 2011).

Stationary Spark-Ignited Internal Combustion Engines

Stationary SI ICEs can be physically similar or identical engines to the nonroad large SI engines previously discussed. The primary difference is in the application rather than the design. Stationary engines are located at a stationary source for more than 1 year, and in the NG configuration, are much more common than nonroad large SI engines. Certifying an engine or engine family is a time-consuming and costly endeavor. With a currently low return on investment, engine manufacturers have not committed the resources for certifying their products to the nonroad SI engine standard for NG engines (National Archives and Records Administration 2011).

This has resulted in confusion in the industry as how to correctly procure and apply nonroad large SI engines. One possible solution may to be to apply for an exception from the local governing agency and use an engine certified for stationary use in a mobile nonroad application. This could prove to be a relatively straightforward process because many of the NG engines described in the stationary SI ICE standards refer back to the nonroad large SI engine standard (National Archives and Records Administration 2011).

The stationary SI ICE standard makes a distinction between rich-burn and lean-burn engines. Engines over 19 kW ordered after 12 June 2006 in a rich-burn NG configuration must comply with the nonroad large SI standard. Lean-burn NG engines over 75 kW ordered between12 June 2006 and 1 January 2011 have the option of complying with the nonroad large SI standard or the limits shown in **Table 8.** Engines ordered after 1 January 1 2011 in lean-burn configuration must comply with the limits in Table 8 (National Archives and Records Administration 2011).

The stationary SI RICE standard is also the only NG engine standard that directly addresses the use of wellhead gas to power an NG engine. It states that on a case-by-case basis, an operator of an SI RICE using wellhead gas as a power source can apply for approval to meet emission standards that deviate from the rest of the SI RICE standard, provided the emissions do not exceed the emission standards for emergency SI RICEs greater than 19 kW and less than 100 kW presented in Table 8 (National Archives and Records Administration 2011).

TABLE 8—STATIONARY SI ICE EMISSION STANDARDS

Engine type and fuel	Maximum engine power	Manufacture date	Emission standards [a]					
			g/HP-hr			ppmvd at 15% O_2		
			NO_X	CO	VOC [d]	NO_X	CO	VOC [d]
Non-Emergency SI Natural Gas [b] and Non-Emergency SI Lean Burn LPG [b].	100≤HP<500	7/1/2008	2.0	4.0	1.0	160	540	86
		1/1/2011	1.0	2.0	0.7	82	270	60
Non-Emergency SI Lean Burn Natural Gas and LPG.	500≥HP<1,350	1/1/2008	2.0	4.0	1.0	160	540	86
		7/1/2010	1.0	2.0	0.7	82	270	60
Non-Emergency SI Natural Gas and Non-Emergency SI Lean Burn LPG (except lean burn 500=≥HP<1,350).	HP≥500	7/1/2007	2.0	4.0	1.0	160	540	86
	HP≥500	7/1/2010	1.0	2.0	0.7	82	270	60
Landfill/Digester Gas (except lean burn 500≥HP<1,350).	HP<500	7/1/2008	3.0	5.0	1.0	220	610	80
		1/1/2011	2.0	5.0	1.0	150	610	80
	HP≥500	7/1/2007	3.0	5.0	1.0	220	610	80
		7/1/2010	2.0	5.0	1.0	150	610	80
Landfill/Digester Gas Lean Burn	500≥HP<1,350	1/1/2008	3.0	5.0	1.0	220	610	80
		7/1/2010	2.0	5.0	1.0	150	610	80
Emergency	25>HP<130	1/1/2009	[c] 10	387	N/A	N/A	N/A	N/A
	HP≥130		2.0	4.0	1.0	160	540	86

This chapter has presented how both diesel and NG are regularly applied in the oil and gas industry alongside the requirements of a land-based drilling rig. The following chapters will discuss each fuel type further and how they may be applied to a drilling application. However, it must be noted that, not only the physical challenges must be overcome, but all working solutions must be engineered to fit within the framework of the pertinent legislation.

CHAPTER III

DIESEL ENGINES

Diesel has been the main source of fuel in the land-based drilling industry since the inception of modern machinery. It has been a dependable and affordable fuel supply that can be easily stored and transported. Combined with the reliable and proven diesel engine performance, it has remained the primary source of power for drilling rigs, from the mechanically driven rigs of the past to today's modern electric drilling rigs. Diesel engines were chosen as the baseline comparison of this study because they are the most commonly used and are the power source for the drilling rig selected for this thesis (Hill et al. 2011).

Diesel engines, or CI engines, are RICEs that use the heat of compressed air to ignite and burn fuel. They operate on what is known as the diesel cycle. Diesels are four-stroke engines that operate by drawing air into the combustion chamber and compressing it to high pressures. This compression causes the air temperature within the combustion chamber to rise above the ignition point for diesel fuel. Injectors introduce fuel to the air in a fine mist that distributes evenly throughout the combustion chamber. As the fuel vaporizes and burns, the rapidly expanding exhaust forces the piston down and delivers power to the crankshaft (Busch et al. 1913).

Diesel engines' high compression ratios cause them to have the highest thermal efficiency of all the RICEs. Where most SI RICEs are only efficient to a maximum of approximately 30 to 40%, diesel engines can reach efficiencies exceeding 50% in some cases (Busch et al. 1913; Takaishi et al. 2008; United States Department of Energy 2003).

Because diesel fuel is introduced directly into the combustion chamber (and not into an intake manifold), it is very responsive to rapid changes in load. Also, the relatively slow burn rate of the atomized diesel fuel gives diesel engines flat torque curves that extend through most of the engines' rpm range. It is these characteristics that allow diesel engines to effectively handle large transient loads (Busch et al. 1913).

Because of the high torque produced by diesel engines, the components must be built to withstand heavy loads. While this results in making a diesel engine very robust, it also makes them heavy. This can be a detractor where weight is a factor.

A major concern when burning diesel is its inherently dirty emissions. For example, diesel engines produce large quantities of HAPs, volatile organic compounds, and other air pollutants that are a threat to public health and contribute to the formation of ozone. They also produce large quantities of particulate matter, which is a lung irritant, and burning diesel fuel containing sulfur produces sulfuric acid, which can contribute to acid rain.

To establish a baseline for this study, two approaches are used for analyzing data: one looks at rig fuel consumption and efficiency, which will later be used to perform an economic analysis, and the other looks at transient load response, an important factor for smooth and consistent operations under various load conditions. Because of its importance, rig operations that incur high transient loads are identified and further discussed.

Methodology

Rig Fuel Consumption and Efficiency

Data. Data were collected from a modern VFD rig drilling a horizontal well in a Haynesville Shale play. The rig was equipped with three gensets; however, no more than two generators at a time were used to drill this well over the course of 27 days.

Using the rig's data collection and management system, data were acquired showing each gensets performance. These data consisted of the rig's fuel usage in gal/hour and corresponding percent load. The percent load is a percentage of the maximum load that can be applied to a genset or the maximum output the genset can achieve. The system acquired data every 10 seconds for the drilling of the well. Some data disruptions were observed, and these data are omitted.

The data were sorted by percent load in 1% increments, and the time spent at each percent load was summed to show the amount of time in hours each generator spent at that particular load. Percent load on the generator and the corresponding fuel usage rate in gal/hour were collected for each of the three gensets in 10-second increments.

Procedure and Results

Although three gensets were available, no more than two were required at any one time during the drilling operation; consequently, the top third of the rig capacity was never utilized. This is normal, however, because while this capacity is available, the primary function of the third genset is for redundancy and backup rather than for regular use.

Normal operation calls for the rig running on one genset until the load reaches, or is expected to reach, a load that exceeds the generator's capacity. When this occurs, a second genset is required and will be brought online with the first. Once synchronized, they will operate together and share the load approximately equally. This operation is left to the driller's discretion.

In order to compare between engine types, the operational parameters that the drilling rig works under must be understood. The fuel consumption change with respect to change in load was determined, as well as the effects of operating in island versus tandem mode. It is also important to understand under what load conditions the engines operate and for what length of time. Once these parameters were known, the fuel consumption rate per percent load point and rig efficiency was determined.

Generator operation was separated by island mode and tandem mode. The time spent in hours at each percent load point was determined for both modes by summing the time spent at each percent load point. This data were then used to plot **Fig. 3.**

Fig. 3 shows the amount of time in hours that each generator ran at each percent load. The data shows that throughout the drilling of this well, the rig ran 25% of the time on one genset and 75% of the time on two. The figure is segmented into when the genset was operating in island mode and when it was working in conjunction with another genset. When operating in island mode, the genset spent the greatest amount of time at approximately 35 to 45% with a less significant amount of time spent around 80 to 90%, where, when operating in tandem, the greatest amount of time was spent between 30 to 40% and another significant amount of time spent around 50 to 60%.

None of the gensets spent time operating below 24%. This represents the maximum turndown due to engine idle. Operationally, the time spent at 35 to 45% represents the load demand just off idle. This is mostly standby power used to maintain controls, lights, air conditioning, and other support systems when the rig is not actively engaged in drilling operations. Some examples of these operations are when rigging-up or -down rig components, testing, repair, cementing, nippling-up or -down blow out preventers (BOPs), and conditioning mud.

The second major range of time spent on one generator is in the 80 to 90% range. It is at this point where the second generator is brought online, and as the total load continues to grow, the two generators now share the load equally. The load imposed on each generator is approximately half of what was imposed on the single generator. This transitions into the range shown for two generators between 30 to 40%. The final range between 50 to 60% on two generators shows the majority of the time spent by the generators on the rig.

It is beyond the scope of this study to attempt to identify the operations performed that contribute to each of the load ranges identified. These could be attributed to one operation or a combination of several that overlap, leading to these ranges of heavy use. The purpose of the creation of these figures is simply to identify at what load and for how long each engine is operating.

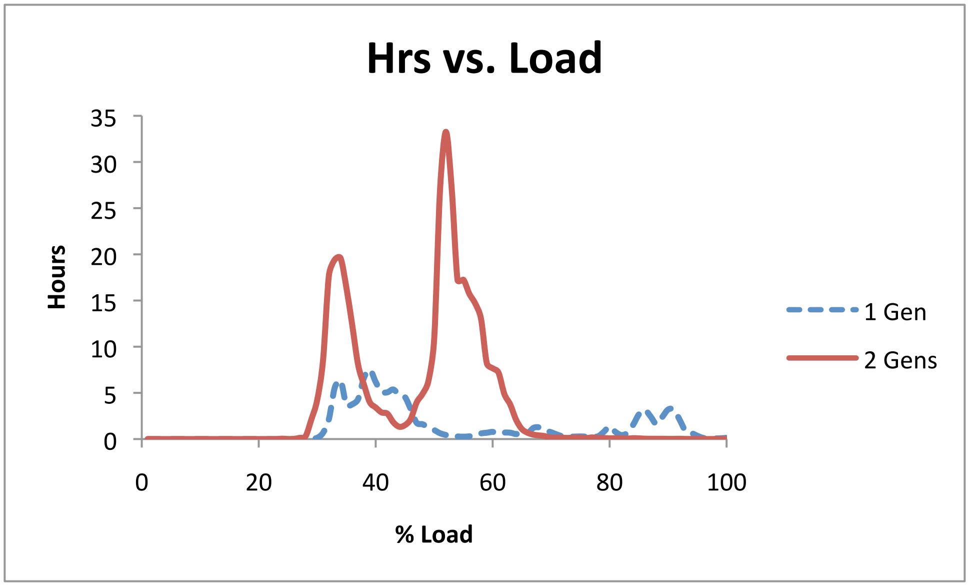

Fig. 3—Hours versus load for gensets in island and tandem mode.

Giving double weight to the tandem mode by multiplying it by two and adding it to the island mode hours, a total hours for all the generators at a given percent load point was determined and used to create **Fig. 4.** This figure is simply an addition to Fig. 3 and shows the total amount of time each generator operates for each percent load, regardless of whether it is operating in island mode or in tandem. This reveals two bands of heavy operation similar to Fig. 3. The majority of the generator's time was spent between 30 to 65% load with major subgroups within that time span, plus or minus 35 and 55% load. Using these data, a clear picture can be formed to show how the generators are used in drilling this well.

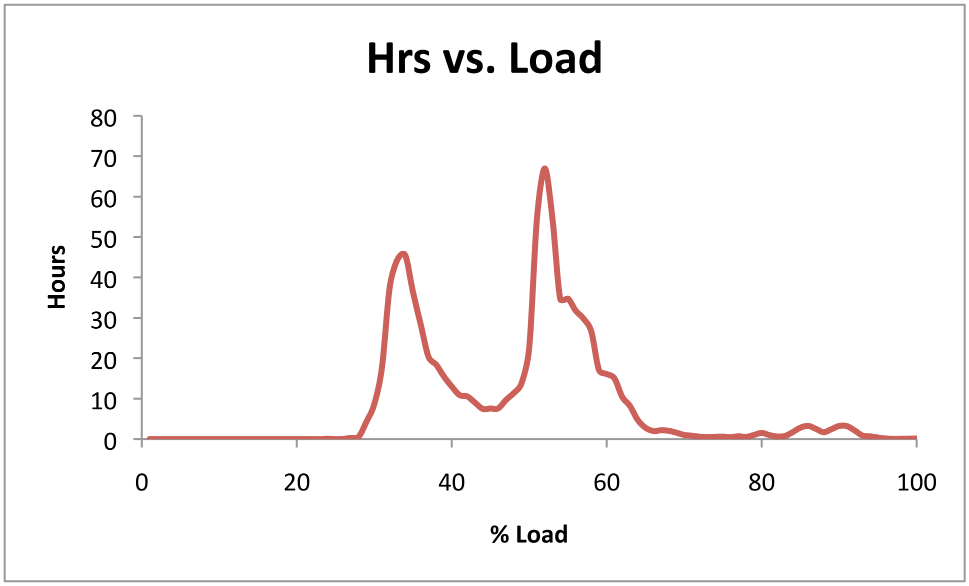

Fig. 4—Hours versus load for gensets.

Because of internal friction, a RICE operating at a given load is generally more efficient than two engines operating at half that load; however, the partial load fuel efficiency (mass burned per energy produced) of a diesel engine is a nearly linear relationship and remains almost constant.

Other types of SI RICEs do not exhibit a constant partial load efficiency, and for this reason, it is important to understand under what loading conditions the gensets operated when drilling this well.

A plot of the fuel usage versus percent load when running one and two generators is shown in **Fig. 5.** This figure shows a nearly linear relationship between the engine load and the fuel usage. This further reinforces the diesel performance characteristics previously discussed: that the operating efficiency of a diesel engine remains relatively consistent throughout the operating range. It also shows that two generators running together exhibit nearly the same performance characteristics as one running in island mode.

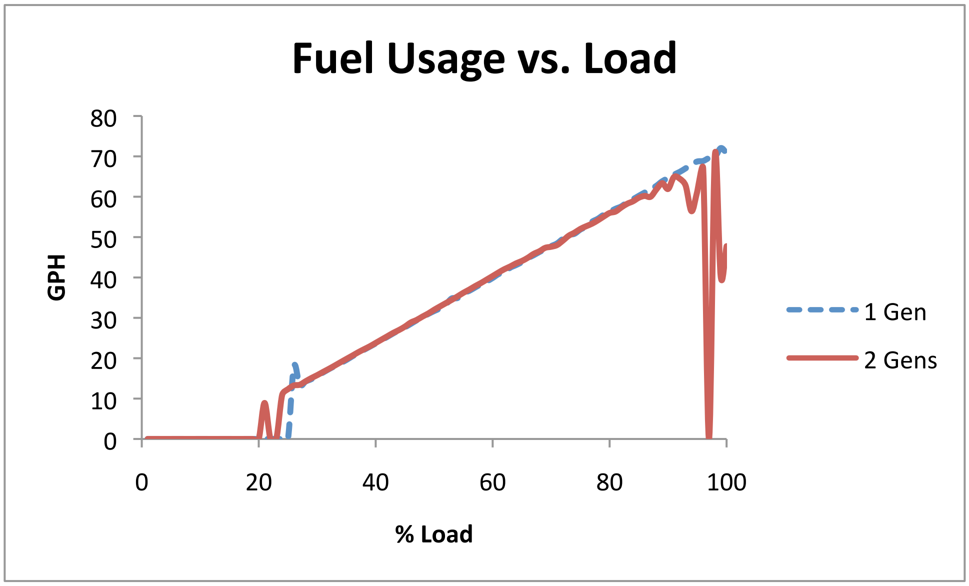

Fig. 5—Fuel usage versus load for diesel gensets in island and tandem mode.

Fig. 5 does show a slight increase in fuel consumption per unit output as the load increases. To determine the rig's efficiency curve, the rig's total average fuel usage at each percent load point was divided by the corresponding percent load point to yield the data displayed in **Fig. 6.** Fig. 6 suggests that running two generators at a lower load is more efficient that running one at a higher load. Where this may be identified as a way to increase fuel efficiency, the additional wear and tear on the second engine, resulting in additional maintenance costs, may offset any observed savings in fuel.

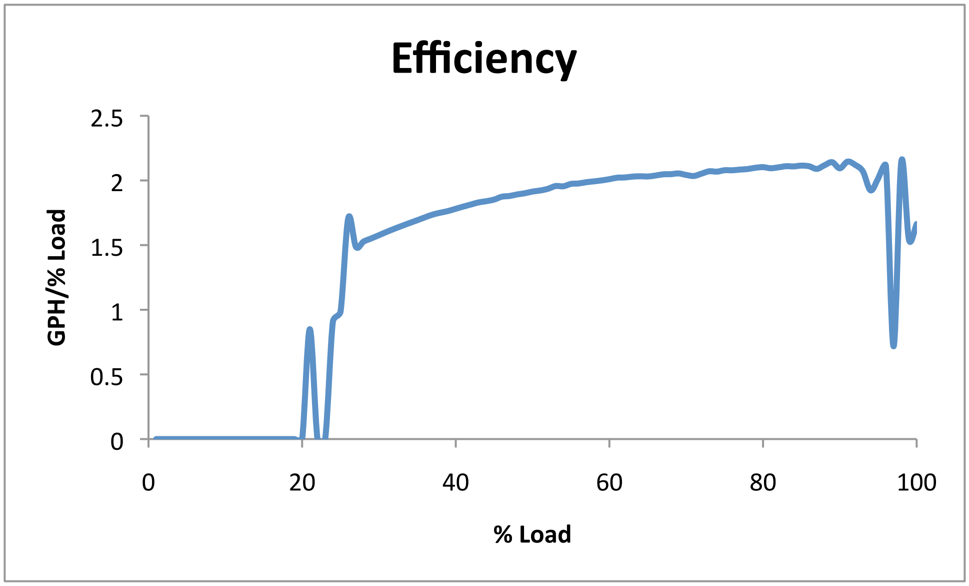

Fig. 6—Diesel engine efficiency.

Transient Response

Procedure

In order to identify critical operations regarding transient response, the raw data for percent load versus time are investigated for repetitively high transient loads. A graphical representation of the load versus time was obtained for the entire well and examined for periods of high load. Whenever these were found, the date and time were noted. By cross-referencing the graph with the daily tower sheets over the same time interval, four critical operations were identified: drilling, circulating, tripping, and reaming. These operations are shown as a percent of rig time for the well in **Fig.7.** Within these operations, periods of rapid change were identified and are analyzed for transient loads.

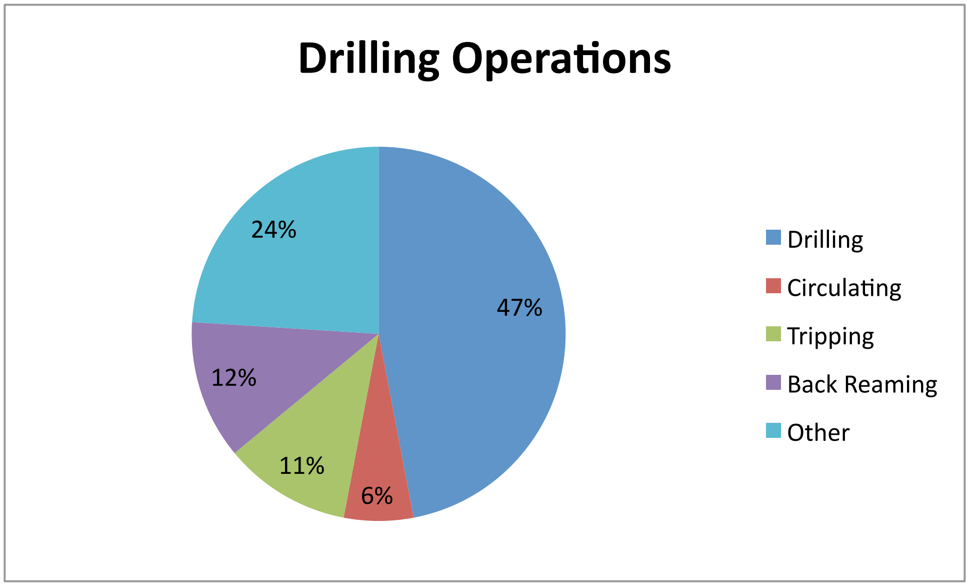

Fig. 7—Drilling operations.

Drilling

Approximately 47% of the rig time for this well was spent drilling. This well was drilled using a mud motor imposing differential pressure that consumes pump hp. Consequently, in order to build and maintain well trajectory, time spent drilling was split between alternating periods of rotating and sliding. Both of these operations rely heavily on the mud pumps, where only the rotating periods require constant use of the top drive. Little load change was observed when switching between these periods, which suggests that the majority of the increased load above the baseline during drilling operations is because of power demand from the mud pumps. An example of the drilling operation load profile is shown in **Fig. 8.**

The mud pumps operate consistently and load increases slightly with depth as a primary result of increased internal drillpipe friction and equivalent circulating density

(ECD) as the drillstring lengthens. The figure shows intermittent breaks in the constant load approximately every 90 ft (one stand) to make a connection. This operation required stopping the mud pumps, which drops the load demand; however, it also requires the draw-works, which creates a momentary spike in demand. Negating the connections, drilling creates a constant load with little variation and low transient load. In this example, the load averages approximately 86% load, but only varies by approximately 7%.

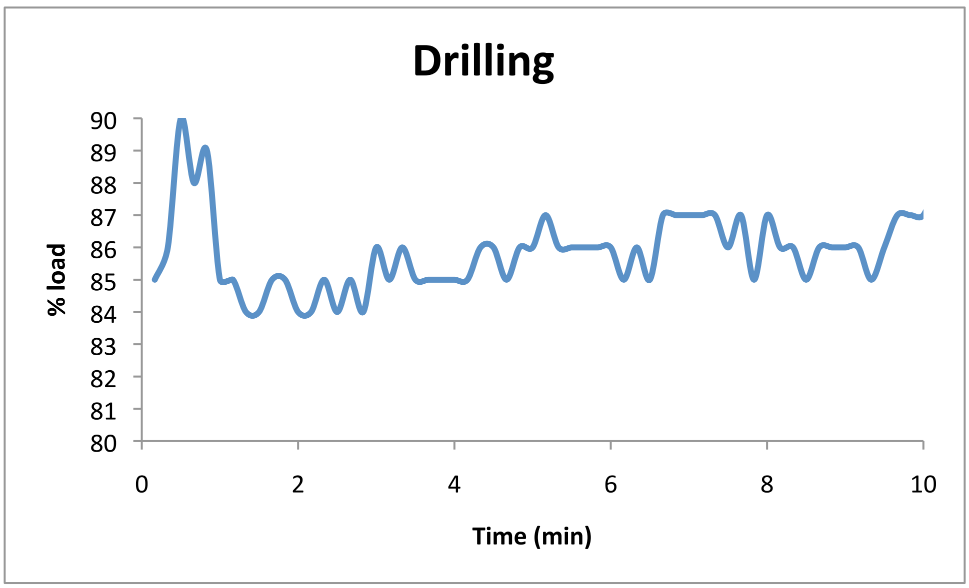

Fig. 8—Drilling load profile.

Circulating

Approximately 6% of the rig time for this well was spent circulating, and an example load profile is shown in **Fig. 9.** This operation shows an operation similar to drilling as it is almost exclusively dependent on the mud pumps; however, the overall load is slightly lower in the absence of weight on bit, causing the differential pressure across the mud motor to be reduced. Also, because the drillstring is stationary, there are no connections to make, which eliminates the sporadic troughs and spikes shown in the drilling charts. This operation shows the most consistent load with lowest transient loading of the four targeted operations. In this case, the load averages approximately 65% load, but only varies by approximately 2% load.

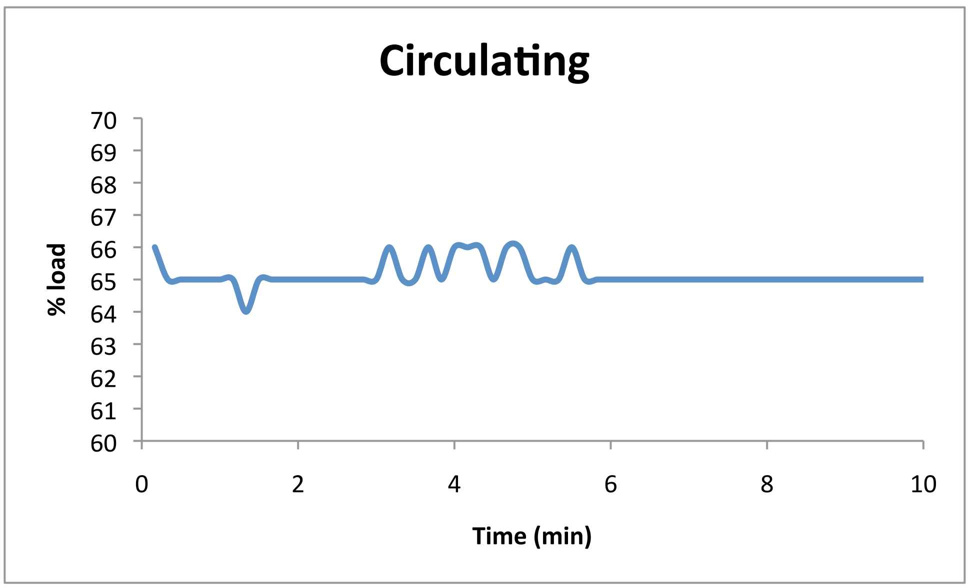

Fig. 9—Circulating load profile.

Tripping

Approximately 11% of the rig time on this well was spent tripping, an example load profile of which is shown in **Fig.10.** A tripping operation requires extensive use of the draw-works, and as it is considered nonproductive rig time, a tripping operation is generally done as quickly as the rig and well conditions will allow. As can be seen by the figure, tripping involves very high and rapid increase in load when the drillstring is being hoisted, followed by an equally rapid decrease when the load is set on the slips and the block is lowered to retrieve another stand. These operations call for the engines to respond to high transient loads created from load fluctuations varying from approximately 30% load to 80% load in less than 20 seconds.

These trip times of approximately 25 stands per hour (or one stand every 2.5 minutes) are not uncommon and create a repetitive and cyclical loading and high transient load. When tripping in, intermittent discontinuities are seen every 25 stands where the tripping operation is paused and the mud pumps are brought online to fill the pipe for well control reasons to maintain bottomhole pressure.

It is important to note that tripping can be in or out of the hole. Tripping out creates the highest load because it requires the draw-works to lift the drillstring, overcoming both weight and drag. Tripping in creates the same cyclic profile with high transient loads; however, the loads are less because of running the blocks up nearly empty and slacking off weight to run the pipe into the hole.

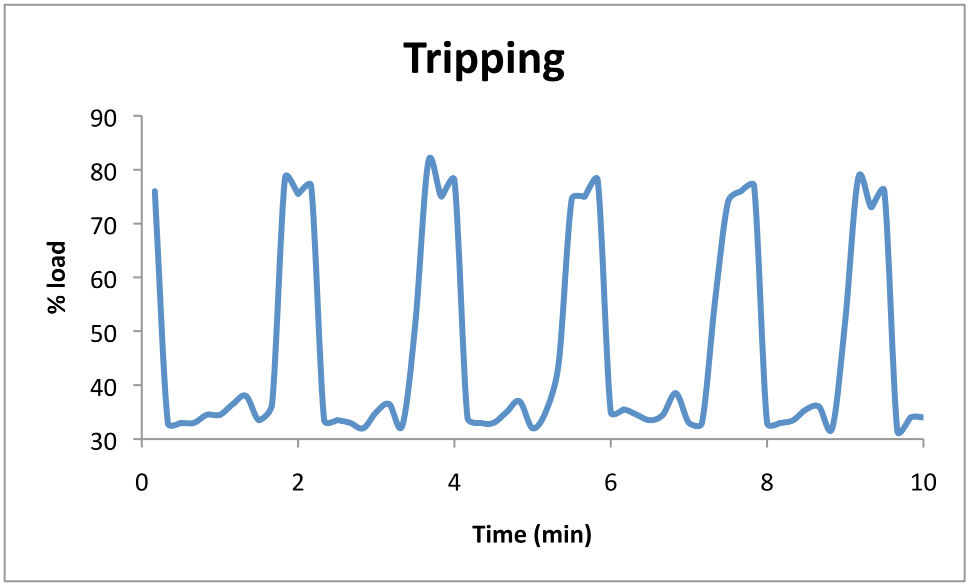

Fig. 10—Tripping load profile.

Back-Reaming

Approximately 12% of the rig time on this well was spent reaming. An example load profile of this operation is shown in **Fig. 11.** Reaming down is a process that very closely resembles drilling, but with slightly lower loads due to reduced differential on the mud motor caused by low weight on bit. Back-reaming, however, incorporates the both the draw-works and mud pumps, creating high sustained loads. The loads are cyclic, as both the pumps must be stopped and the block lowered to make a connection. The transient loading is high, ranging from approximately 35% load to 70% load, but this 35% increase occurs over the course of several minutes and the frequency of connections are not rapid like during tripping operations, taking approximately 8 minutes to complete a cycle.

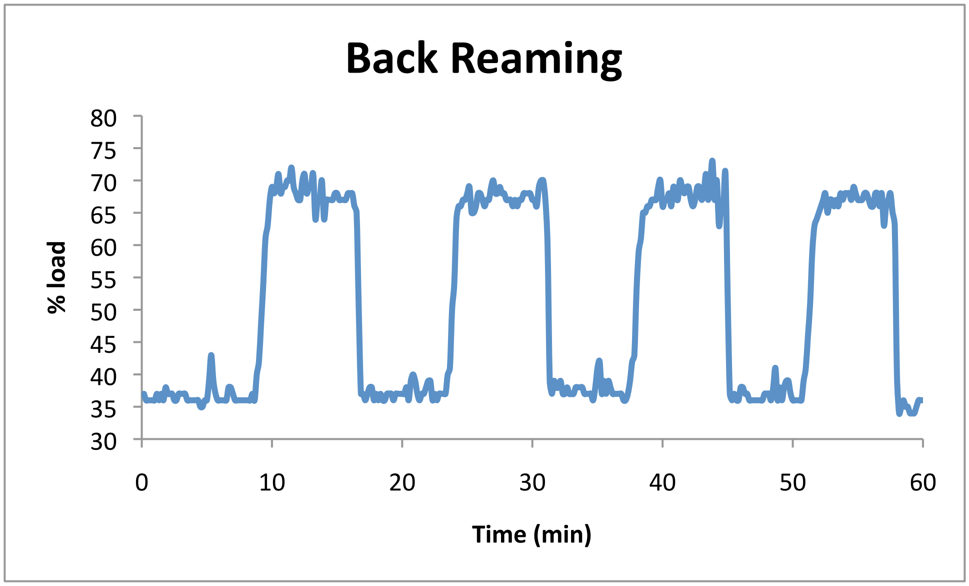

Fig. 11—Back-reaming load profile.

Other Operations

The other rig operations not identified as critical consist of other operations such as nippling-up or -down BOPs, waiting on cement, rig repair, rig maintenance, cut and slip drill line, and other rig operations that are not directly related to drilling. These are all lumped together as other operations and are generally low-power operations where a single genset is run at or near idle.

Discussion

Diesel has been the primary source of fuel for drilling rigs for years. Because of its prominent stance in the industry, it was chosen to be the baseline of this study. A well drilled by a diesel-powered modern VFD land-based drilling rig was selected and analyzed. The engine fuel usage and loading during the drilling of this well was determined, and critical operations were identified.

Based on the results, diesel engine fuel usage is nearly directly proportional to its percent load, with the fuel efficiency dropping off slightly as the percent load increases. The drilling rig operates with two generators the majority of the time at loads below half capacity. This does increase fuel efficiency; however, it is primarily a result of rig power requirements. The highest power requirements and transient loads were found to be primarily a result of four basic rig operations: drilling, tripping, circulating, and back-reaming. It will be these four operations that are of major importance when performing an engine comparison. Similar characteristics are analyzed for NG engines in the following chapter.

CHAPTER IV

NATURAL GAS SOLUTIONS

As previously discussed, the use of NG as a fuel in the oil and gas industry is not new; however, the application of using it as a fuel source for drilling applications can be seen as an emerging technology. NG is an abundant, economical, clean, and environmentally friendlier alternative fuel, and it is the cleanest of all the HC fuels. It burns cleaner than diesel, reducing emissions of harmful air pollutants. NG is also an abundant domestic energy source. Because it can be produced in vast quantities within the United States, utilizing it can help reduce dependence on foreign sources of energy (Hill et al. 2011).

Current market conditions have driven up the cost of diesel; however, at the same time, NG prices have dropped substantially. The current market price for diesel is at approximately 2.60 USD/gal, and NG is currently at around 4.50 USD/MMcf. Because diesel is a liquid and NG exists as a gas at standard conditions, it can be difficult to compare the quantities of the two directly. This is overcome by normalizing the units on a per-Btu basis. Assuming that 1 scf of NG contains approximately 1,000 Btu and 1 gal of #2 diesel contains 129,500 Btu, these units can be normalized on a per-Btu basis. Both of these fuels are commodities and their prices change daily; however, currently, on a per-Btu basis, #2 diesel costs approximately 21.1 USD/MMBtu and NG costs approximately 4.50 USD/MMBtu. Another useful unit that helps relate these two fuels is to refer to NG on a gal/US of diesel equivalent. This is that amount of NG that would contain the same amount of energy in 1 gal of diesel. Normalizing these prices on a gal/US of diesel equivalent brings the cost of NG to 0.59 USD/gal of diesel equivalent. However it is presented, NG is currently less than 25% the cost of diesel fuel (United States Department of Energy 2003).

Emissions from Natural Gas Engines

As outlined in the previous sections, the EPA has set out through regulation to reduce the amount of harmful matter being emitted by nonroad engines in the United States. NOx, CO, unburned HC, and PM are of primary concern. NG by default is a cleaner burning fuel source than diesel, and the emissions from the engines that burn it will be discussed here.

In an ideal world, the combustion of NG follows the following formula:

$CH_4 + 2O_2 + 7.5N_2 = 2H_2O + CO_2 + 7.52N_2$,

where CH_4 is methane, O_2 is oxygen, H_2O is water vapor, CO_2 is carbon dioxide, and N_2 is nitrogen. This is referred to as stoichiometric combustion; however, this ideal combustion is never the case in reality. Many factors come into play to cause deviation from this ideal case. The previous equation is for pure methane, which even in pipeline-quality gas, is accompanied by other gases such as ethane, propane, and butane. Consequently, the formula differs, becomes more complex, and produces different and undesirable products, the quantities of which vary greatly depending on operating conditions, such as combustion temperature, air/fuel ratio, engine load, and engine design (Caterpillar 2007).

If a pure methane fuel source could be obtained and ideal stoichiometric combustion could be carried out in an internal combustion engine, the only byproducts of combustion would be water vapor and carbon dioxide (Caterpillar 2007).

Products of Combustion

Water is a harmless, naturally occurring, nonpolluting byproduct in exhaust and not an environmental concern. Carbon dioxide is inert and is a major natural component of our atmosphere. It is used by plant life in photosynthesis to generate atmospheric oxygen. While it is not considered a hazardous substance such as an irritant or carcinogen, carbon dioxide's possible tie to global warming has legislators working to limit its emissions. Coincidently, NG as a fuel source produces the lowest quantity of carbon dioxide per unit of energy of all the HC fuels (Caterpillar 2007).

Nitrogen is also a naturally occurring component of the atmosphere. As shown in the aforementioned ideal combustion formula, under ideal combustion conditions, it passes directly through the combustion process unchanged. In its natural form it is an inert gas and has no adverse effects to warrant its regulation; however, when exposed to high exhaust temperatures, it will combine with oxygen to form various oxides of nitrogen. Nitrogen oxide is a general term primarily referring to nitric oxide (NO) and nitrogen dioxide (NO_2). Nitrogen oxide is a known lung irritant and contributes to the formation of ozone (O_3) (Caterpillar 2007).

Anytime combustion is not considered ideal, particles other than water and carbon dioxide will form during the combustion process, many of which are harmful to public health and the environment.

Carbon monoxide can form when there is not enough oxygen present to sustain complete combustion and, as a consequence, incomplete combustion results. This normally results when the air/fuel mixture is too rich or when it is so lean as to not allow for complete combustion. Combustion chamber design can also contribute to the formation of carbon monoxide. Carbon monoxide is a health risk to humans, and inhaling it reduces the blood's ability to deliver oxygen to the body (Caterpillar 2007).

When incomplete combustion occurs, unburned HCs pass through the combustion chamber and enter the exhaust stream. The type of HC exhausted depends on the type and composition of fuel being burned, and their reactivity varies greatly by type. While some unburned HCs are nearly inert, others are highly volatile, and when combined with nitrogen oxide and ultraviolet light form ozone and smog. Unburned HCs are generally grouped into two categories: THC and NMHC. THCs comprise all NG component gases, as well as any other higher chain HCs. NMHC comprise all THCs with the exception of methane. NMHCs are often referred to as volatile organic compounds (VOCs) and are more reactive then methane, which is highly unreactive. Because NG is composed of primarily of methane, an NG engine's THC emissions are nearly equal to its NMHC emission levels. While methane's nonvolatile nature limits its ability to form smog, similar to carbon dioxide, it is considered a greenhouse gas and its allowable emission levels are controlled (Caterpillar 2007).

HAPs are specific products of combustion that have been identified by the EPA as having specific properties hazardous to human health. The type of HAP emitted is dependent on the fuel type being burned, but of all the possible HAP emitted from an engine, the majority consists of four aldehydes: formaldehyde, acrolein, methanol, and acetaldhyde. Aldehydes are the product of incomplete combustion, and formaldehyde is the most common. Aldehydes are often irritants, carcinogens, and/or corrosives (Caterpillar 2007).

PM is tiny solid particles of matter suspended in the exhaust stream. It often refers to soot or elemental carbon, but can also be composed of other products of combustion such as sulfur dioxide (SO_2). Although other classifications exist, the classification of primary concern with emissions is PM_{10}, less than 10 μm in diameter. PM is a respiratory irritant and carcinogen (Caterpillar 2007).

Sulfur dioxide will be emitted in the exhaust stream when there is sulfur in the fuel. Sulfur is a naturally occurring element produced with HCs; however, it is nearly completely removed in the refining process. Modern fuels and engine oils will only have trace levels of sulfur present to form sulfur dioxide in the combustion chamber. Sulfur dioxide contributes to the formation or sulfuric acid in the atmosphere and, consequently, acid rain (Caterpillar 2007).

Engine Types

NG RICEs can be either rich-burn or lean-burn, depending on which combustion model they are designed to follow.

Rich-burn engines are designed to achieve stoichiometric combustion by using the exact amount of air required to react with all the fuel. The goal is that after combustion, there should be no oxygen or fuel left over in the exhaust. The results are high combustion temperatures and corresponding high nitrogen oxide levels in the exhaust. These same high combustion temperatures also drive down the levels of carbon monoxide and HC in the exhaust. In general, nitrogen oxide levels are inversely proportional to carbon monoxide and HC levels, as shown in **Fig. 12.** High levels of nitrogen oxide can be counteracted by some form of exhaust after treatment. Rich-burn engines are limited in power because of the high exhaust temperatures and are less efficient than lean-burn engines (Caterpillar 2007).

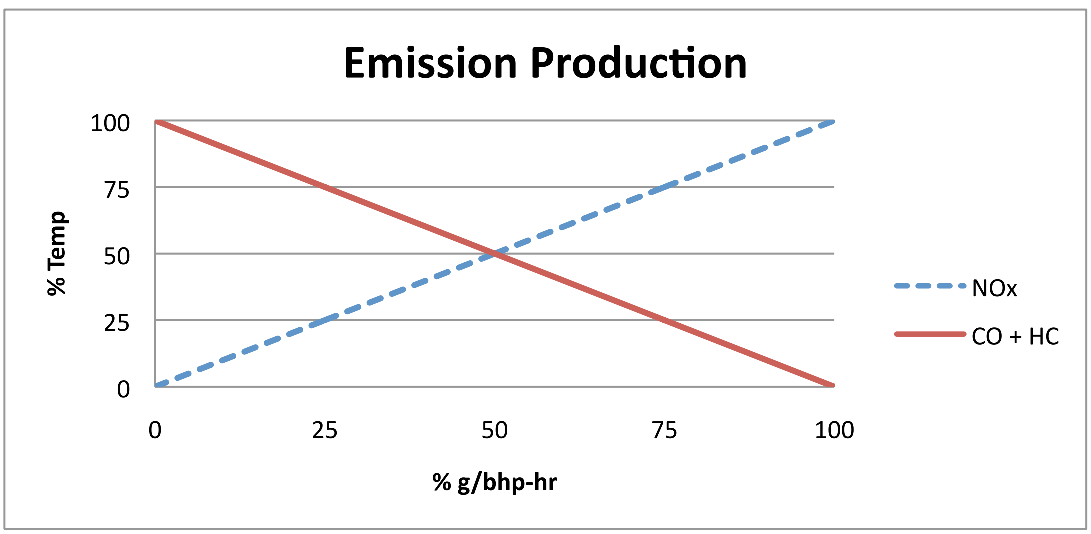

Fig. 12—NG engine emission production.

Lean-burn engines operate with large amounts of excess air drawn into the combustion chamber. The quantity of air varies, but can be as much as two times the quantity required to achieve stoichiometric combustion. This excess air absorbs heat and lowers the combustion temperature and pressure. This reduction in temperature and pressure lowers the levels of nitrogen oxide in the combustion stream, but also raises carbon monoxide and HC levels because they are inversely related. The introduction of inert exhaust gas into the combustion chamber through the use of an exhaust gas recirculation (EGR) valve absorbs heat in the combustion process and lowers nitrogen oxide levels, as does retarding the ignition timing. Lean-burn engines are generally more efficient than their rich-burn counterparts. The lower combustion temperatures raise the specific heat ratio, which increases expansion work and therefore efficiency (Caterpillar 2007).

Lean-burn engines come in two different varieties: open-chamber and enriched-prechamber. Open-chamber engines ignite the fuel/air mixture with a spark plug located directly in the combustion chamber. The use of a spark limits how lean the fuel/air mixture can be by increasing the chance of predetonation or misfire as the mixture is leaned out. Enriched-prechamber engines use a small secondary chamber that is ignited at near-stoichiometric conditions as a high-energy ignition source used to ignite even leaner mixtures (Caterpillar 2007).

Natural Gas Engine Solutions

Dedicated Spark-Ignited Reciprocating Internal Combustion Engine Natural Gas Engines

Most major engine manufacturers manufacture dedicated NG SI RICEs for various industrial uses. These are proven technologies with well-known performance characteristics.

When compared with a dedicated diesel engine, NG engines exhibit different properties in both fit and function:

- For the comparable power output, an NG engine must be larger in both footprint and displacement. The drilling rig we are examining for this study currently uses 12-cylinder 52-L diesel engines. To get a comparable output from an NG engine would require a 16-cylinder 69-L engine. The footprint would increase from approximately 108 to 160 ft^2, an increase of approximately 30% (Caterpillar 2009, 2010b).
- NG engines also do not react as quickly to transient loads. Most NG engines control throttle by either a carburetor or some type of gas mixing valve or assembly. Similar to diesel engines, a control system calls for an adjustment on the throttle depending on an increase or decrease in engine load; however. unlike a diesel where fuel is delivered directly in to combustion chamber for immediate power production, the distance and volume between the throttle assembly and the combustion chamber creates a time difference between when the engine requires additional fuel and when it receives it. This time gap creates a lag in the engine’s

response time and causes the consequent voltage and frequency dip and overshoot associated with transient load.

Transient loads vary in both size and duration. If the load change is small and brought on slowly, the lag may not be noticeable; however, if the load change is large and drastic, the associated frequency and voltage dip or overshoot could cause operational problems. If large enough, it could trip the circuits offline and cause a rig blackout. The engine performance and the demand must both be known and matched properly to avoid performance problems (Caterpillar 2006b, 2009, 2010b).

The problems NG engines have when responding to rapid and severe transient loads can be mitigated by a modern drilling rig in one of two ways, the first of these being the use of a load bank. A load bank puts an artificial load on a genset and keeps the engine working at a higher output when the rig requirements are low. As the rig demand increases, the load bank sheds the load and transfers it to the rig. The load bank is electronically controlled and can shed and accept load almost instantaneously. Because the load bank can shed and take load quicker than the engine can respond, the engine is prevented from having to ramp up and down as severely and reduces voltage and frequency dip and overshoot. The ideal operating environment for an NG engine with a load bank is with an induced constant load of approximately 60% (Hill et al. 2011). While this makes the engine operate more smoothly, it also makes the engine work harder than necessary. The load bank dissipates the extra work as heat, and it is lost. This greatly reduces the efficiency of the engine, but only during operations where transient loads are high. When under a constant load, the load bank would not be required, and the engine could be allowed to operate on its own (Caterpillar 2010a, 2006b, Hill et al. 2011).

A second method of mitigating slow response to transient load is directly with the rig's automation system. When the system senses voltage and frequency dip or overshoot, it will slow down the load transfer to allow the engine time to respond. Going a step further, if the rig demands a transient load that exceeds the output capacity of the genset, the control system can be set to temporarily scale back the demand from other systems to prevent a blackout. For example, when drilling and the draw-works are suddenly engaged, which puts a sudden load on the genset, the automation system could momentary slow down the mud pumps to reduce power demand and prevent the voltage and frequency dip from becoming so sever as to black out a rig (Hill et al. 2011, Personal communication 2011[1]).

Bi-Fuel Technology

Bi-fuel technology works on a diesel platform and could be used to partially take advantage of the low cost of NG while still maintaining the flexibility and performance of a diesel engine. This could be offered as an addition to new rigs or as a retrofit to an existing diesel fleet. Bi-fuel technology is an external bolt-on retrofit that does not require any modification to the internal components of the diesel engine or its control system.

[1] With an automation engineer, Victory Rig Equipment, Nisku, Alberta

It allows diesel engines to operate on a mixture of both NG and diesel. It works by introducing NG into the intake air stream prior to the turbocharger. It replaces a percentage of the diesel consumed with an equivalent quantity of NG in gal diesel equivalent. This mixture of air and NG are mixed with diesel in the engine's combustion chamber. The mixture is ignited by a diesel pilot when diesel is injected onto compressed air/gas mixture the combustion chamber. The NG is burned along with the diesel and provides the required power output to maintain speed and load with a reduced quantity of diesel consumed (Altronic 2011).

The system allows for combustion of up to 70% NG in continuous low-load situations; however, 50 to 60% is more typical. As the load demand on the engine increases, the quantity of NG is reduced and diesel increases up to approximately 80% of the continuous rating of the engine. Once this load demand is reached, the engine will run on 100% diesel up to its full load rating. The engine can be automatically and seamlessly switched between diesel and gas during partial- or full-load conditions while maintaining current speed, power, and stability. Engine response to transient or block loading on bi-fuel is equal to the performance on diesel operation (Altronic 2011).

The allowable percentage of NG injected is limited by several external factors in addition to load, including ambient air temperature and fuel quality. The control system regulates the NG flow depending on either the engine vacuum, as determined by a manifold air pressure (MAP) sensor or directly as a function of the load. An exhaust gas temperature (EGT) and knock sensor continuously monitor the engine and provide primary control over the activation and deactivation of the bi-fuel system. Control of the diesel metering is maintained by the original engine control system. It will continue to operate normally to maintain a constant rpm by metering back the diesel injection while NG levels are increased. Therefore, no interface is required between the engine control system and the bi-fuel system (Altronic 2011).

In the combustion process, gas is injected downstream of the air filters and upstream of the turbochargers, and the normal diesel CI sequence is followed. At the highest possible fuel injection rate of 70%, the NG comprises only 3% of the total volume of gas drawn into the intake. Methane possesses a lower explosive limit (LEL) of 5%. The high auto-ignited temperature of the lean mixture prevents predetonation from occurring (Altronic 2011).

Ideality, compatible fuel consists of pipeline-quality gas consisting of approximately 97% methane or greater. Lower-quality gas such as wellhead or associated gas may contain varying levels of other HC gasses such as ethane, propane, or butane, as well as other compounds such as carbon dioxide and hydrogen sulfide (H_2S). Levels of these gases in the fuel change the heating value and properties of the gas and could result in a reduction of engine performance or gas substitution rate. In extreme cases, some field gases can contain less than 50% methane. This “hot gas” can possess heating values much higher than pipeline-quality gas. Other contaminants, such as sulfur and water, in the gas can result in the formation of acid and damage system components (Altronic 2011).

The engine efficiency is unaffected by the use of the bi-fuel system. The primary economic advantage is the difference in the cost of the fuel per Btu. If NG is relatively inexpensive as compared with diesel, the economic advantage of a bi-fuel system is high; however, as NG prices near diesel, the advantage of such a system diminish proportionally (Altronic 2011).

In addition to reduced fuel costs, this system comes with many other advantages. The burning of NG will reduce overall emissions; however, it will not eliminate the after-treatment requirements brought on by the Tier 4 emission standards. It does not have any adverse effects on engine longevity or maintenance intervals; in fact, because of the cleaner burning of NG, it may extend the life of parts and increase engine oil change intervals. Operationally, the most distinct advantage is the system's ability to maintain the diesel characteristics of response to transient loading. Another important advantage is the system's ability to run on 100% diesel should NG supplies be unavailable or uneconomical in a particular area.

Major disadvantages to this system are that it does not affect the need to comply with Tier 4 emission standards, and, as it still burns diesel in varying quantities, it does not take full advantage of the lower cost of NG.

While this is a viable way to take advantage of some of the benefits of NG, the specific performance data are not available for this system in this particular application. With these limited data, a direct comparison cannot be made. More research into this system is required.

Dual-Fuel Engines

Dual-fuel engines can operate on two different fuels, but unlike bi-fuel, they only run on one fuel at a time. They include two different fuel systems and can switch seamlessly between the two fuels. They are generally SI RICEs, but engines that run on diesel as a primary fuel source are also available. Dual-fuel engines are typically offered in light- to medium-duty applications and are more common in the automotive industry. Turbines are also available in dual-fuel configurations and can be set up to run on two or more fuels. Dual-fuel applications are out of the scope of this thesis and will not be discussed further (Hill et al. 2011).

Natural Gas Sources, Transport, and Storage

Important considerations when using NG as a fuel source for drilling applications are where to obtain sufficient quantities and then how to transport and store it. There are several major sources that have been identified that could be utilized for a drilling application. They are pipeline gas, field gas, and compressed NG/ liquid NG (CNG/LNG). All possess the ability to be a viable fuel source; however, they are not without their drawbacks and limitations. All sources of NG vary in quality and makeup. Engine performance and emissions will vary with the gas makeup and impurities. In cases where gas quality varies greatly, adjustments to the engines may become necessary.

Pipeline Gas

If supply lines of treated gas are available nearby, it may be possible to lay a new temporary line directly to the drilling pad. In this case, the gas will be dry and of a high consistent quality. NG gensets could be easily connected to this pipeline and fueled directly (Hill et al. 2011).

Whether this is feasible is dependent on several factors. First, the distance from the NG source will have a direct impact on the cost of installing the line. Natural obstructions, property rights, and permitting are all challenges that need to be considered before laying new lines. If the path a pipeline would have to take is not direct, the length of the line could be much longer than the straight-line distance between the two points. Second is the number of wells at the final location. If a number of wells are being drilled near each other, or in the case of pad drilling with multiple lateral wells being drilled off the same location, the time and cost of laying a dedicated pipeline will be more economical then if only one well is being drilled at that location. The greater the quantity of wells being drilled in the area, the more economical the dedicated line will be.

Field Gas

In mature or developed fields, a sufficient pipeline network may be available to tap into existing gathering lines. In this case, the gas quality may be low, but the composition will be known and consistent. If the gas contains liquids or is of low quality, onsite field processing may be an option. This is also the case for wellhead gas.

If pad drilling and completed wells are onsite, NG could be brought directly from the wellhead to the engines through a field processing unit (Hill et al. 2011).

An example schematic of a field processing unit is shown in **Fig. 13.** From a wellhead or gathering line, the gas is routed through a series of separators, dehydrators, and filters to remove liquids and impurities until the gas is of a sufficient quality to be sent to the engines (Hill et al. 2011).

If the field gas is available, it could be a viable fuel source; however, some considerations must be kept in mind. First, the gas being produced from a field is subject to a lease, and several separate parties will have a stake in the production. Royalty agreements and tax laws would have to be honored to access the field gas. Any cost savings seen from using this method may be counter-balanced by legal costs and delays in writing new agreements to allow for field gas use. Also, the field separator will need to be purchased and maintained. Should mechanical problems be encountered, a redundant system may be required to prevent costly downtime. The additional cost associated with the field processing my make the use of field gas unattractive.

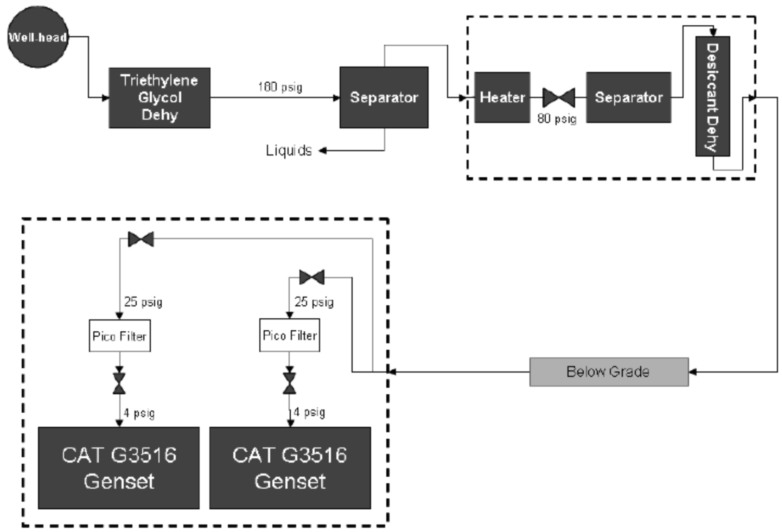

Fig. 13—Field gas processing unit (Hill et al. 2011).

Compressed Natural Gas/Liquid Natural Gas

If for any of the reasons discussed above, pipeline or field gas is not available or economical, NG can be trucked into a location in the form of CNG or LNG.

CNG can be trucked to site in trailer-mounted tanks that contain NG compressed to approximately 3,500 psi and can hold up to 350 Mcf of gas. For the rig used in this study, running with two gensets at 50% load, this is only approximately 20 hours worth of fuel. When near idle with one generator, running this same tank could last nearly 3 days. When drilling operations are taking place, multiple tanks would be required onsite with shipments arriving daily. When compared with a diesel storage tank, which will only require filling once every 7 to 14 days, the additional shipping costs can become significant. Diesel is also generally more readily available, and the distances traveled to source it can be much smaller. As a consequence, diesel shipments can be made more frequently and in smaller volumes (Hill et al. 2011).

LNG is shipped to site in trailer-mounted cryogenic tanks. Because the gas is liquefied rather than simply being compressed as with CNG, each tank contains a much larger quantity of NG. Under the same conditions as the CNG discussed above, a single tank of LNG would last approximately 2 days. This helps to alleviate some of the shipping constraints of CNG, but is still far from resembling diesel in shipping frequency. The availability of LNG is also a concern as it is not as readily available as CNG or diesel and could require long shipping distances and times (Hill et al. 2011).

The use of LNG also requires additional equipment. The cryogenic tanks require a dedicated evaporator unit to convert the LNG to a low-pressure gas that can then be delivered to the NG engines. As is the case with all mechanical equipment, mechanical failure is always a concern; therefore, the need for a redundant system to reduce the risk of downtime should be considered. All these items have an associated cost and take up space on the drilling pad.

Both CNG and LNG are composed of consistent-quality refined gas with known properties. The use of either of these systems would make set up and operation of the NG gensets relatively simple and consistent. No field processing of gas or adjustments to the engines would be required; however, the cost of the fuel associated with the CNG/LNG solution on a per-Mcf basis would be significantly higher than with field gas.

Methodology

Data

The closest comparable NG engine in size and output to the diesels used on the drilling rig is a Caterpillar® G3516. This is a 16-cylinder engine built on the same platform as the Caterpillar 3512 diesel used on this drilling rig. The 3516 performance data for power output versus fuel consumption was obtained from manufacturer data sheets.

Procedure and Results

The data sheets only provide fuel consumption data in scf/hr at three points: 50%, 75%, and 100% load. To compare with the diesel engine, though, all data points between idle and full load (25 to 100%) were required (Caterpillar 2009). To obtain them, the points were plotted to create **Fig. 14.** A line was fitted to the data points, and the equation of that line was determined. That equation was used to interpolate all points between 25 and 100%.

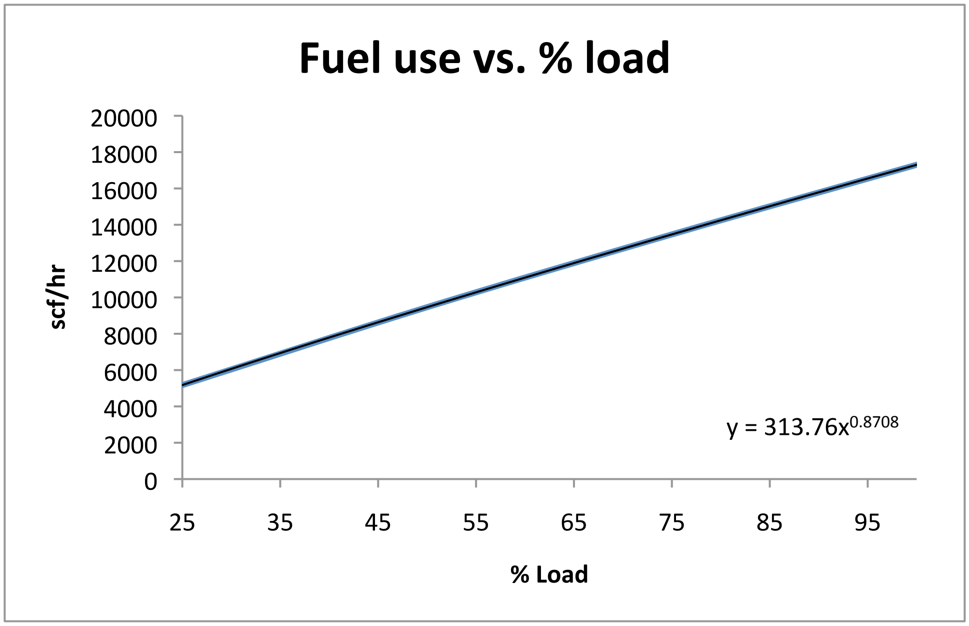

Fig. 14—Fuel usage versus load for an NG engine.

As the line is not linear, the NG engine efficiency changes with the percent load. The fuel rate was divided by the percent load and plotted to show how the fuel consumption changes with changing load. The results are shown in **Fig. 15.**

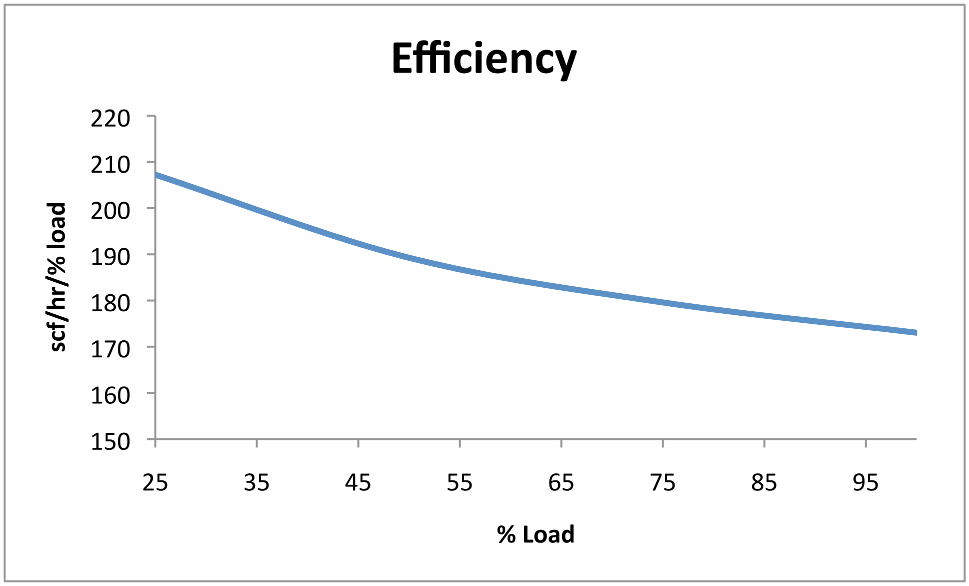

Fig. 15—NG engine efficiency.

Discussion

NG as a fuel is an abundant, clean, and cheap alternative to diesel. Utilizing NG in a drilling application can help reduce emissions and fuel costs. Transportation and storage can be challenging, but methods exist to make its use feasible. It can be sourced from a variety of locations and can be burned by an assortment of engine configurations. Operational challenges do exist with NG engines, such as their response to transient load, but can be overcome with advancements in technology.

CHAPTER V

COMPARISON AND CONCLUSION

Methodology of the Comparison

The goal of this chapter is to compare a diesel engine with a dedicated NG solution, in both ability and economic operation, in order to draw conclusions about the advantages and disadvantages of utilizing the NG engine on drilling rigs. For a better understanding of the scenario, a comparison of each variable analyzed will be discussed: operational constraints, efficiency, and cost.

Operational Constraints and Benefits

Transient Response

Operationally, NG engines do not respond as well as diesel engines to transient loads. When high transient loads are experienced, such as when tripping or back-reaming, if the engine is not able to respond quickly, the voltage and frequency dip or overshoot could become severe enough to black out a rig. While this can and does occur with current diesel gensets, the risk of it occurring with an NG genset is much higher because of its inherit lower torque and slower response times. This can be overcome with advances in the rig automation system that slow the transfer of the load to the genset to within acceptable levels. If required, the automation system can temporarily transfer power from one component to another to allow the genset time to ramp up. An example of this is when back-reaming: when the draw-works are engaged, a high transient load is transferred to the genset, and if the automation system automatically slows the mud pumps simultaneously, it will slow the load transfer to the genset and allow the NG engine more time to respond. To put this into perspective, if the gensets are sized correctly, the difference in response time between a diesel and a comparable NG engine would be measured in seconds rather than minutes. While the idea of regular rig blackouts is operationally unacceptable, the extra time required when ramping up an NG engine would be almost negligible.

During most rig operations, these extra seconds would have only a minor impact on time; however, it may have an adverse effect on trip times as these operations cycle greatly in both power required and frequency. For the rig examined, tripping occurred at intervals of approximately one stand every 2 minutes with an instantaneous power increase from approximately 35 to 80% load. Over the span of an entire tripping operation, this ramp-up time could have some effect on trip times; however, swab/surge constraints as well as safety concerns also limit these times and could make this effect negligible.

Another method of increasing an NG engine's transient response is through the use of a load bank. A load bank places a dedicated load on the generator, which is converted to heat and dissipated. When rig power demand is low, the engine power output is kept artificially high by the load bank. When the rig requires additional power, the load bank sheds the load off itself to the rig. While the rig is getting the instantaneous cyclical power it requires, the genset does not see the full transient load and operates continuously at or near the high output required by the rig. The rig automation system is able to shed and take on load from the load bank nearly instantaneously, which alleviates the need for the engine to respond as quickly.

While the use of a load bank greatly reduces the effect of an NG engine's transient response, it comes at the expense of efficiency. In this application, the engine continuously operates at a high power output to accommodate the load put on it by the load bank. This additional energy produced is converted to heat by the load bank and lost. The effect is that the genset produces much more power than necessary to perform the operation, and this energy is never recovered. It is likely, however, that the use of a load bank would only be required during tripping operations because of the high transient load associated with this operation. With only11% of the total rig time being used for tripping, this loss in efficiency would only be incurred during that time interval, which would not contribute significantly to the total fuel consumed for the NG engine.

Overall, while the transient response of an NG engine is substantially lower than a diesel engine, technology available on modern land drilling rigs have made it possible to overcome this obstacle. While technology cannot eliminate it completely, it can be mitigated such that it does not significantly hinder rig performance.

Fuel Storage and Transport

From a transport and storage standpoint, diesel is a much more practical fuel source. It is easy to transport by truck and can be stored onsite in normally pressurized tanks. NG requires either a fuel source nearby, such as a wellhead or pipeline, or that the NG be transported and stored as CNG or LNG. CNG requires the presence of highly pressurized vessels onsite and requires space for the storage of multiple tanks. LNG requires the presence of cryogenic tanks and evaporators. The amount of room required per Mcf is much smaller with CNG than with LNG, but is still far greater than with diesel tanks. Both CNG and LNG are not as widely available as diesel, which may make logistics and transportation more difficult and costly.

Emissions and Regulation

Burning NG is more environmentally friendly than burning diesel. NG emits the smallest amount of CO_2 per unit of energy and far fewer other air pollutants that contribute to atmospheric and public health damage than any other HC fuel. It does not completely eliminate harmful emissions; however, it does greatly reduce them. It is this property of NG that causes it to fall under different legislation and, in some cases, even be exempted from certain air quality regulations.

From the standpoint of emissions and regulation compliance, NG is clearly superior to diesel; however, there are still challenges associated with regulation compliance that the industry needs addressed. Major engine manufactures are yet to certify their NG engines to the mobile nonroad standards. Without these certifications, the permitting process may be more difficult if not impossible. Also, as previously discussed, the exemptions purposely built for NG engines cannot be taken advantage of until Tier 4 Final–compliant diesel engines are available for distribution.

Engine Efficiency

In the previous chapters, the performance characteristics of both diesel engines and NG engines were determined. The fuel usage for the diesel engine to drill a sample well was empirically measured and used to determine the actual efficiency of the diesel engines as used on a rig under field conditions. The resultant graph was presented in Fig. 6. A similar graph was created for the NG engine using manufacturer data and is shown in Fig. 12.

Because diesel is in a liquid form, the fuel usage for a diesel engine is in gal/hr. For an NG engine, the NG is in a gaseous state, and fuel usage is measured in scf. To make a direct comparison of the two, the fuel usage units must first be converted to common units. Both diesel and NG can be converted to Btu, and this unit will be used for the final comparison.

One gallon of diesel contains 129,500 Btu; therefore, multiplying each point on the graph in Fig. 6 in gal/hr/percent load by 129,500 Btu/gal yields Btu/hr/percent load. The resultant graph is shown in **Fig. 16.**

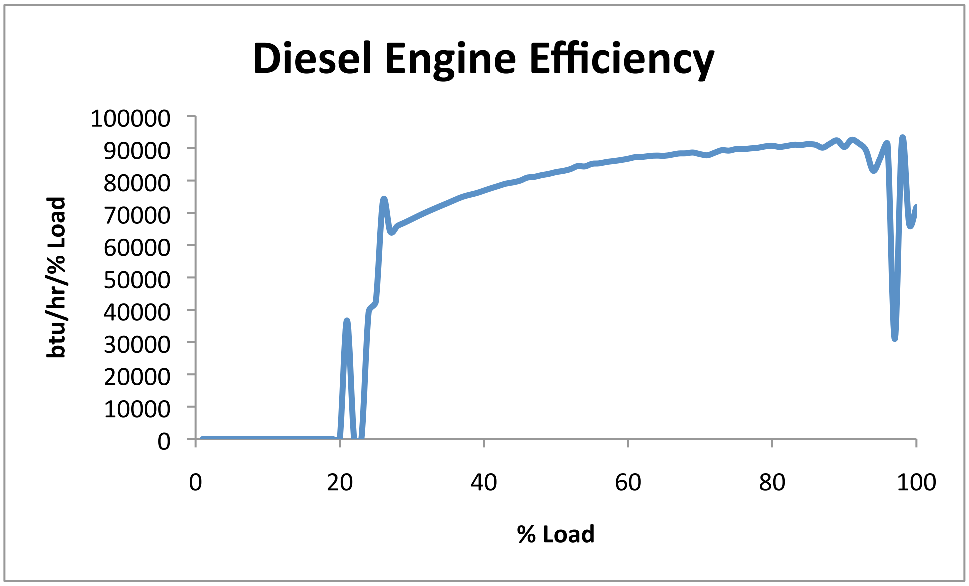

Fig. 16—Diesel engine efficiency in Btu.

The process was repeated for the NG engine, and a similar graph was created for the NG engine shown in Fig. 12. One scf of processed NG contains approximately 1,000 Btu; therefore, multiplying each point on the graph in **Fig. 17** in scf/percent load by 1,000 Btu/scf yields Btu/hr/percent load.

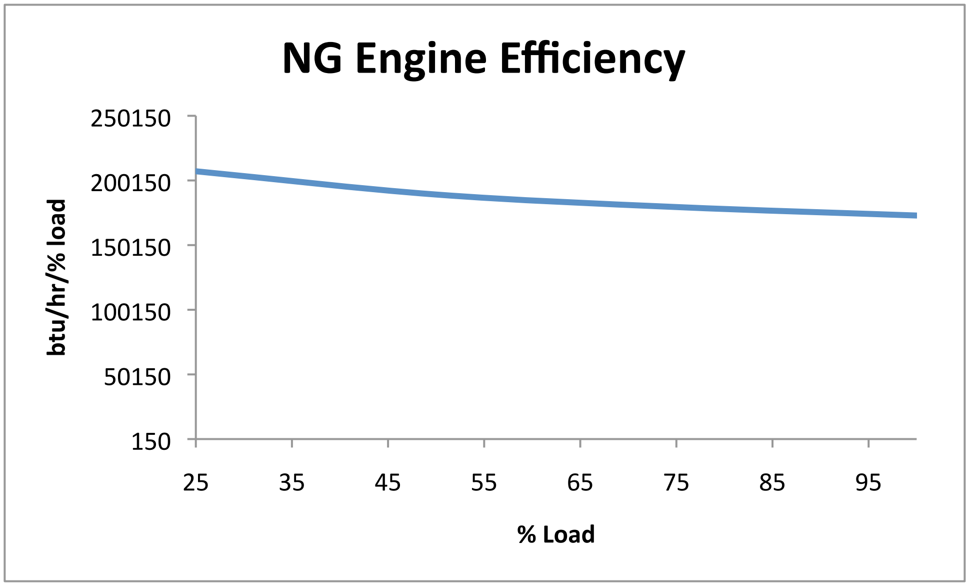

Fig. 17 – NG engine efficiency in Btu.

Once in the same form, the efficiencies of the two engines can be compared on a per-percent-load basis. Unfortunately, the engines are not identical in output and therefore, the identical percent load for each engine represents a slightly different power output. In this case, the maximum electrical output capacity for the NG engine is larger than the diesel. The equivalent electrical kilowatt (ekW) output for each percent load was calculated for the diesel engine by dividing the maximum engine output by the percent load. The ekW was divided by each percent load and multiplied by the previously determined Btu /hr/percent load to yield Btu/hr/ekW. The process was repeated for the NG engine. The results for both engine types are graphed on **Fig. 18.**

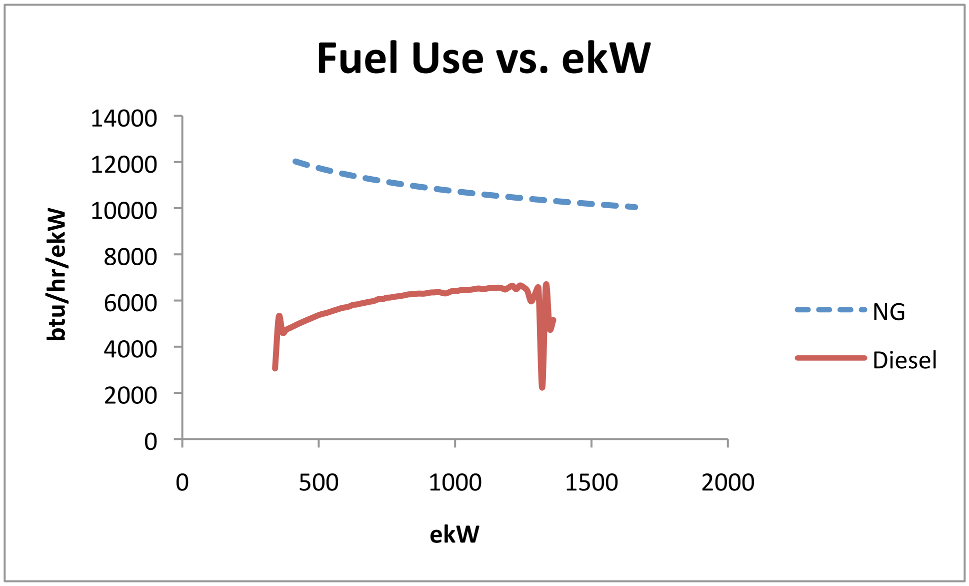

Fig. 18—Diesel and NG engine efficiency in Btu versus ekW.

Fig. 18 shows the diesel engine being more efficient at lower power demand than at the upper limits of its operation. The NG engine, on the other hand, has the opposite performance curve characteristics: as the load increases, the efficiency increases. This is to be expected as they are both known properties of each type of engine. This can be restated in this manner: as the load increases on a genset, if the prime mover is an NG engine, the efficiency will increase, but if the prime mover is diesel engine, the efficiency will decrease.

What must be noted, however, is the gap between the two performance curves. Regardless of where on the curve each engine is performing, the curves never intersect. Even at its most efficient point, the NG engine will never operate as efficiently as the diesel engine.

Fuel Usage

With both the diesel engine and NG engine performance calculated and graphed, a comparison can be made between the total energy consumed to drill this well with the diesel engine and an estimate of the energy consumed to drill the same well with an NG engine. Again, because the fuel types are different and the engine efficiencies vary, each will be converted to Btu before a comparison is made.

To calculate the Btu consumed with the diesel engine, the hours at each percent load are multiplied by the fuel rate to yield gallons of diesel at each percent load point. These are summed to give total gallons of diesel consumed and then multiplied by 129,500 Btu/gal of diesel to determine total Btu consumed to drill the well. The results show that 26,105 gal of diesel was consumed during the drilling of this well, which equates to approximately 3.38 billion Btu.

The process to calculate the estimated Btu required for the NG engine to drill the same well was a very similar process; however, the fuel consumption in scf for an equivalent diesel power output in ekW needs to be determined before an estimated fuel total can be reached.

Using previously calculated data, a plot was created of the NG engine's fuel rate in scf/hr versus ekW output. A line-fit was performed on this curve, resulting in the equation $y = 26.197x^{.8708}$. This equation was then used to calculate the fuel rate in scf/hr of the NG engine at each of the diesel engine's percent load points by substituting the power output of the diesel engine in ekW for each percent load point. With this information, the fuel rate of the NG engine at each of the diesel engine's percent load points was multiplied by the time the diesel engine spent at that load, and the associated scf consumed was acquired. These quintiles were summed and multiplied by 1,000 Btu/scf of NG, and the total estimated Btu required to drill the same well with the NG engine was obtained. The results show that to drill the same well with an NG engine, approximately 6.34 million scf (6336 MMcf) of NG would be consumed during the drilling of this well, which equates to approximately 6.36 billion Btu.

The difference in efficiency discussed in the previous section has a direct effect on the difference in Btu required to drill this well. As shown in Fig. 4, for the majority of the time drilling the well, the generators were operating between 30 and 55% load. This represents the area on Fig. 18 between 400 and 750 ekW. When operating in this range, the two graphs are diverging and are nearing their farthest points from each other. As the lines diverge, the difference in efficiency between the diesel and NG increases. This is a contributing factor to the NG engine requiring nearly twice as much energy or Btu to drill the same well as the diesel.

Economic Analysis

The question then becomes, can this gap in total Btu consumed be bridged with dollars? Even though the NG engine requires more thermal energy to generate the same amount of power, the price gap between NG and diesel per Btu may make the NG more economical to operate from a fuel consumption perspective.

Diesel engines are more efficient on a per-Btu basis than their NG counterparts, as was shown in the previous section. However, because of the low price per Btu of NG, the gap in efficiency can be easily closed as NG prices drop. Despite their higher first cost, the clean burning properties of NG engines also add to economic benefit because they do not require additional after-treatment in the exhaust system to pass Tier 4 emissions standards.

Table 9 shows the comparison of cost of ownership between the NG and diesel engines over a genset's expected life span of 60,000 hours. The estimated purchase price of the NG engine is approximately 60,000 USD, or 15% larger than the equivalent diesel and is an upfront cost.

TABLE 9—ECONOMIC COMPARISON

Type	First cost (USD)	Maintenance (USD)	Emissions equipment (USD)	Operation (USD)	Total (USD)
Diesel	1,200,000	1,650,000	420,000	6,213,645	9,483,645
NG	1,380,000	690,000	0	2,898,551	4,968,551
Bi-fuel	1,350,000	1,650,000	420,000	4,549,780	7,969,780

Regular scheduled maintenance cost is spread over the life of the engine and consists mainly of valve adjustments, cylinder head rebuilds, and one complete overhaul. The overhaul cost for the diesel is much higher, mainly because of the necessary replacement of parts of the fuel system including fuel injectors. These are costly items that are not utilized in an NG engine fuel system, and therefore are not included in an NG engine overhaul. Even though the NG engine is larger and has more cylinders, the overhaul of the NG engine requires fewer and less expensive parts to be replaced, and therefore the total cost of maintenance over the lifespan of the NG engine is substantially lower. Another advantage of the NG engine is that is burns cleaner than a diesel, which can increase the time interval between oil changes when the oil is monitored and tested. The oil changes comprise a much smaller portion of the overall cost of maintenance, but do have an effect on cost over the lifespan of the engine.

Although not currently required, when Tier 4 Final takes effect, exhaust after-treatment will be required on all non-road diesel engines. While these systems are currently available as aftermarket additions, the original equipment manufacturers will be responsible for furnishing and installing these systems. The additional emissions equipment is expected to increase the purchase price of diesel engines by approximately 30 to 40%, but NG engines do not require these emission controls.

Over the life of a genset, the operational cost, consisting of fuel consumption, is by far the largest constituent of the total cost of ownership. For comparison purposes, the calculated values were used for the diesel consumed and NG required for the same operation.

The calculated value for the energy consumed while drilling this well is approximately 3.4 billion Btu for the diesel engine and 6.3 billion Btu for the NG engine. This shows that on a per-Btu basis, the NG engine requires much more energy to deliver the same results. These numbers converted to gallons of gasoline equivalent (GGE) are 29,654 GGE for diesel and 55,576 GGE for NG. Based on the price of commercial #2 diesel at 2.60 USD/gal and the price of NG at 4.50 USD/Mcf (United States Energy Information Administration 2011), the calculated fuel cost of drilling this well is approximately 68,000 USD in diesel, and the calculated cost for NG is 31,000 USD.

If wells similar to the well examined in this study are to be repeatedly drilled for the full 60,000-hour expected engine lifespan, the cost to the owner would be approximately 7.3 million USD for a diesel genset, but only 3.6 million USD for the NG equivalent. This number does not take rig move times into account, which would add several days per well to the “other” category discussed earlier, but it shouldn’t have a substantial effect on the overall cost of operation.

The first cost favors the diesel engine by approximately 60,000 USD per genset; however, once emissions equipment is added, the NG engine becomes lower in first cost by nearly 80,000 USD. After operating the rig for approximately 7 years (the estimated lifespan of a genset), the difference in total cost of ownership between equivalent gensets is approximately 4 million USD in favor of the NG engine.

It should be noted that the bi-fuel option presented in Chapter II is a means of partially taking advantage of the economic benefit of NG without compromising the flexibility and performance of diesel. If it can be assumed that the NG content of the Btu consumed from 25% load (idle) to 80% load on the diesel engine varies linearly from 70% NG at idle to 0% NG at the top end above 80% load, the relative economic impact of the bi-fuel system is shown in Table 9. A graphical representation of the fuel mixture throughout the load range is shown in **Fig. 19.**

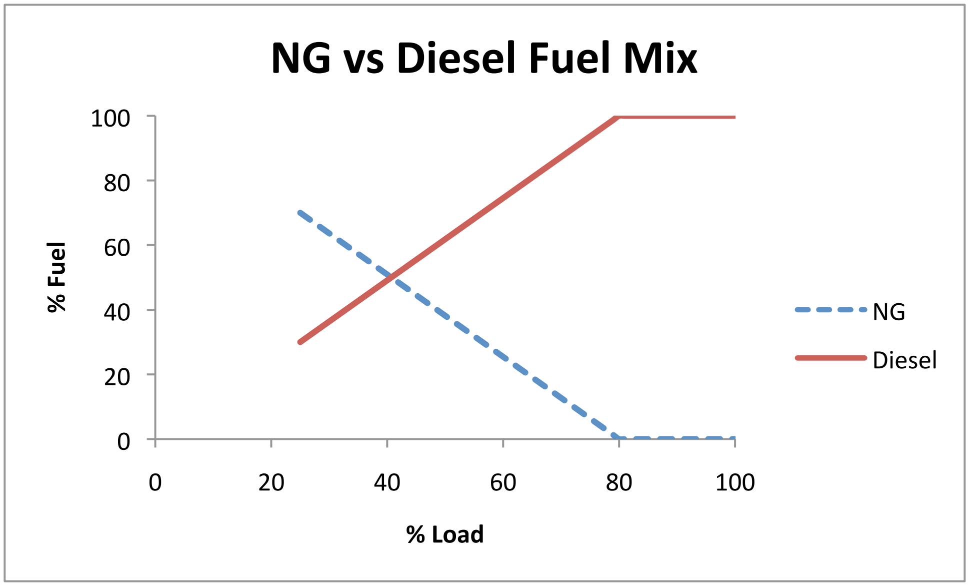

Fig. 19—Bi-fuel NG versus diesel fuel mix.

Because the bi-fuel system is installed on a diesel platform, it will increase the first cost, but the remaining maintenance and emission equipment costs will remain relatively consistent. The maintenance costs may actually decrease because of the reduced wear and tear as an effect of burning NG, but this will need to be assessed on a case-by-case basis and is not taken into account in the economic analysis. Compliance with Tier 4 emission standards will still be necessary and therefore, all the after-treatment equipment will be required.

Because the thermal efficiency of the diesel engine is not affected, the total Btu consumed with the bi-fuel system is the same as with the diesel engine. When accounting for the time the engine operates at each load point when drilling this well and the corresponding quantity of NG substituted for diesel, the operational cost equates to a diesel fuel savings of nearly 1.7 million USD over the same 60,000-hour period. This solution, however, is still subject to fuel price fluctuations and the issues discussed earlier with transport and storage of NG without taking full advantage of the economic advantages. Also, the assumptions made may not hold true when tested under field conditions. For this reason, further research with empirical data is required to make an effective direct comparison with the dedicated diesel and NG solutions presented here.

The economics are very price sensitive and are based on current market prices for both diesel and refined NG. These are both commodities, and the prices of each are subject to independent and volatile price fluctuations, which can severely affect the economics if this application. If diesel prices were to remain constant, the price of NG could increase to 1.22 USD GGE before it became uneconomical compared with diesel over the life of an engine. It must be noted that the pricing data do not take external factors into account that are associated with the sources of the fuel, such as transport and equipment. These will be site-specific and must be factored in on a case-by-case basis.

If field gas is used, the purchase price will vary, as will the cost of field treatment if required. If the CNG/LNG option is used, additional transport costs could be incurred, as well as equipment purchase or rental. If a temporary pipeline is required, the cost of installation will also have an effect on the onsite fuel costs. Transport can also have an effect on diesel if the source of fuel is far or difficult to transport. All these factors need to be considered before a decision on fuel type is made.

Discussion

Recommendations

In situations where NG is readily available and can be delivered to site at or near current market prices, NG engines should be utilized because of the cost savings and reduced environmental impact. In all other cases, particularly where transport costs may encroach on the cost benefit, it may still be better to continue using diesel engines to power drilling rigs because of the operational ease of use.

Limitations

While this study analyzed major characteristics of two source engines, one must note that the NG engine data were taken from manufacturer data, which were most likely measured under laboratory conditions and not in a real-world application like the diesel engine rig data. However, because there are no field data available for NG-powered rigs, an estimate of its feasibility based on a comparison with a diesel-powered rig drilling a real well in the field is relevant.

Conclusions

The purpose of this study is to determine whether NG can be utilized as a viable fuel source for modern land based drilling rig. Based on analysis of the operational constraints and economic impact, I conclude that given the right economic environment, NG-powered drilling rigs can be very beneficial to the industry. Obviously, further studies with actual field results are needed.

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