The Future of Gas Turbine Technology
8th International Gas Turbine Conference
12-13 October 2016, Brussels, Belgium

Paper ID Number (12-IGTC16)

GAS POWER SYSTEMS FUEL CAPABILITIES

Jeffrey Goldmeer, Ph.D. [1], Michal Knapczyk [2], Patrick Pastecki [3]

[1] GE Power, Gas Power Systems
1 River Road, 37-323
Schenectady, NY 12345, USA
jeffrey.goldmeer@ge.com

[2] GE Power, Gas Power Systems
Engineering Design Center
Aleja Krakowska 110/114
02-256 Warsaw, Poland
Michal.knapczyk@ge.com

[3] GE Power, Gas Power Systems
16415 Jacintoport Blvd.
Houston, TX 77015, USA
pastecki@ge.com

ABSTRACT

The functional objective of any power plant is to produce electricity at the lowest cost possible. This is primarily determined by the operational cost of the fuel consumed. Hence, it is paramount to end users that the energy infrastructure installed provides the greatest fuel flexibility with respect to the composition thresholds and rate of change limits. Drivers for this capability are the expertise, equipment, and experience provided by an OEM to advance the state of the art in gas turbine technologies.

Plant value can be enhanced when gas turbines are capable of operating on alternative fuels that can have elevated levels of inert, heavier hydrocarbon content, or exhibit high variation in composition over a short duration. This is also true when gas turbines are capable of operating on a variety of lower cost liquid fuels.

The purpose of this paper is to illustrate the current technology landscape and recent developments of GE's Gas Power Systems gas turbine product portfolio, which includes both aeroderivative and heavy-duty gas turbines. It is through these recent developments that gas turbines present an opportunity to redefine the vertical integration into end user applications for power generation and mechanical drive. Fuel capability enables new applications of turbines in plant designs and access of new opportunities previously unobtainable.

INTRODUCTION

The process of choosing a fuel for electrical power generation is a complex task that is influenced by multiple factors including fuel price and availability, as well as government policy and regulation. Gas turbines, which are a key part of power generation globally, are capable of operating on a wide variety of gaseous and liquid fuels as described by Jones, et al. (2011), and Schornick, et al. (2013). Even though gas turbines have broad fuel flex capability, many power plant developers and owners select natural gas for power generation due to its availability and low emissions. However, what happens when the supply of natural gas is interrupted due to routine pipeline system maintenance, disturbances at the gas treatment facility, or natural disaster? A large number of power plants have back-up fuel capability to ensure continuous power generation, and for many plants, the back-up fuel of choice is distillate oil #2. Not all power producers want to burn distillate, which is a highly refined product that can be very costly. Instead, some power producers want to use low cost, locally available alternative liquid fuels for power generation.

Since 1980 there have been more than 80 GW of awards for new power plants (over 35 MW in size) using non-traditional fuels. (In this paper, the terms non-traditional and alternative fuels are defined as fuels other than natural gas and distillate fuel oil #2.) These awards required more than 800 new gas turbines.

As the portfolio of non-traditional or alternative power generation fuels expands, it is important to ensure that advanced, highly efficient gas turbines are able to operate on these fuels. This capability includes the ability to operate on an existing hydrocarbon gas or liquid that is being applied for the first time as a power generation fuel, or operating on an existing fuel with increased tolerance of variation in composition.

The ability to operate on a wide range of fuels is not new, nor is the process of expanding the range of potential fuels. The development of these capabilities has been ongoing for decades. As part of this process of developing new combustion technology, GE draws on insights gleaned from more than 70 million fired hours on lean pre-mixed combustion systems, and more than 5 million fired hours operating on low BTU gases and liquid fuels. This field experience is combined with learnings from combustion testing in GE's state of the art test facility to facilitate the development of new combustion systems, including both the gas turbine and required support systems.

The power generation industry continues to request that gas turbines be capable of operating on an ever expanding variety of gas and liquid fuels. Although this is a global phenomenon, alternative power generation fuels tend to be locally generated, and therefore there can be significant variation in the fuels that are seen globally. Figure 1 shows power generation fuels of interest by global region. An example of this is the use of crude oils and other alternative liquid fuels in power plant projects in Saudi Arabia. The Green Duba integrated solar combined cycle (ISCC) project is planning to use a combination of fuels (condensate, natural gas, and Arabian Super Light crude oil) in a pair of F-class gas turbines.

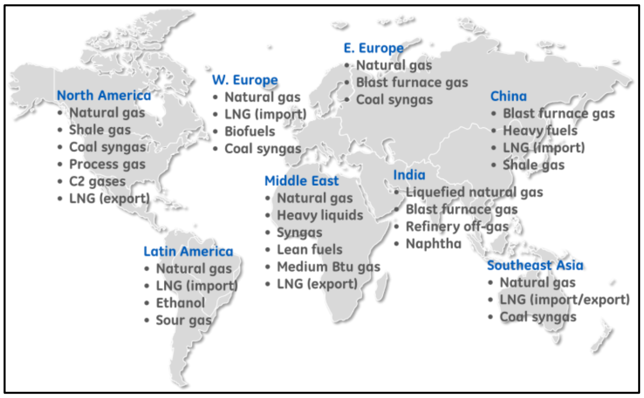

Figure 1 - Regional power generation fuels

A second example is the rising in interest in LPG and ethane as power generation fuels. In the United States, increased production of unconventional gases (which includes shale gas) has caused ethane prices to be at or near parity with natural gas and caused an equivalent drop in LPG. The increased availability of ethane and LPG is driving new infrastructure projects for transporting ethane both domestically and internationally, creating the potential for using ethane as a global feedstock or even as a global power generational fuel potentially acting as a replacement for LNG.

These examples highlight the ever changing requirements of the power generation industry. To meet these changes GE adapts current technology as well as developing technology to provide solutions for new challenges. This also includes the need to expand the fuel capability of GE's gas turbines. This paper will highlight current fuel capability and provide insights into new fuel capabilities.

NOMENCLATURE

AEV	Advanced environment burner
ASL	Arabian super light crude oil
AXL	Arabian extra light crude oil
BFG	Blast furnace gas
BTU	British thermal unit
C2+	Hydrocarbon gas compounds heavier than methane
CBM	Coal bed methane
COG	Coke oven gas
DO #2	Diesel oil #2
DLE	Dry low emissions
DLN	Dry low NOx
DME	Dimethyl ether
EV	Environmental burner
GC	Gas chromatograph
H2	Hydrogen
HFO	Heavy fuel oil
LHV	Lower heating value
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MWI	Modified wobbe index
MGO	Marine gas oil
NG	Natural gas
NOx	Oxides of Nitrogen (NO, NO_2)
RCR	Ramsbottom carbon residue
ROC	Rate of change
T	Temperature

GAS TURBINE FUEL CAPABILITY

GE's gas turbines are capable of operating on a wide variety of gas and liquid fuels. The graphic in Figure 2 highlights many of the fuels that can be used in conjunction GE's aeroderivative and/or heavy-duty gas turbines. More details of gas turbine performance on standard natural gas, as well as capabilities for ethane, propane, hydrogen, and inerts are shown in Table 1.

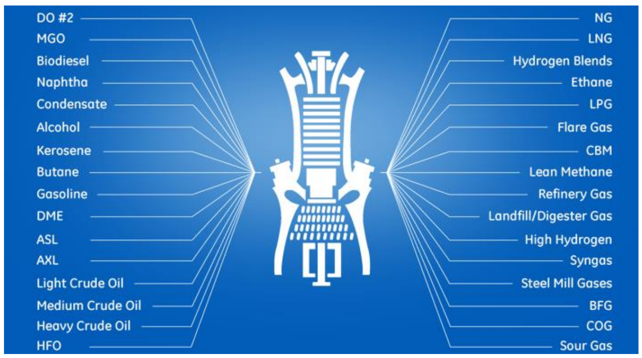

Figure 2 - GE gas turbine fuel capabilities

This table presents the capability of the premixed combustion system, typically referred as dry low emissions (DLE) or dry low NOx (DLN) combustors. NOx emission and turndown have been provided based on a standard fuel, i.e. pipeline quality natural gas. For non-standard fuels in general, an increase in amount of H2 and/or C2+ increases the NOx emissions, while increase in amount of inerts decreases the NOx emissions. However, the emissions capabilities on non-standard fuels will vary based on project specific fuel composition as well as on ambient conditions and site location.

Additional rows provide an overview of nominal wobbe variation (%). The maximum amounts of specific components (by volume %) such as hydrogen, inerts, or higher order hydrocarbons included are based either on specification limits, validated values resulting from combustor or full-scale gas turbine testing.

Table 1 – Nominal GE Gas Power Systems gas turbine (DLE/DLN) fuel capabilities

Gas turbine	LM2500[(1)]	LM6000[(1)]	LMS100[(1)]	6B.03	7E.03, 9E.03, 9E.04	13E2	6F.01	6F.03
Combustor	DLE	DLE	DLE 2	DLN 1/1+	DLN 1/1+	AEV	DLN 2.5	DLN 2.6
Simple cycle output (MW)	23.8-37.1	45 - 57	108-117	44	91/132/145	203	52	82
NOx (ppm) @15% O2	25	25	25	4	15	15	25	15
Min Turndown (% load)	50%	25%, 50%	50%	50%	35%	70%	40%	52%
CO (ppm) @ 15% O2 at min turndown w/o abatement	25-250	25-150	125-139	25	25	80	9	9
Wobbe Variation (%)	± 20%	± 20% - ± 25%	± 20%	> ± 30%	> ± 30%	± 10%	± 10%	+10% -15%
Ethane (vol %)	~30-35%	~15-24%	~15%	100%	100%	~23%	~25%	~15%
Propane (vol %)	~35%	~15-24%	~15%	~100%	~100%	~23%	~15%	~15%
H2 (vol %)	~5%	~5%	~5%	~30-32%	~30-32%	~5%	~ 0%	~5%
Inert (vol) % (CO2, N2)	~50%	~25-30%	~15%	~40%	~40%	~20%	~5%	~15%

Gas turbine	9F.04	9F.06	7F.05	7F.06	9HA.01	9HA.02	7HA.01	7HA.02
Combustor	DLN 2.6+	DLN 2.6+	DLN 2.6+	DLN 2.6+	DLN 2.6+ AFS	DLN 2.6+ AFS	DLN2.6+ AFS	DLN2.6+ AFS
Simple cycle output (MW)	281	342	232-241	270	429	519	280	346
NOx (ppm) @15% O2	15	15	5-12	9	25	25	25	25
Min Turndown (% load)	35%	38%	44 - 46%	30%	30%	30%	25%	30%
CO (ppm) @15%O2 at min turndown w/o abatement	24	9	9	9	9	9	9	9
Wobbe Variation (%)	± 15%	± 15%	± 7.5%	± 7.5%	± 15%	± 15%	± 10%	± 10%
Ethane (vol %)	~25%	~25%	~25%	~25%	~25%	~25%	~25%	~25%
Propane (vol %)	~35%	~25%	~35%	~25%	~35%	~35%	~25%	~25%
H2 (vol %)	~5%	~5%	~5%	~5%	~5%	~5%	~5%	~5%
Inert (vol) % (CO2, N2)	~15%	~15%	~30%	~15%	~15%	~15%	~15%	~15%

Note 1 - There are multiple configurations available for GE's Aeroderivative gas turbines as well as the 13E2, and the values presented in this table are representative of the capability of the specific gas turbine model. Actual performance and capability are site and fuel specific.

GE's aeroderivative and heavy-duty gas turbines can also be configured with diffusion flame combustors. On an aeroderivative gas turbine, this is the single annular combustor (SAC). On heavy-duty gas turbines there are two configurations, the single nozzle (SN) or standard combustor, and the multi-nozzle quiet combustor (MNQC). These combustors have much larger fuel capabilities than DLE or DLN combustion systems, including the capability to operate on synthesis gas (syngas), high H2 fuels, and a variety of liquid fuels (i.e. distillate, crude oil, heavy fuel oil). For example, GE's fleet leader on the use of high H2 fuels is 6B.03 (configured with a Standard Combustor) that has over 100,000 fired hours on a fuel with a hydrogen concentration that varies from 85-95%. NOx emissions from diffusion flames are much higher than from lean premixed flames (i.e. DLE or DLN combustors) and are mitigated through the use of diluent injection (i.e. water, steam, nitrogen).

Although not addressed directly in this table, GE is committed to continuing to expand the fuel capabilities of its products. This also includes capabilities of burning non-standard fuel that are challenging today or are yet unknown and will emerge in the future. As these fuels emerge, we explore them analytically and via in-depth test campaigns of varying complexity to adjust or modify our products.

Aeroderivative gas turbine fuel capability

GE's Aeroderivative gas turbines are flexible and reliable power generation packages with aviation derived engines. The installed fleet has over 100 million operating hours of experience, including operation on a variety of power generation fuels as described by Knapczyk (2015), including natural gas, distillate, kerosene, liquefied petroleum gas (LPG), propane, synthetic gas (syngas), coke oven gas and others shown in Figure 1. As aeroderivative turbines are frequently used in industrial applications, the ability to handle rapid fuel composition changes in the fuel may be a critical requirement. The next sections summarize this capability.

<u>MWI Rate of Change</u>

The ability of a gas turbine to maintain operability during a change in fuel composition before the change is fully measured and reported to the controls system represents tolerance to fuel variability. This error tolerance in LHV is a function of the combustion system, fuel quality sensor, and the controls system capabilities. The permissive LHV error tolerance can be found using the ratio of the gas turbine error tolerance over the cumulative instrument response time. This provides a time resolved metric that defines acceptable or non-compliant changes in gas fuel properties.

$$Rate\ of\ Change\ \left[\frac{\%}{second}\right] = \frac{System\ Error\ Tolerance\ [\%]}{Instrument\ Response\ Time\ [seconds]} \quad (1)$$

The inertia of a gas turbine's instantaneous operating conditions results in limited tolerance to change in LHV, especially without a known terminating point for a transient. Excursions outside acceptable engineering tolerances may manifest as unfavorable emissions, acoustics, and the possible change or loss in power output from the gas turbine.

An example of fuel variability is illustrated in Figure 3 in a three hour observation of the gas fuel heating value at a customer site that is subject to periodic variation. The black line represents the actual volumetric lower heating value (Btu/scf). The light blue line represents a gas chromatograph signal with cumulative response time of 180 seconds and corresponding value. The green and red lines represent the upper and lower specification limit of the ±0.5% and ±1.5% error tolerances, respectively.

Within this survey of gas properties there was a transient event that occurred faster than the capability of the gas chromatograph (GC) to measure and report the gas fuel properties on a practical time scale. A smaller subset of data during the disturbance is presented in Figure 4 to illustrate the time periods of stable operation and the transition into the potentially non-compliant operational conditions as the fuel sensor signal lags to measure the actual gas properties when they change rapidly.

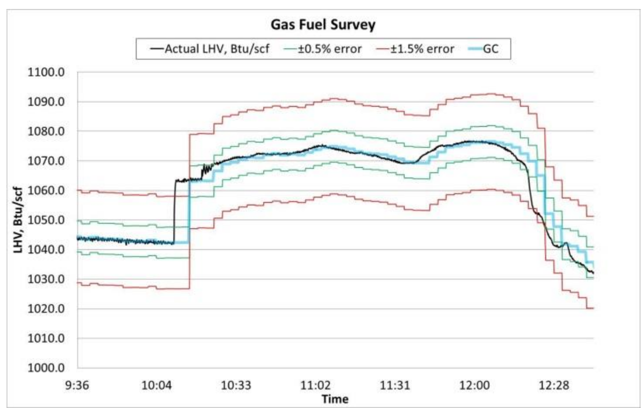

Figure 3- Three hour gas survey from customer site

The left hand side of Figure 4 represents a transient gas properties event in which the rate of change in the baseline reference LHV measurement exceeds the assumed gas chromatograph signal with the latency of three minutes. The gas chromatograph cannot detect changes in gas properties that are taking place within the response time of the instrument, resulting in the potential for imminent operability issues, if this sensor is the primary guidance system for gas turbine fuel schedule. The right hand side of Figure 4 represents the GE proprietary gas fuel property tracking system algorithm's ability to retire the risk of the fuel variability and provide compliant operability.

Figures 5 and 6 represent a longer 10 hour observation period. The plots depict the LHV output signals versus the percent relative change from previous measurement value. Lower part of each plot illustrates the distribution of frequency of these LHV measurements in 0.05% bin increments. The comparison of Figures 5 and 6 illustrates the difference in capability between the GC and algorithm-based fuel property signals. For the GC, there are points when the LHV signal diverges significantly from the actual properties, because it cannot be resolved fast enough for the rate of change observed in this example.

The nominal operation of the gas turbine takes place within the desired ±0.5% LHV error tolerance range. Excursions above ±0.5% and below ±1.5% LHV produce the potential for operability issues of emissions, acoustics or stage down in power output . Operation in excess of the ±1.5% LHV error tolerance will increase the potential for an engine trip.

The purpose of a fuel sensor is to provide a replica of physical phenomenon and dynamics taking place upstream of the point of use to schedule fuel flow appropriately to maintain a stable GT operation. When there is a divergence in the actual and reported gas properties, maintaining stable operating conditions may become more difficult. The latency in measured and reported gas properties presents an information gap, in which signal error is introduced into controls systems, that may become the source of poor operability, which may result in high emissions, acoustics, or possibly an engine trip from unsustainable combustion conditions. Figure 7, further discussed below, represents the enhanced accuracy of the GE proprietary gas fuel property tracking system algorithm, which maintains the gas turbine within the acceptable operating range.

<u>*Robust response to dynamics fuel composition changes*</u>

As shown above, rapid excursions in fuel composition can occur in real applications. When this happens, the gas turbine needs a robust control system capable of maintaining stable operation of the gas turbine. To validate this capability a rapid fuel change was demonstrated on a LM2500+G4 DLE. In this evaluation, natural gas was mixed with HD5 propane to obtain C2+ mole concentrations of up to 50% to produce, at each power setting, a target MWI of 63. (HD5 is a propane specification that limits non-propane constituents to less than 10% (by volume) of the gas.)

During the demonstration of step changes in fuel composition and MWI, there were no difficulties with burner mode staging, no difficulties with steps to minimum load or idle, no flameouts, no trips, and no observed unstable operation. The gas turbine operated at steady state at a high power output. Enriched fuel composition was validated with a GC measurement prior to the demonstration of dynamic fuel MWI variation. Additional metrics referencing the 48 MWI baseline heated natural gas were provided for context of the transient event. The rate of change capability was demonstrated by the execution of the MWI ramp rate >3.7% /second between MWI values, as shown in Figure 7.

The transient events produced in this demonstration validated greater fuel flexibility and robust performance by leveraging the GE proprietary logic and balance of plant hardware in a fuel schedule guidance system. This system provides stable power output while limiting sustained high acoustics, incipient blowouts, and other potential adverse behavior, all without operator intervention.

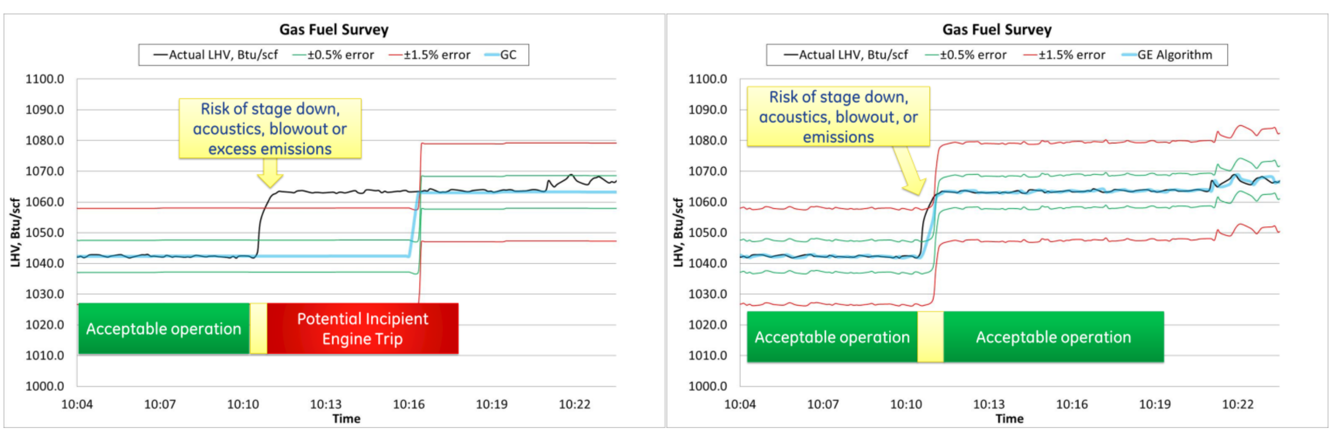

Figure 4 - Comparison of lagging GC signal and algorithm signal during a transient composition event

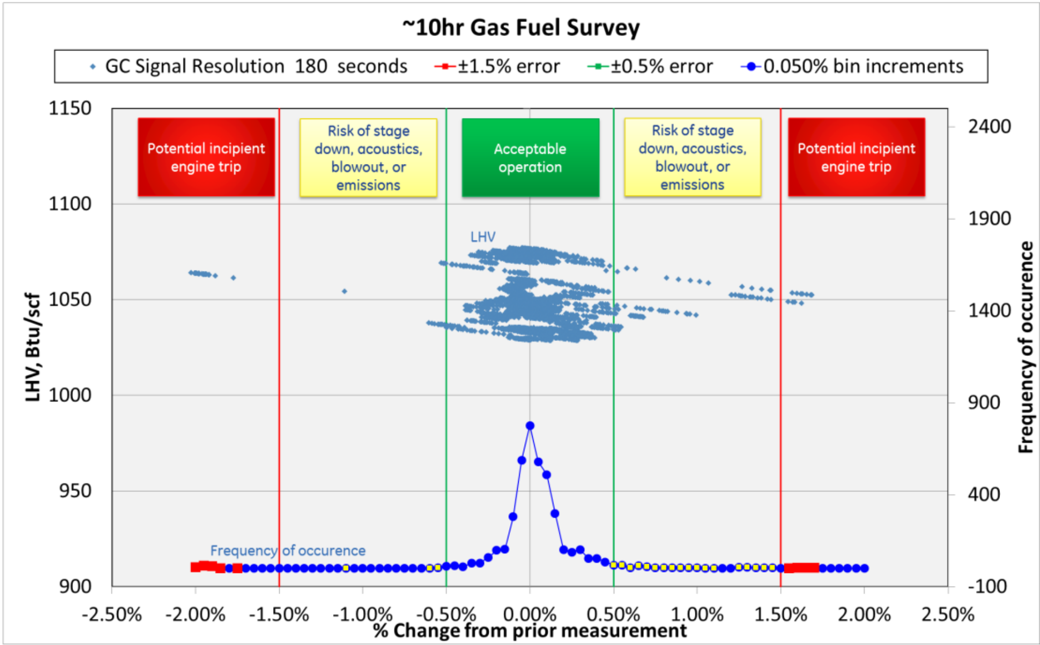

Figure 5 - GC LHV resolved by percent change in adjacent measurements during the fuel survey

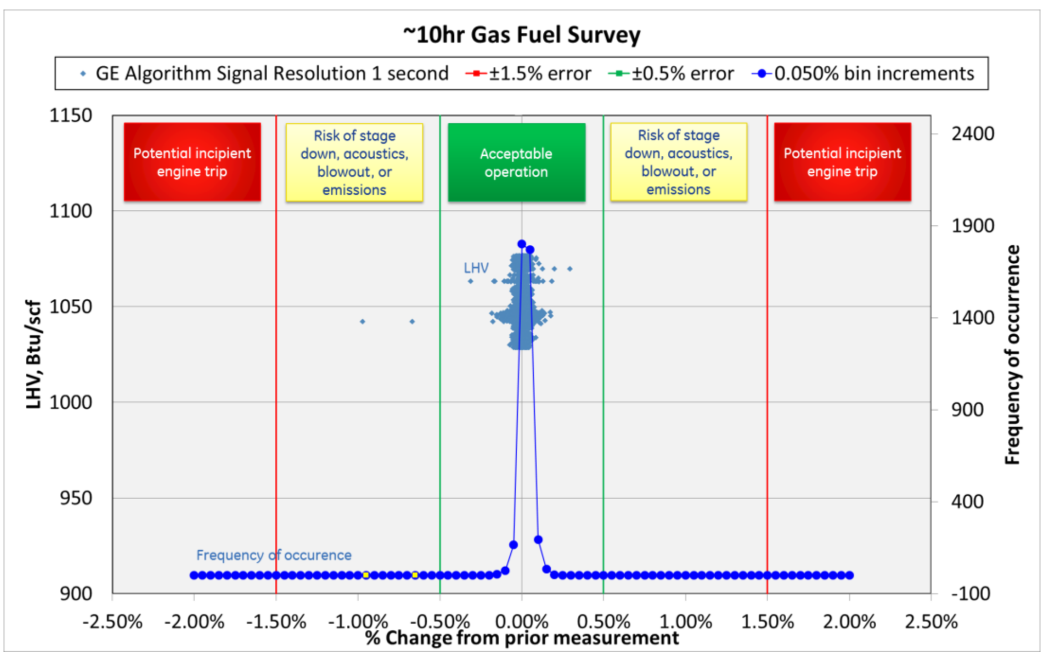

Figure 6 - Algorithm produced LHV resolved by the percent change in adjacent measurements during the fuel survey

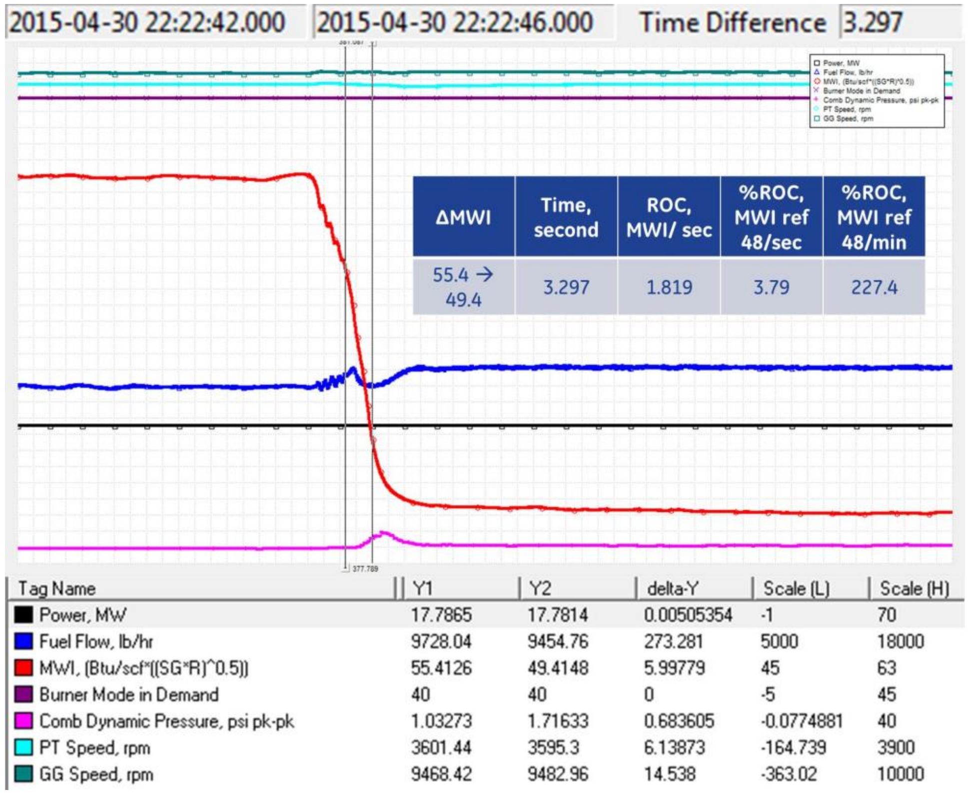

Figure 7 - Operation at > 3.7% MWI/second rate of change on a LM2500+G4 DLE using blended natural gas and HD5 propane

Heavy-duty gas turbine fuel capability

GE's heavy duty gas turbines platform includes E, F and H-class products. GE introduced F-class technology nearly 30 years ago and has the world's largest fleet, with more than 1,100 installed units, and 50 million operating hours of experience. The E-class turbines are rugged even in harsh climates with the capability to operate on a wide variety of alternative gas and liquid fuels. The installed fleet includes more than 3,000 units and more than 143 million operating hours of experience.

Over the last few years, there have been shifts in large utility scale power generation and the need to burn alternative fuels. One example is the need to operate F-class gas turbines with DLN combustors on crude oil, and the ability for large frame gas turbines to operate on fuels with shifts in heating value.

Non-methane hydrocarbon capability

GE's heavy-duty gas turbines are capable of operating on a variety of fuels, including fuels with significant non-methane hydrocarbon content. This capability can be segmented into two categories: blending of hydrocarbons, and pure (hydrocarbon) fuels.

GE's B and E-class turbines are capable of operating on a range of gaseous fuels, including ethane and propane. Ethane, propane or LPG can be used either blended with natural gas or as single fuel in a DLN1 or DLN1+ combustion system. GE's F-class turbines can operate a blend or 100% ethane. The 6F.01 and 6F.03 with DLN2.5 and DLN 2.6 combustors, respectively, can operate with a blend of these fuels and natural gas, up to 15% non-methane on the 6F.03 and 25% ethane on the 6F.01. The 7F.05 and 9F.04 gas turbines configured with the DLN2.6+ combustion system can operate with a blend up to 25% ethane. For these gas turbines, operating with 100% ethane (or other hydrocarbon) requires a MNQC combustor. This capability exists for both new units and units in the field. Existing units may require updates and/or configuration changes for combustion and fuel accessories as well as controls. In addition, the 7HA and 9HA gas turbines configured with the DLN2.6+ combustion system are capable of operating on ethane blends.

GE has experience blending fuels in a variety of applications. An example is a petrochemical plant that had excess hydrogen, which was blended into natural gas and used with a set of 7F.03 gas turbines configured with the DLN2.6 combustion system as described by Goldmeer and Rojas (2012). For this application, GE provided advanced controls and the fuel blending system, including the blending hardware, which is shown in Figure 8.

Figure 8 - Fuel blending system hardware

Use of crude oil on F-class gas turbines

Arabian Super Light (ASL) crude oil is a stabilized crude oil that was being considered for use as back-up fuel for advanced F-class gas turbines (configured with DLN combustion systems) in Saudi Arabia. To determine if this oil would be a viable fuel for use with DLN combustion systems, a detailed fuel evaluation procedure was followed as described by Goldmeer (2014). This evaluation included detailed analytical characterization of ASL, combustion test, and culminated with field operation. Details of the evaluation are provided by Goldmeer, at al. (2015), and Goldmeer at al. (2014).

The results of a comparison to distillate are shown in Table 2; note that many properties are the same. The most significant difference in this data was the carbon residue. The ramsbottom carbon residue (RCR) is determined by taking a fuel sample of a given weight and heating at high temperatures until nothing but solid carbon remains. The reported RCR value is the percentage of the final weight of the solid carbon to the weight of the original liquid fuel sample. This parameter is an indicator of a fuel's propensity to form carbon-rich deposits, often referred to simply as "coke".

The evaluation of ASL required multiple steps, including ignition studies and full pressure, full temperature single nozzle combustion testing. The ignition testing evaluated the ability of ASL to ignite in an atmospheric test facility. (As ASL is a true crude oil, it had a broader distillation curve, with the potential for increased volatility.) A picture of the ASL flame from the ignition study is shown in Figure 9. The single nozzle combustion testing yielded a large set of data which showed that ASL is very similar to distillate. As an example, figure 10 shows non-dimensional NOx and CO emissions from ASL compared to distillate; note that the ASL and distillate emissions were very similar. The same trend was found when comparing combustion dynamics and combustion liner temperatures.

Table 2 – Comparison of ASL crude oil and distillate

PROPERTIES	Unit	ASL	Distillate
Heating value (Gross)	BTU/lbm	19329	19420
Density	g/cc	0.778	0.83
Viscosity @ 37.7 °C (100°F)	cSt	1.76	2.6
Carbon	Weight %	86.36	85
Hydrogen (calculated)	Weight %	13.6	13
Ash	ppm (mass)	3	100
Ramsbottom carbon residue	Weight %	0.32	0.035

Figure 9 - ASL flame

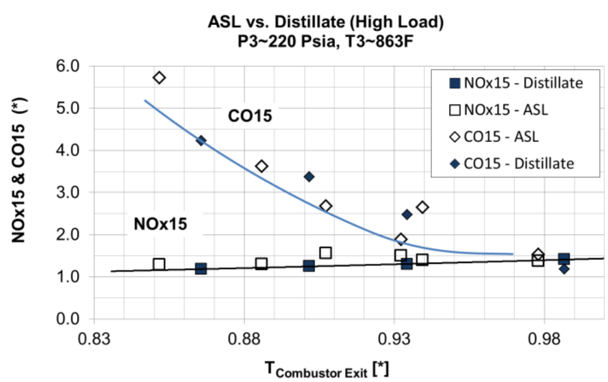

Figure 10 - Comparison of ASL and distillate emissions

The next step in the process was a field evaluation of ASL. This was performed at the Riyadh PP11 power plant in Saudi Arabia. The plant is shown in Figure 11. In the first phase of the demonstration, the gas turbine was fired on ASL at part load (~38% of base load) for roughly 22 hours. In the second part of the test, the gas turbine was operated on ASL at base load. The seven gas turbines at

Figure 11 - Riyadh PP11 combined cycle power plant

this site have since been fully commissioned on ASL and are in commercial operation. Including this plant, GE has been awarded 33 F-class gas turbines in Saudi Arabia that will use ASL as back-up fuel, including Riyadh Power Plant 12, which has commissioned it's eight GE 7F.05 gas turbines on ASL.

SUMMARY

Robust operation and flexibility are key requirements for power generation applications. The ability of a gas turbine to operate on a wide variety of fuels provides a path to change the feasibility and economics of potential opportunities. Shifts in fuel availability and economics have driven some power generators to look at new fuels, or fuels that would not have been considered in the past. GE's aeroderivative and heavy-duty gas turbines are capable of operating on a wide variety of fuels, and can provide robust operability for power generation in a variety of applications.

REFERENCES

Jones, R., Goldmeer, J., Monetti, B., 2011, "Addressing Gas Turbine Fuel Flexibility", GER4601B, GE Power & Water.

Goldmeer, J., Rojas, T., 2012, "Burning a mixture of H2 and natural gas" Turbomachinery International, Jan/Feb 2012, p. 24.

Goldmeer, J., 2014, "Gas Turbine fuel evaluation process: A case study on the application of Arabian Super Light Crude oil for use in GE 7F-class Dry Low NOx (DLN) combustion systems", Power Gen International, Pennwell.

Goldmeer, J., Kihara, K., Fujimoto, H., 2015, "Recent advancements in gas turbine fuel flexibility", International Gas Turbine Congress 2015, Tokyo, Japan, paper 210.

Goldmeer, J., Symonds, R., et al, 2014, "Evaluation of Arabian Super Light Crude Oil for use in a F-class DLN Combustion System", ASME TurboExpo, GT2014-25351.

Knapczyk, M., 2015, "GE's Aeroderivative Gas Turbines Fuel Flexibility for Japan", International Gas Turbine Congress 2015, Tokyo, Japan.

Schornick, J, Knapczyk, M., Pastecki, P., DiCampli, J., 2013, "Aeroderivative Gas Turbine Fuel Flexibility", PowerGen Asia, Pennwell.