USING LNG FOR UPSTREAM OIL AND GAS OPERATIONS

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ABSTRACT

Noble Energy, Inc. recently conducted a field study to evaluate the use of liquefied natural gas (LNG) to reduce diesel fuel usage in their drilling and hydraulic fracturing (frac) operations. Noble contracted four drilling rigs with three different types of aftermarket kits that enabled diesel engines to run on a combination of diesel and vaporized LNG, which is referred to as dual-fuel operation. The boilers on these rigs were converted to run on either 100% LNG or 100% diesel as a backup. Noble also contracted two frac crews with engines that utilized dual-fuel kits. Several field test programs were carried out from 2013 - 2016 with the objective of evaluating LNG kit and supplier performance.

In this paper, Noble and Trimeric will summarize this evaluation of LNG use in upstream drilling and fracturing operations. The paper will discuss how equipment reliability and field support from LNG suppliers and kit manufacturers are differentiating factors in the success of LNG use. It will also discuss the importance of minimizing disruptions caused by the LNG supply and equipment in order to keep the operations crews onboard with the LNG use campaign. The importance of load optimization in order to maximize diesel displacement and minimize total fuel use will be reviewed, along with how this affects drilling and hydraulic fracturing operations differently. Generalized conclusions from safety reviews and an emissions testing campaign will be presented.

INTRODUCTION

This paper summarizes Noble Energy's efforts to displace diesel with liquefied natural gas on drilling rigs and hydraulic fracturing spreads through the use of aftermarket kits that allowed engines to run on a mixture of diesel and vaporized LNG (dual-fuel). The boilers on the dual-fuel rigs were also converted to run on LNG. This effort was driven by a desire to reduce overall emissions, with potential fuel cost savings. Noble installed three different types of kits and tracked their performance through various fuel use metrics, emissions testing, and feedback from operations. This paper is intended to share how Noble has reduced diesel consumption in their operations and give some of the valuable findings from the LNG campaign.

BACKGROUND

Goals of the Noble LNG Campaign and Trimeric Support

Noble Energy, Inc. recently conducted a field study to evaluate the use of liquefied natural gas (LNG) to reduce diesel fuel use in their drilling and hydraulic fracturing (frac) operations. Noble contracted four drilling rigs with three different types of aftermarket kits that enabled the diesel engines to run on a combination of diesel and vaporized LNG. Noble also contracted two hydraulic fracturing spreads with aftermarket LNG kits. Additionally, Noble converted the diesel boilers on the drilling rigs to run on 100% LNG, while retaining the backup capability of running on 100% diesel.

Noble had two primary goals for the use of LNG in their upstream operations. At the time that the testing began in 2012 and 2013, the cost savings associated with LNG compared to diesel were significant. However, these cost savings will vary over time due to commodity price fluctuations, especially for diesel. The second primary goal was reducing the environmental footprint of Noble's operations and fulfilling Noble's commitment to being a good neighbor to residents in the areas around their operations. The use of LNG in drilling engines can reduce nitrogen oxides, volatile organic compound, and particulate matter emissions compared to diesel.

Noble enlisted Trimeric's help beginning in 2013 to provide engineering support for Noble's LNG operations. Original goals of the project were to track LNG and total fuel use and to improve operations to maximize LNG use while minimizing overall fuel use. Trimeric also assisted Noble in evaluating and comparing aftermarket kits from three different manufacturers as well as other general support items.

Description of Noble Operations

As is typical for upstream oil and gas operations, there are a number of different parties involved in utilizing LNG on both the drilling rigs and hydraulic fracturing spreads. Noble owns and operates the sites and contracts a third party to run and maintain the drilling rigs or frac spreads. Another company is responsible for delivering, storing, and vaporizing LNG, as well as maintaining sufficient onsite LNG inventory. The aftermarket LNG kits require general servicing by the kit manufacturer or a certified contractor. The engine themselves must also be maintained; this is typically the responsibility of the drilling or fracturing contractor. Finally, Noble has a separate safety department that oversees all operations. In order to have success in LNG operations, it is critical that good communication and commitment to facilitate LNG operations ("buy in") is established between all parties involved.

SYSTEM DESCRIPTION

Types of Natural Gas Engine Operations

Drilling rigs and hydraulic fracturing pumps are typically powered by diesel engines that run generators to produce electricity for the drilling or frac equipment. There are several different terms used to describe the way that engines can incorporate the use of natural gas or LNG to displace diesel. These terms are dual-fuel, bi-fuel, and dedicated. Dual-fuel typically involves installing an aftermarket kit that allows the engine to run on a mix of natural gas (vaporized LNG or CNG) and diesel. Bi-fuel engines can switch between running on either 100% natural gas or 100% diesel. The bi-fuel option is more common in automobile engines that have been retrofitted to run on natural gas. Finally, as the name implies, dedicated natural gas engines are designed to run solely on natural gas. In some cases, field gas is used to displace diesel. Noble's testing campaign exclusively used highly purified LNG that was produced offsite and delivered to the field for use in dual-fuel engines.

The aftermarket kits evaluated by Noble that are the subject of this paper all fell under the dual-fuel category. The advantage of dual-fuel operations in a pilot program is that it gives the flexibility to fall back on conventional, 100% diesel operation. If there are LNG delivery issues or the LNG system shuts off for any reason, the engines automatically switch to diesel-only operation, without any interruption in the power supply. Supplying natural gas to remote locations or during bad weather can be difficult. Because LNG is less commonly used, there are fewer supplier backup options than there are for diesel. Reliability of LNG supply and delivery was one of the first issues addressed in this field campaign and significant improvements made this nearly a complete non-issue by the end of the campaign. However, as will be explained in more detail later, a potential downside of the ability to switch to diesel-only operations is that it is easier for problems with the LNG system to go unnoticed, which means less LNG is used and less diesel is displaced. The economic and environmental benefits of dual-fuel systems may also be less significant than dedicated LNG operations, since only a portion of the diesel is displaced by LNG. Finally, another potential disadvantage of dual-fuel operations is that both diesel and LNG must be stored onsite in bulk quantities.

General Process Overview

Figure 1 is a general process overview of the LNG system on a drilling rig. LNG is stored in a large trailer at approximately 50 psig. A third party vendor provides delivery, storage, and vaporization of the LNG. The LNG is vaporized and warmed upon demand and flows to the boiler, to the kits, and then engine air intake. There are a number of regulated setback distances for the LNG trailer to ensure that flammable materials under pressure are a sufficient distance from ignition sources such as vehicles or generator engines. Therefore, the LNG trailer is often located along the edge of the site, away from other equipment.

The re-gasified LNG is typically transferred to the engine house through flexible metal hoses, which may be partially buried, run through hose ramps, and/or blocked off by concrete barriers to minimize exposure. Outside of the generator housing is an emergency shut-off valve on the gas line which can be activated by an emergency stop switch also located outside the generator housing. Once inside the generator housing, the gas pressure is reduced to approximately 5 psig before it is sent to each of the dual-fuel kits. A schematic of a generic dual-fuel kit is given in Figure 2. The dual fuel kits mix the vaporized natural gas with combustion air in the air intake manifold and it is then burned in the engine to displace diesel consumption. The exhaust of a retrofitted engine is typically modified to include a catalyst (if one is not already installed) to oxidize carbon monoxide (CO) and Volatile Organic Compounds (VOC) to CO_2. The takeoff for the boiler is located between the emergency stop valve and the pressure regulator valve.

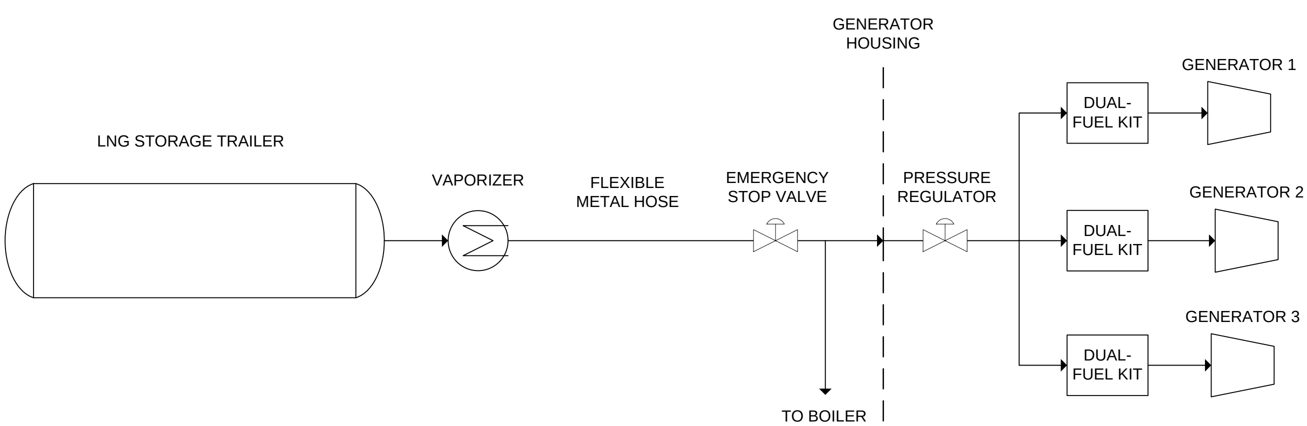

Figure 1 Overview Schematic of LNG System

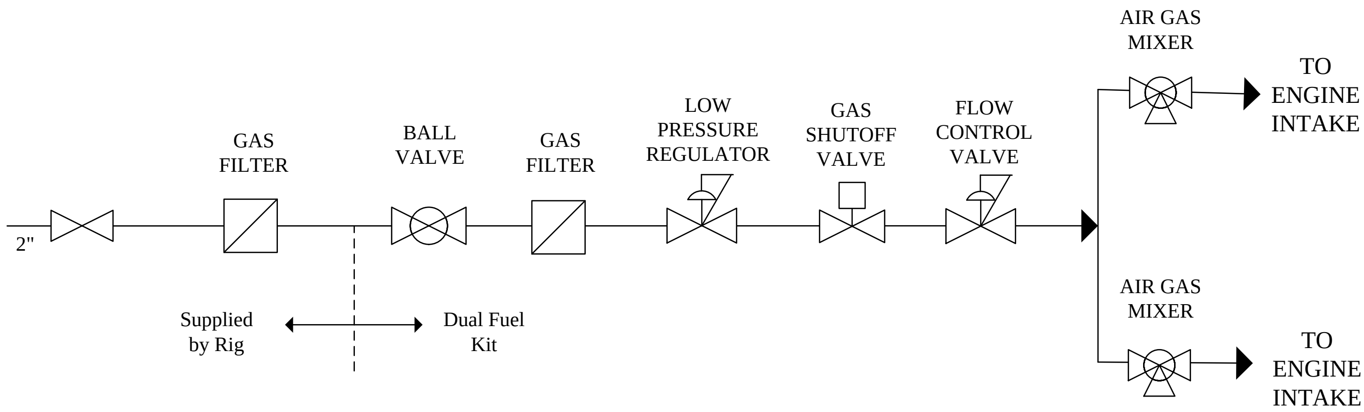

Figure 2 Generic Dual-Fuel Kit

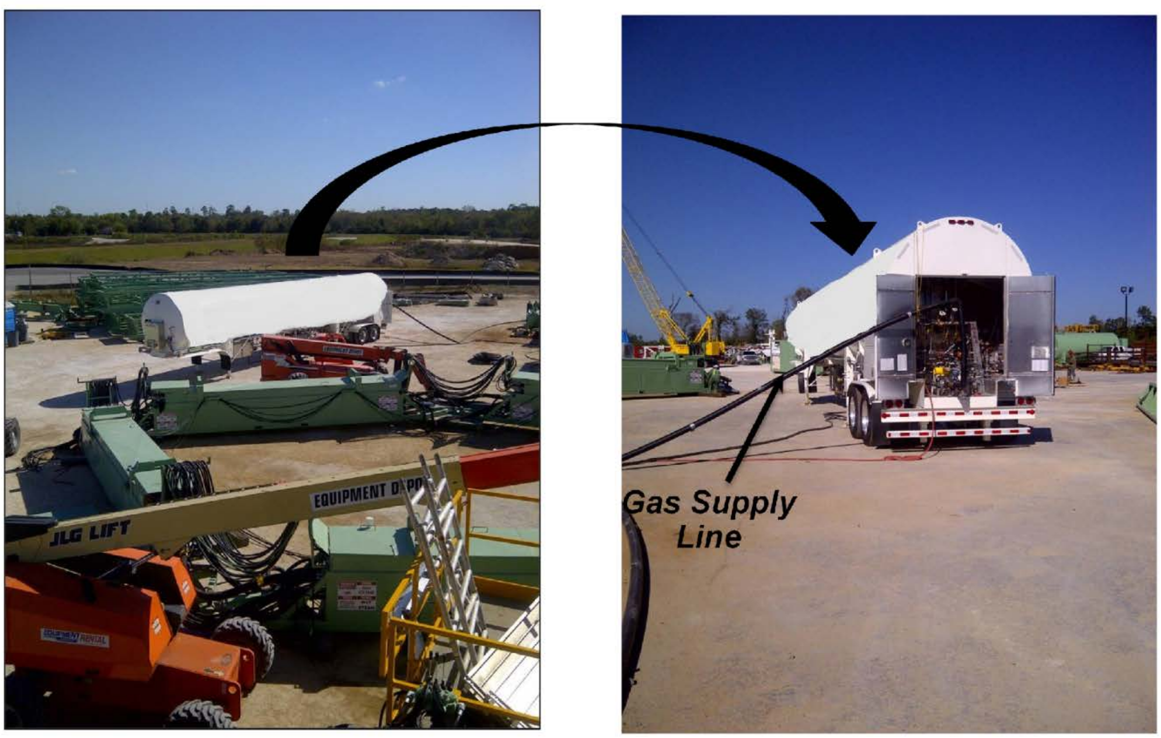

Figure 3 LNG Storage Trailer

Figure 4 Generator House, Gas Supply Lines, and Shut-Off Valve

General Kit Operating Principles

There are a number of different manufacturers of dual-fuel kits, but all kits tested operate in a similar manner: the kit feeds natural gas to the engine via the air intake. With the fuel addition, less diesel will be required to meet a given load requirement. The energy contents on a volume basis differ for LNG and diesel (approximately 82,644 Btu/gal and 139,000 Btu/gal, respectively), so it takes about 1.68 gallons of LNG to provide the energy equivalent of a gallon of diesel, assuming 100% combustion efficiency. Because of this difference, LNG is often discussed in terms of “diesel gallon equivalents” or DGE - 1 DGE = 1.68 gallons of LNG.

There is a theoretical maximum amount of vaporized LNG that can be used at a given load for an engine that was originally designed to run on 100% diesel, because the engine requires a minimum amount of diesel to operate safely and effectively. Figure 5 shows a conceptual plot of the theoretical maximum percent LNG DGE versus engine load. The amount of LNG that can be introduced at low loads is minimal, and most kits do not start introducing LNG until around 20% engine load. The theoretical amount of LNG reaches a maximum at around 50% engine load, with about 70% diesel displacement. Factors such as engine knock, vibration, and exhaust temperature and LNG kit tuning parameters oftentimes result in the actual % LNG DGE being lower than the theoretical maximum. Kits are programmed to reduce LNG use above about 70% engine load to avoid high exhaust temperatures and other issues with engine operation.

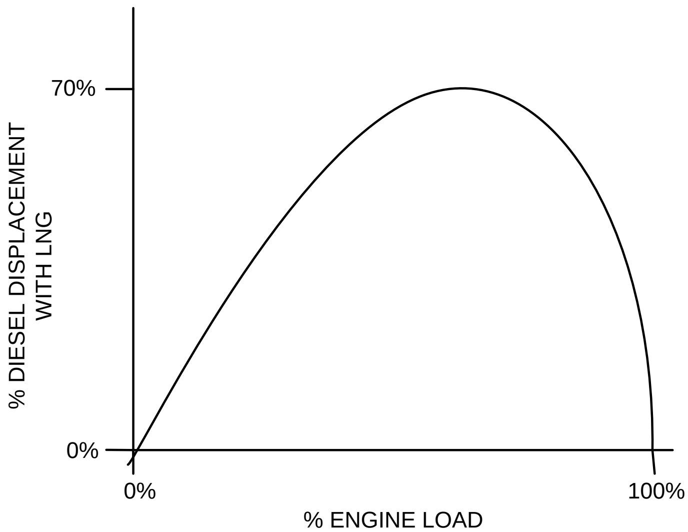

Figure 5 Theoretical Maximum Percent Substitution

Kits Tested

Noble engaged in a pilot test that involved installing three different types of aftermarket kits on four different drilling rigs. While the general principles of the different aftermarket kits are similar, each of the kits differs in the way that it determines when to introduce LNG and how much LNG to introduce at different loads. The names of the three kits tested will not be disclosed, but instead the kits from the different manufacturers will be referred to generically as Kit A, Kit B, and Kit C. The following paragraphs explain operating principles of each of the kits used during the testing campaign.

Each of the kits independently monitored basic engine functions, such as exhaust temperature, coolant temperature, and/or manifold air pressure, to ensure that the engines stayed within normal operating parameters. This was done either through independent sensors or by reading information from the engine control module. If any parameters went out of range, the LNG supply from the kit would automatically be reduced and the engine would seamlessly run on reduced LNG or revert to diesel-only operating mode.

Kit A used a series of different solenoid actuated valves to introduce LNG based on the electrical power in kW generated by the engine. The kit had independent kW sensors to determine the power output of the generator. Based on the measured generator power output (also referred to in terms of the corresponding % engine load), the kit would open one of several valves to introduce vaporized LNG to the air intake on the engine. Vaporized LNG was introduced to the air manifold downstream of the engine air cleaner housing and upstream of the turbocharger compressor inlet. Combustion of the vaporized LNG causes a slight increase in engine speed, which is detected by the existing (and unmodified) diesel governor on the engine. The diesel governor then reduces the diesel flow rate to the engine.

Each valve on the Kit A dual-fuel system opened and closed at a different % LNG DGE based on the engine load (or generator power). These settings had to be manually calibrated to the engine and operating conditions. For example, the kit could be calibrated to open the first valve at 20% engine load, and introduce 20% LNG DGE at engine loads from 20% - 35%. At 36% load, the next valve would also open, to allow approximately 35% LNG DGE and at 45% load the next valve would also open to flow 50% LNG DGE, etc. The amount of LNG introduced would step down in a similar manner as the load further increased, mirroring the theoretical maximum percent substitution in Figure 5.

Kit B had many similarities to Kit A such as the location of vaporized LNG introduction and the use of the existing diesel governor to reduce diesel fuel consumption in dual-fuel operations. However, Kit B did not have LNG usage variance of Kit A; Kit B targeted a nearly-constant 50% LNG fuel substitution for the load range at which LNG was introduced. The kit was calibrated to introduce about 50% LNG DGE at engine loads from 25% to 70%. Gas flowrate was proportional to the engine load. While other kits may offer the potential for higher percentage of LNG fuel substitution at some conditions, Kit B had a simplicity in design and operation that was preferable for some drilling rig operators.

While Kit C has some common features with the other kits such as the introduction point for the vaporized LNG, Kit C used a more complex series of algorithms built into the engine controller to determine the amount of LNG to introduce once a minimum of 20% load was reached. Integrated feedback systems allowed the generator set to react to fuel and engine operating conditions to conserve fuel and protect the engine without affecting the power output of the engine. Maximum percent substitution (up to 70%) is set by the user. Kit C targets this substitution, but will reduce the amount of LNG used as needed based on parameters such as engine percent load, exhaust temperature, engine knock (detonation), or vibration. For example, if the exhaust was running hot on a summer day, Kit C could lower the amount of LNG fed to the engine to lower the exhaust temperature, instead of shutting off LNG use as would be the case with other kits.

KIT EVALUATION FOR DRILLING

Daily Fuel Use Tracking

A key method for evaluating kit performance on the drilling rigs was to track the daily fuel use. Similar usage tracking was also done for the frac spreads. Daily and weekly fuel use tracking was most useful in monitoring the operational status of the kits. A significant, unexplained drop in LNG could indicate a supply issue, trips that were not addressed, a need for kit calibration or repair, or engine maintenance. Drilling operations are dynamic with many parties involved and no two sites are the same; since a drop in LNG use did not affect the drilling operations, it was common for LNG system issues to be missed or ignored. Regular fuel tracking reports sent to all stakeholders increased the visibility of the operations and served as a reminder to address LNG system issues as they arose. Figure 6, Figure 7, and Figure 8 are examples of some of the information provided in the weekly LNG reports for drilling.

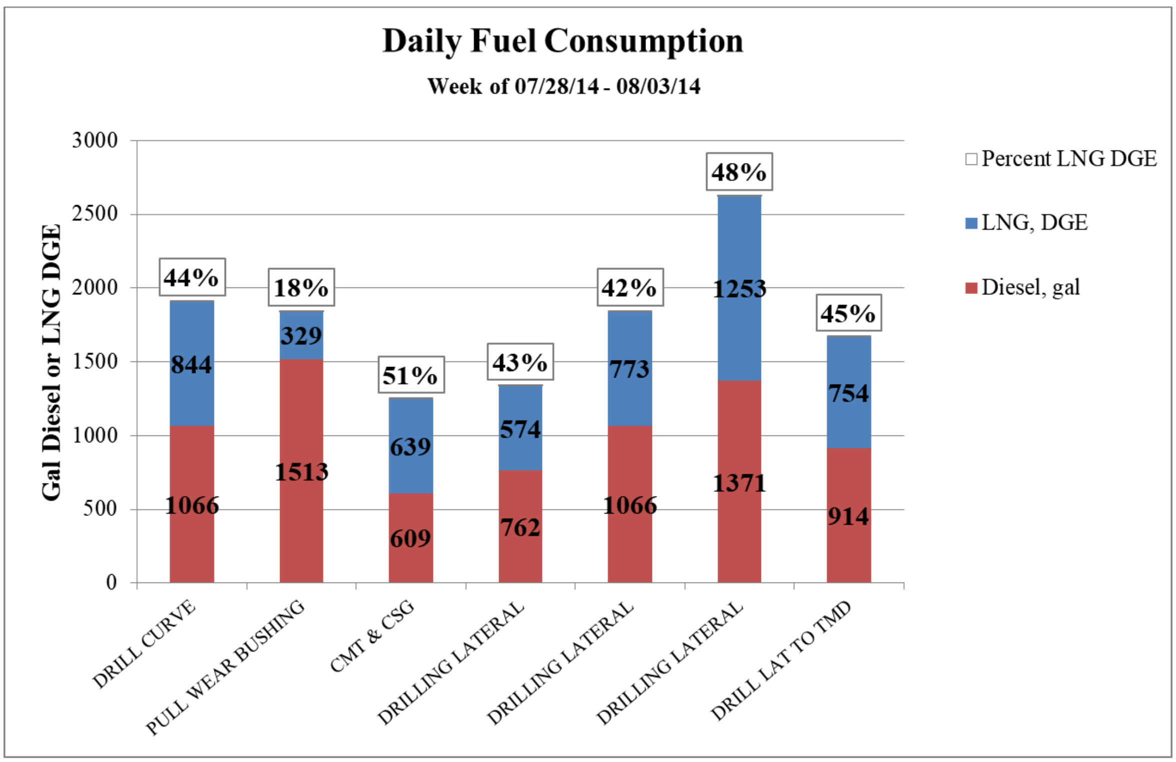

Figure 6 Example Weekly Drilling Report Graph: Daily Fuel Consumption

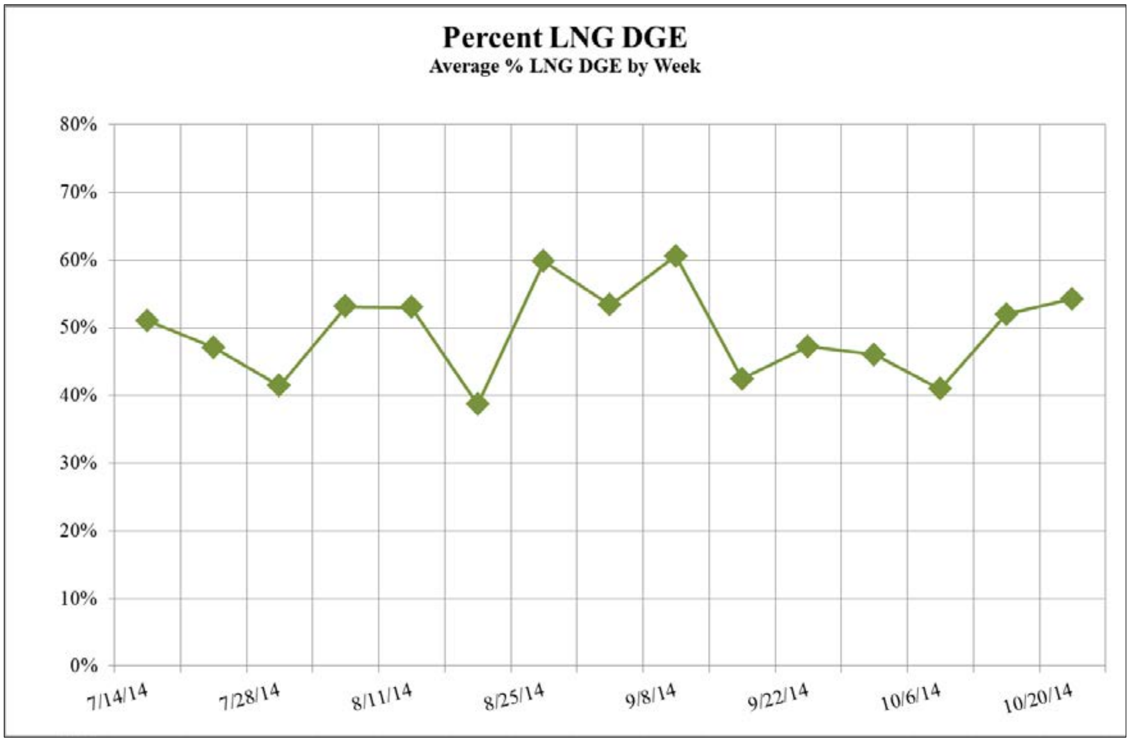

Figure 7 Example Weekly Drilling Report Graph: % LNG DGE by Week

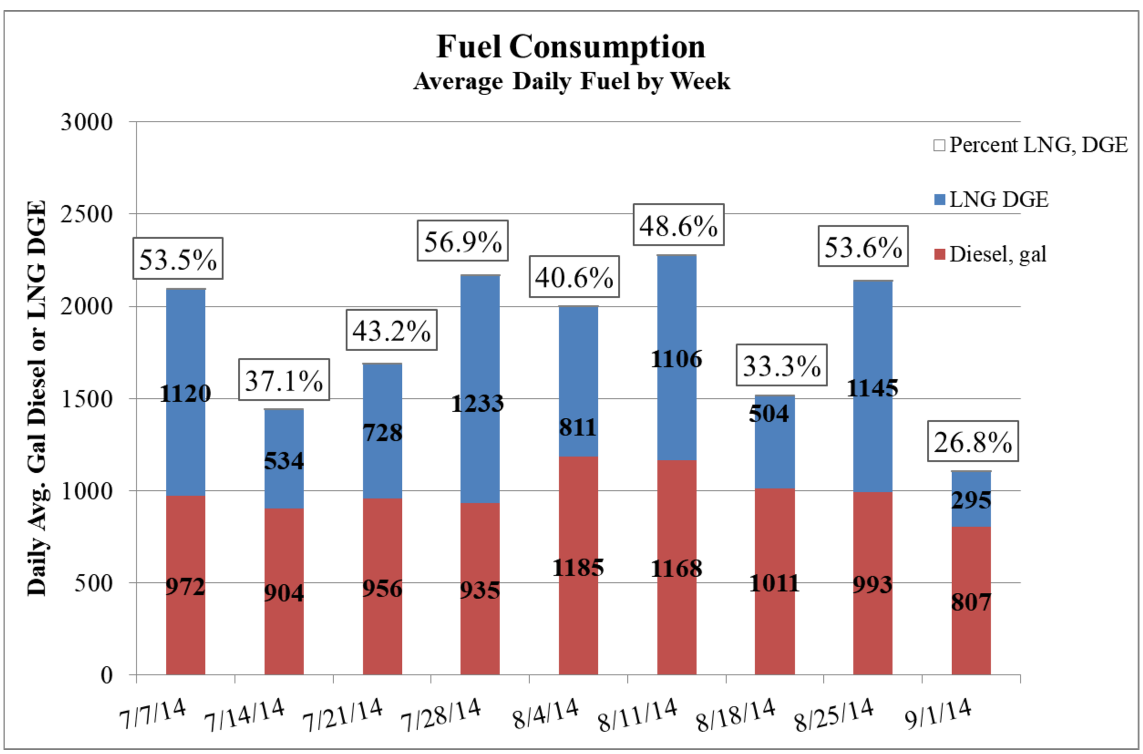

Figure 8 Example Weekly Drilling Report Graph: Average Daily Fuel by Week

Longer Term Fuel Analysis

Longer term fuel analyses were conducted to examine various metrics in order to compare kit performance, including overall % LNG DGE per well, per pad, and total fuel used per foot drilled. (A pad is a group of wells drilled at one location.) While LNG use was higher in the winter while fueling the boiler, evaluation of summer operations provided a clearer picture of diesel substitution on the engines because the boiler was not in operation. On a very cold day, running the boiler could account for over half of the total daily LNG use and boiler fuel use was not monitored separately.

There were a number of factors other than the kits themselves that affected the amount of diesel displaced, and these factors must be considered when comparing the performance of different kits. Meaningful comparisons can only be made when drilling operations are similar: well depth, lateral length, geology, and drilling parameters such as bit size all affect the engine loading and therefore the theoretical and actual diesel displacement. Care was made to consider these parameters when comparing kit performance. Data for reasonably similar wells were collected for each of the kits for a minimum of three months. Kit A consistently used less LNG than Kits B & C. Kits B & C averaged 45 – 50% LNG DGE per well for the engines when the boiler was not in use. The percentage of LNG use during times when the boiler was running was significantly higher.

Improvements

Detailed analysis of fuel use in the earlier part of the campaign indicated a possible overall increase in the amount fuel used in dual-fuel operations compared to diesel operations. With many changes over the years in the campaign including drilling practices, different kits, different engines, and personnel changes, the total amount of fuel used for dual-fuel operations has decreased dramatically when reported on a per foot drilled basis and was comparable to previous diesel-only operations.

Noble has continued with dual-fuel drilling operations over the last few years and also continues to track fuel use with the methods previously described in this report. Drilling practices have changed from setting three strings of casing to setting only two strings of casing, with the latter referred to as monobore drilling. By utilizing monobore drilling, significantly less time is spent running casing and tripping out of the hole, which contributes to a faster drilling rate. The engine loading is steadier, with fewer swings from high to low load. Monobore drilling operations also result in relatively less run time at low engine loads, where engine efficiency is lower. Drilling crews have changed as well, and the best of the operators were retained as many oil and gas companies started to reduce drilling rig counts after oil prices dropped in 2014. With these changes, Noble has also seen DGE per foot drilled on the dual-fuel rigs be reduced to values similar or less than the diesel-only baseline data used in the initial comparison. For example, one dual-fuel rig average 0.78 DGE per foot over seven wells in the summer of 2017, compared to 2014 diesel-only averages just above 1.0 DGE per foot. The reduction in fuel consumption is likely due to a combination of changes in drilling practices and crew technique.

Economics

Fuel use tracking was also used to conduct an economic analysis on dual-fuel operations vs. diesel-only operations. The economic comparisons of dual-fuel vs. diesel-only are dependent on many factors and will vary field to field and by operating company. In addition to the importance of the difference in diesel and LNG costs, an operator must consider the initial economic investment, contract costs for LNG delivery and storage, and the amount of LNG used compared to the achieved diesel reduction. The realized diesel substitution rate depends not only on the kit tuning parameters, but also on the engine loading and operating practices. Noble found that conversion of the boiler from 100% diesel to 100% LNG greatly improved the economics of using LNG when the fuel price differences favored LNG.

MAXIMIZING LNG USE

Load Management

Load management is a significant factor in overall fuel efficiency for both diesel-only and dual-fuel operations. Engines generally operate more efficiently at greater than 50% load, compared to lower loads. The best theoretical efficiency is as 100% load is approached. For a given well, DGE per foot drilled is expected to be lower if the amount of run time spent at low loads, with low fuel efficiency, is minimized. Load management also has significant impact on the amount of diesel displaced in dual-fuel mode. Maximum diesel displacement can theoretically be achieved between 50% – 75% load; however factors such as engine exhaust temperature can prevent maximum diesel displacement, particularly at the higher end of this range. The experience of Noble's LNG campaign has been that in most cases there is a "sweet spot" at about 40 – 60% engine load, which achieves both high fuel efficiency and high diesel substitution.

The drilling rigs Noble used in this campaign had three main engines. It was typical to run all three engines for the duration of drilling a well. This practice is common industry-wide in order to minimize the chance of a brownout or blackout on the rig, which occurs when a large, sudden, power demand cannot be met by the engines in operation. A blackout, particularly, causes a full shutdown of the rig and is both a safety and operational concern.

Running all three engines may be necessary during higher power drilling operations, but there are also points in the drilling process that are much lower in energy demand. Examples of these operations include drilling the shallow part of the vertical section, running casing, and tripping out of the hole. Running all three engines during these types of operations often meant that each of the engines was running at only 20 – 30% engine load for extended periods of time. These lower loads result in low overall fuel efficiency and low diesel substitution with LNG. While it certainly can be difficult to change long-standing operations, shutting down one engine during low power demand operations would increase fuel efficiency and LNG displacement of diesel.

Low loads were common during the testing campaign, but high loads can also limit the amount of diesel substitution with LNG. Noble drilled in some locations using techniques that had higher energy demands. In these locations, the loading on the engines was 70% or higher for a significant amount of the drilling cycle. While the theoretical substitution curve suggests that LNG can still displace some diesel at these higher engine loads, operationally it was found that LNG use dropped off quickly once the engine load exceeded around 70%. This breakpoint may be even lower in extreme heat. At the relatively higher loads, the kits either reduced or shut off the LNG due to deviations in the engine parameters. This is particularly true in extreme climates, for older engines, or for engines in need of maintenance.

Improving the Perception of LNG on Drilling Rigs

Initially, the perception of LNG on the drilling rigs was mixed at best. In the beginning the campaign was generally seen as just another operating hassle by those involved in the day-to-day operations. As with any operation, it can be difficult to make significant changes to the way things have been done for many years. LNG meant additional pieces of equipment, another bill to pay, more vendors to track, and another fuel to store and manage. The cost savings were hard to demonstrate and the site had an overall weariness about the system. Negative comments such as “you can’t run a dual-fuel engine like a diesel engine” were not uncommon. While some of these comments were misplaced, these sentiments spoke to the hesitation of incorporating LNG into operations. (Dual-fuel engines produce the same power and transient performance as diesel-only engines.)

However, notable progress was made. Initial LNG supply and delivery issues were greatly improved, largely due to the supplier relocating an experienced person from another part of the country to provide permanent local support. A considerable effort was made by Noble, Trimeric, drilling operator personnel, and kit suppliers to improve the reliability and performance of the kits Noble continued to operate. Onsite personnel involved came to see that LNG operations helped Noble achieve its larger goals with respect to integrating drilling and fracturing operations with the surrounding community.

Other Factors for LNG Use

Diesel substitution with LNG was lower than expected in the early phases of the campaign. As is often true for operations involving multiple parties, it was sometimes difficult to determine the root cause of issues or and which party was responsible for making corrective actions when the equipment was not operating optimally. In the beginning, some of the rigs experienced difficulty in getting responses from kit manufacturers for service requests or for operation-related inquiries. Since the engines can seamlessly switch to diesel-only operations in the event of LNG system issues, it was easy for operations to ignore persistent or unresolved issues with the kits, particularly when service was slow or unsatisfactory. Eventually, it was determined that there were at least a couple of broken transmitters on the kits which resulted in frequent shutdowns of the LNG system. The kits were not calibrated to optimize substitution with the typical engine loadings, resulting in minimal LNG use at the relatively lower loads where the engines spent significant run time. Frequent communication and prompt supplier support is critical to launching a successful LNG program.

Regular engine maintenance is also important for maximizing LNG use, maintaining optimal engine efficiency, and reducing emissions. One of the common reasons for reduced LNG use was high engine exhaust temperature. While this situation may be difficult to avoid on a hot summer day, proper maintenance will reduce the occurrence.

A final way to increase overall diesel displacement on the rig is to convert the boilers to LNG. This conversion is relatively simple compared to the engine conversion, requires minimal operator attention, and completely eliminates diesel use in that piece of equipment. On cold days, the boiler could account for half of the LNG used on the rig, or more, and can be a significant factor in realizing the benefits of LNG use on a rig.

HYDRAULIC FRACTURING OPERATIONS

Difference in Frac vs. Drilling Operations

Noble also installed dual-fuel kits on the engines on two of their hydraulic fracturing spreads. One spread used Kit B and the other used Kit C. The frac operations were ideal for dual-fuel systems because the engines loadings were consistent and most of the run time was spent around the optimal engine loadings of 50 – 70%. Fracturing operations also do not have the engine load swings that are inherent with drilling operations. These factors allowed for maximum diesel displacement with LNG, with minimal operator intervention required. Additionally, the daily fuel use for the hydraulic fracturing operations was approximately 5 times more than the drilling operations. Using dual-fuel on the frac spreads was a way for Noble to significantly increase diesel displacement in their upstream business.

The frac spreads required daily LNG deliveries due to much higher fuel use than on the drilling rigs. The LNG storage tank onsite was the same as the storage tank on the drilling rigs, but a higher capacity vaporizer was required to meet the fuel demand of the ten engines. Because of the higher fuel demand, a representative from the LNG provider was onsite at all times on the frac spread to oversee the equipment and communicate delivery needs. While this may be cost prohibitive on a drilling rig, the higher fuel use on a frac spread resulted in higher potential for fuel savings, justifying the extra personnel. Having the representative onsite ensured high reliability of the LNG supply system.

Both of the frac spreads consistently used 40% – 50% LNG DGE per well. Operations feedback on the LNG systems was neutral to positive and generally much more positive than the feedback from drilling. The frac spreads did not seem to have issues with the kit suppliers as was seen early in the LNG campaign on the drilling rigs. The kit with the vendor that gave the slowest support on the drilling rigs was not installed on the frac spreads. The consistent engine loadings of the frac spreads also helped to reduce any issues with the kits themselves.

Similar to the drilling rigs, fuel was also tracked for the frac spreads and fuel reports were generated for the stakeholders. Frac fuel reports were issued less frequently than drilling fuel reports; because of the consistent diesel displacement with LNG on frac spreads there was less need for week-to-week fuel tracking. Figure 9 is an example of some of the information provided in the weekly LNG reports for frac spreads.

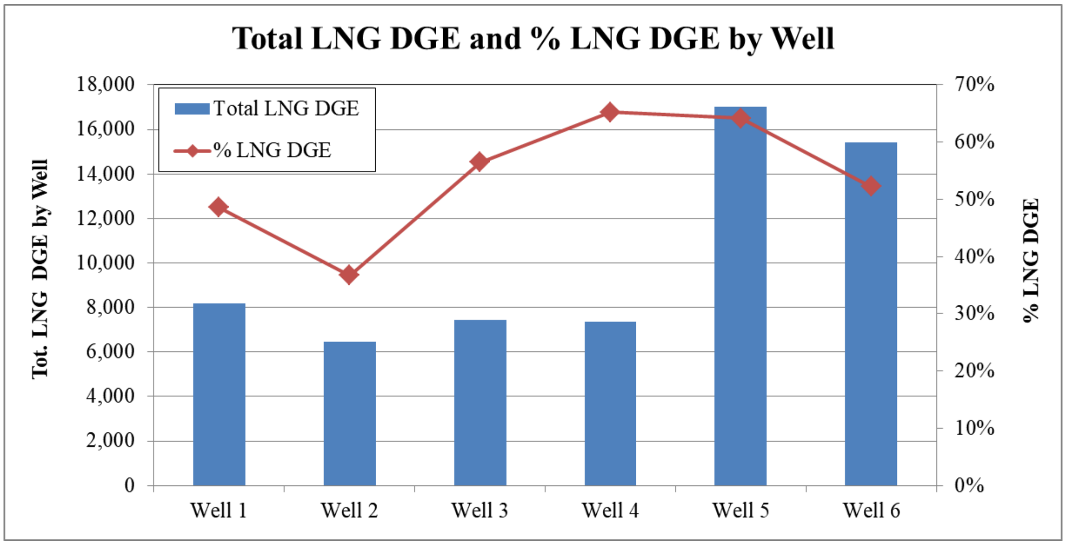

Figure 9 Example Frac Fuel Report: LNG Use by Well

EMISSION TEST CAMPAIGN

Approach to Emission Tests

Noble commissioned emission tests on four of the drilling rigs. Two of the drilling rigs were equipped with Kit A, one was equipped with Kit B, and one was equipped with Kit C. Trimeric led the emissions testing effort and URS Corporation (now AECOM) performed the actual measurements to determine concentrations of compounds of interest and the exhaust flow rates. URS used FTIR spectroscopy with simultaneous measurements upstream and downstream of the oxidation catalyst in the exhaust system to determine concentrations, coupled with tracer gas injection tests to estimate the total exhaust flow rates. (Noble's dual-fuel engines were equipped with catalysts on the exhaust to convert CO and VOC to CO_2.) Concentrations of NO_X, CH_4 and CO were determined. URS also measured formaldehyde and alkane hydrocarbon concentrations, although these were of secondary interest. By use of the tracer gas to estimate exhaust gas flow rates, mass emission rates could be calculated.

One dual-fuel engine was tested on each rig utilizing a load bank, which serves as a large resistor to set a steady load on the engine for the duration of the test. Each engine was tested at several engine loads in dual-fuel mode: 20% load, 35% load, 50% load, and 65% load. The range covered lower loads when the LNG was just being activated, a mid-range load with optimal LNG use, and a higher load when the kits were reducing or stopping LNG delivery. Tests were also conducted for diesel-only operations at 20% load, 50% load, and 65% load for comparison to the dual-fuel operations.

Figure 10 Load Bank (left) and URS Testing Trailer (back)

Figure 11 FTIR Equipment

Emission Tests Conclusions

The specific results of the emission tests are confidential, but this section provides some generalized conclusions from the emission tests. The tests compared the relative performance of each of the kits as well as dual-fuel vs. diesel-only operations. For the dual-fuel vs. diesel-only analysis, comparisons given are for data collected downstream of the oxidation catalyst.

For dual-fuel vs. diesel-only, the tests found reduced NO_X emissions for most of the data points collected. Dual-fuel mode had increased CH_4 emissions, which was expected because methane emissions are near-zero in standard diesel engines. CO emissions were minimal for both operating modes, since the engines were equipped with a catalyst to convert CO to CO_2. The tests did show a significant increase in CO emissions upstream of the oxidation catalyst in dual-fuel mode, which is why it is important to consider a converter for a dual-fuel retrofit of existing diesel engines. It also is noted that particulate matter was not measured. Particulate matter is expected to be significantly reduced by diesel displacement with LNG.

Measured emissions were generally comparable between the three different dual-fuel kits in regards to NO_X, CH_4, and CO. One pattern observed was that at higher loads, methane emissions were less on a relative or percentage basis which further reinforces the importance of good load management. Since the kits had comparable emissions, this also suggests that kit selection can be made based on other factors, such as pricing, operational considerations, maintenance considerations, and supplier support.

PROCESS SAFETY DESIGN

Safety Review Approach and Findings

Noble conducted Process Hazard Analyses (PHAs) for the LNG storage and vaporization unit and two different kits on the drilling rigs. Noble also conducted a PHA for the LNG storage unit, LNG vaporizer, and one type of kit on a hydraulic fracturing spread. The form of PHA chosen was a HAZOP (Hazard and Operability Study). The team did not find any significant safety concerns with the LNG systems. The primary reason for this is that equipment suppliers had already performed internal safety reviews of this commercially available equipment and had already addressed any concerns found in those reviews. One key recommendation that Noble implemented was to install gas detection in the generator house with an emergency shutdown, since an undetected gas leak could have serious safety ramifications. Most of the other findings were related to the interconnecting equipment and ensuring procedures were in accordance with Noble standards. Other example recommendations implemented included hose-whip checks during rig up, cryogenic training for onsite personnel, and implementing procedures to ensure that only authorized personnel work on cryogenic equipment.

It is important to note that this equipment is frequently moved from one site to another. The moves themselves can pose a safety risk. For example, leak checks may be required after each move to a new site. There are also site-specific safety implications at each new site. Ingress and egress for each site, as well as policies for beginning work on each site must be understood and respected by all parties. As an example, it is a requirement to sign in and out on a roster at the site entrance and to check in with a site supervisor before beginning work on each site in order to be aware of any site specific hazards.

CONCLUSIONS

Noble Energy successfully and safely implemented dual-fuel kits on their drilling rigs and hydraulic fracturing spreads. Metrics for tracking dual-fuel system performance were established and used to compare dual-fuel kits. Best performing dual-fuel kits were identified and selected for operations that continue today. Other issues such as ensuring reliable LNG delivery to the site and consistent supply to the engines were completely resolved. Adding LNG fueling options on the boilers can significantly increase LNG use and decrease diesel use at drilling sites. Dramatic changes in costs for diesel and LNG over the course of the campaign highlighted the sensitivity of the LNG systems to fuel costs and related costs such as lease fees for LNG storage and vaporization systems. The LNG program also demonstrated reduced air emissions, lowering the environmental footprint of upstream operations.