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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

Contents

Abstract

Ash-bearing heavy liquid fuels, such as crude oil or heavy fuel oil, have traditionally only been used by B and E-class turbines for power generation. While these crude oils contain high levels of metal contaminants, some can potentially be used in F-class turbines. In particular, Arabian Super Light (ASL) crude oil's unique properties—including low levels of vanadium—make it an excellent candidate for use as a fuel for heavy-duty gas turbines.

This paper presents a case study of GE's fuel evaluation process using ASL. It details the steps required to validate a new fuel for use in a gas turbine. Using this process, GE determined that ASL is a viable fuel for use in F-class gas turbines. The study concluded with a field demonstration of GE's 7F gas turbines successfully running on ASL in Saudi Arabia. This significant milestone offers the first example of an F-class gas turbine running on crude oil.

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 play a key role in global power generation—can operate on on a wide variety of gaseous and liquid fuels [1]. While gas turbines offer broad fuel flexibility, many power plant developers and owners select natural gas for power generation due to its wide 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 lower cost, locally available alternative liquid fuels for power generation. For example, the use of crude oil as power generation fuel is an attractive idea in the Middle East. Specifically, in Saudi Arabia there is interest in using Arabian Super Light (ASL) as fuel in advanced F and HA-class turbines configured with Dry Low NOx (DLN) combustion systems.

For many years, crude oils have been successfully used as fuel for B and E-class gas turbine power generation applications. To date, GE has more than 190 E-class turbines that have operated on crude oil or heavy fuel oil, accumulating more than 5 million operating hours. Using crude oil as a fuel adds additional complexity over refined liquid fuels, especially when considering using these oils in F-class turbines. Some of the operational challenges associated with operating a gas turbine with crude oil are highlighted in Figure 1.

Crude oil can contain a variety of components that can lead to corrosion, erosion, and fouling in a gas turbine. Sodium (Na) and potassium (K) can cause corrosion, but they can be removed by washing the fuel. The upper limit on these metals varies by original equipment manufacturer; GE's liquid fuel specification permits continuous operation with up to 1 ppm of sodium and potassium [2]. In certain conditions, liquid phase paraffin components in crude oil can solidify creating solid wax particulates that can impact the operability of the fuel accessory system. Crude oil also contains vanadium (V), which is typically present as part of the heavy, oil soluble fuel components, and unlike sodium and potassium, cannot be removed with a water wash. In the gas turbine, vanadium can contribute to accelerated hot gas path hardware corrosion. GE's liquid fuel specification permits continuous operation with up to 0.5 ppm of vanadium without treatment; above 0.5 ppm of vanadium, GE required that an

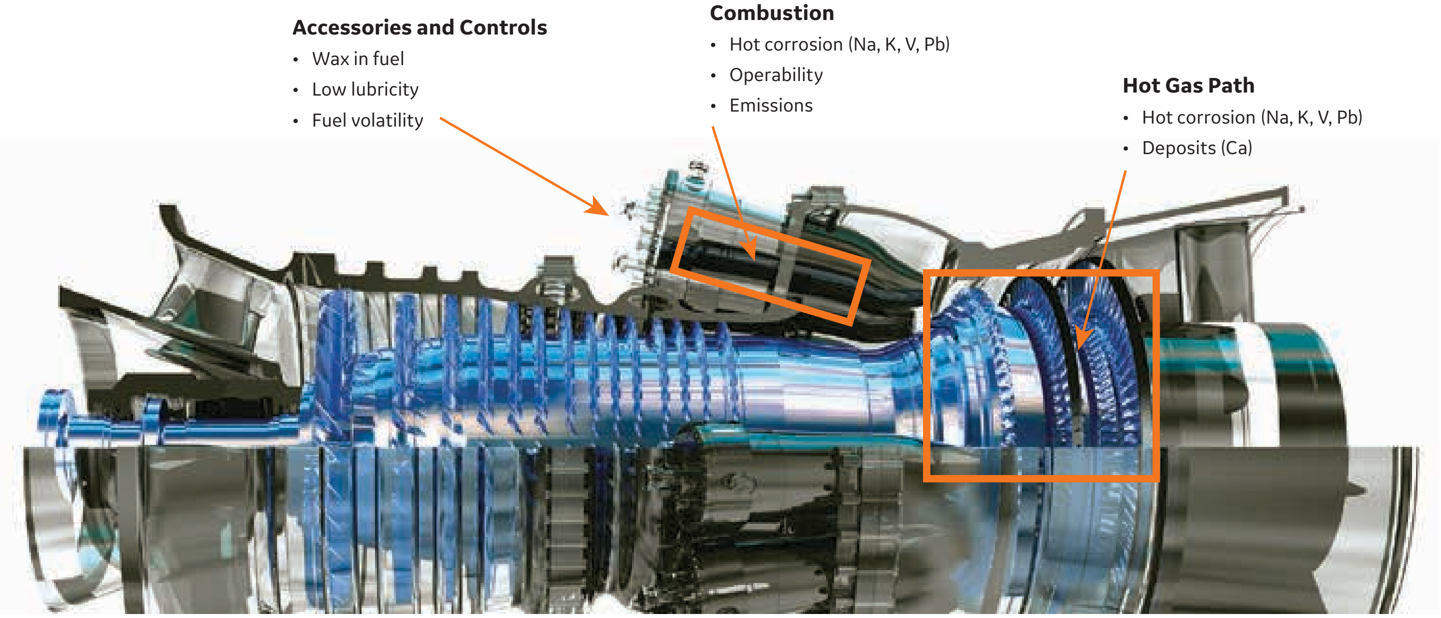


Figure 1 - Operational challenges with crude oils

inhibitor be added to the fuel to prevent the formation of corrosive ash [2]. Fuel with high levels of carbon residue can potentially create coke deposits on fuel nozzles, which may affect liquid fuel injection. The presence of other fuel contaminants can lead to fouling in the hot gas path. Examples of these operational challenges are shown in Figure 2.

Thus, before approving a new fuel, it is critical to have a complete understanding of a fuel's physical properties as well as specific details about components that can impact gas turbine performance, operability and/or hardware durability. This paper presents the process GE uses to determine if a new fuel is viable for use in a heavy-duty gas turbine, while specifically addressing the question of ASL applicability for use in an F-class gas turbine as a case study.

Characterization of new power generation fuels

Before providing details on the evaluation of ASL, it is important to understand the overall process used to evaluate a new gas turbine fuel. This multi-step process determines specific fuel characteristics and properties related to combustion and fuel handling. The four typical, major steps shown in Figure 3 establish the fuel source, analytic fuel characterization, fuel (combustion) testing, and field demonstration. Each step can include multiple sub-steps required to provide detailed information on a specific fuel property or characteristic. Depending on results of fuel testing, additional analytical characterization may be required. If during the fuel characterization step, it is determined that the new fuel is similar to a fuel that is already approved, some portion or all of the final steps could be eliminated.

1. Fuel source determination

Knowing the source of a fuel, the type of fuel (gas or liquid, and refined or unrefined for a liquid), fuel pre-treatments, and transport logistics are key to being able to determine applicability of a fuel for a gas turbine. If the fuel is being generated from a refining operation or a chemical process, are there controls in place to ensure consistent fuel composition, or might this vary over time, and if so, by how much? If the fuel is being taken directly from a well, are there any planned pre-treatments? What contaminants might be present in the fuel that could affect gas turbine operability, performance, or component durability? How will the fuel be transported to site, and might this introduce any variation or contaminants? The answers to these questions are important as they can provide insights to help guide the next steps of the process.

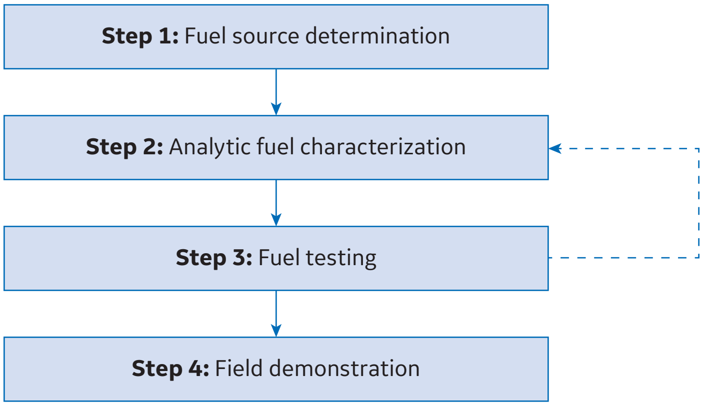
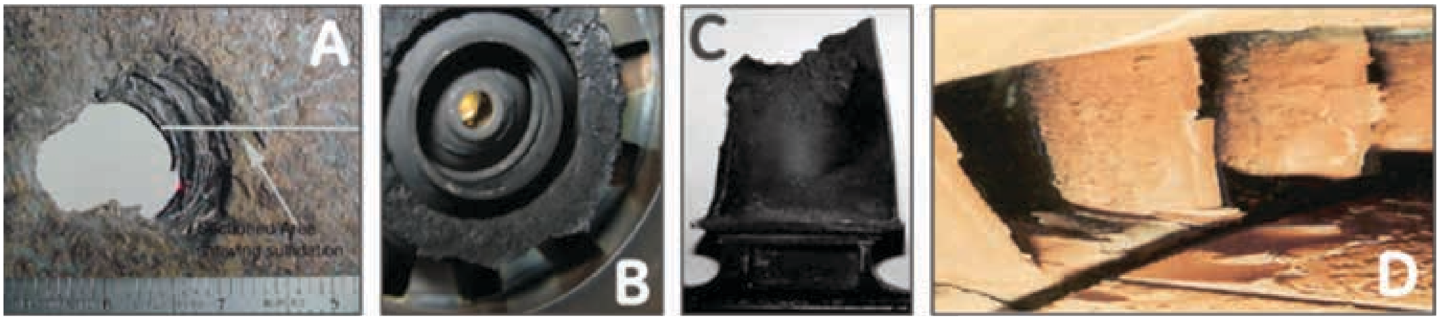


Figure 3 - Fuel evaluation process

2. Analytic fuel characterization

It is important to understand fuel composition and key fuel properties before using a new fuel in a gas turbine. In the case of a gaseous fuel, a detailed listing of the percent (by volume) of each constituent gas is required to determine the heating value, Modified (temperature corrected) Wobbe Index, as well as potential risks from contaminants such as hydrogen sulfide. This information allows the fuel to be properly matched to the appropriate combustion system. GE provides fuel analysis data sheets (see Figure 4) for the various fuel properties along with suggested American Society for Testing and Materials (ASTM) methods for measuring the various properties [2, 3].



(A) Corrosion on a transition piece
(B) Coke build up on a fuel nozzle tip
(C) Corrosion of a turbine bucket
(D) Fouling in the hot gas path

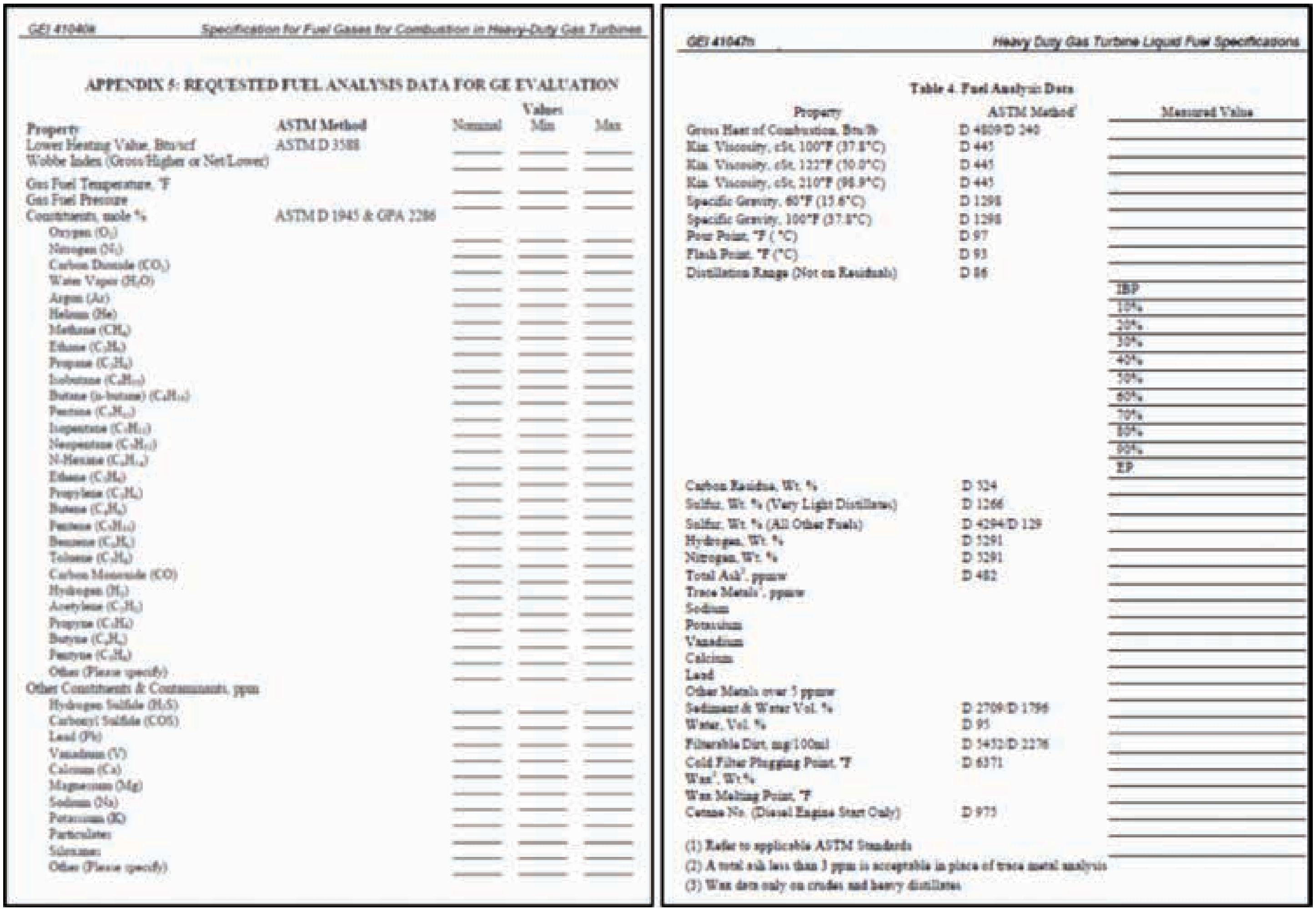
Figure 2 - Examples of coking, corrosion, and fouling

Evaluating liquid fuels is even more complicated because a list of individual components is not always readily available. Typically the liquid fuel's heating value, density (specific gravity), and kinematic viscosity are available. Additional information that is required, but not always initially available includes the flash point, carbon residue, and distillation curve, as well as specific information on the content of hydrogen, H2S, ash, and wax.

The distillation curve helps determine if the fuel is a refined product (which will have a narrow curve with well-defined initial and final boiling points) versus an unrefined liquid fuel, such as a crude oil (which will have a broad curve). It is also necessary to perform detailed analyses to determine if there are any metals (sodium, potassium, vanadium, calcium, or lead) in the fuel, that can lead to erosion, corrosion, and/or fouling of turbine components.

As part of this process, an OEM may require that a detailed physical and chemical analyses be performed on a collection of small samples. In many cases, the samples can be sent to third party, ISO certified laboratories to perform the needed tests.

Once all of the required information has been collected, an initial determination of the applicability of the fuel can be made, and, if it is found to viable, testing of specific fuel characteristics can proceed. An additional task in this step is an initial determination of the applicable combustion system; this is critical in defining the specific combustion hardware (fuel nozzles, liners, etc.) and fuel system to be used in the fuel-testing step. Depending on the properties of the fuel, the volume of fuel available (which can set the size or class of the gas turbine), and the application being considered, there can be multiple combustor options, including diffusion flame combustor or premixed (Dry Low NOx) combustor. GE offers a variety of combustion systems, some of which are highlighted in Figure 5.



GEI 41040k *Specification for Fuel Gases for Combustion in Heavy-Duty Gas Turbines*

APPENDIX 5: REQUESTED FUEL ANALYSIS DATA FOR GE EVALUATION

Property	**ASTM Method**	Values		
		Nominal	Min	Max
Lower Heating Value, Btu/scf	ASTM D 3588			
Wobbe Index (Gross/Higher or Net/Lower)				
Gas Fuel Temperature, °F				
Gas Fuel Pressure				
Constituents, mole %	ASTM D 1945 & GPA 2286			
Oxygen (O_2)				
Nitrogen (N_2)				
Carbon Dioxide (CO_2)				
Water Vapor (H_2O)				
Argon (Ar)				
Helium (He)				
Methane (CH_4)				
Ethane (C_2H_6)				
Propane (C_3H_8)				
Isobutane (C_4H_{10})				
Butane (n-butane) (C_4H_{10})				
Pentane (C_5H_{12})				
Isopentane (C_5H_{12})				
Neopentane (C_5H_{12})				
N-Hexane (C_6H_{14})				
Ethene (C_2H_4)				
Propylene (C_3H_6)				
Butene (C_4H_8)				
Pentene (C_5H_{10})				
Benzene (C_6H_6)				
Toluene (C_7H_8)				
Carbon Monoxide (CO)				
Hydrogen (H_2)				
Acetylene (C_2H_2)				
Propyne (C_3H_4)				
Butyne (C_4H_6)				
Pentyne (C_5H_8)				
Other (Please specify)				
Other Constituents & Contaminants, ppm				
Hydrogen Sulfide (H_2S)				
Carbonyl Sulfide (COS)				
Lead (Pb)				
Vanadium (V)				
Calcium (Ca)				
Magnesium (Mg)				
Sodium (Na)				
Potassium (K)				
Particulates				
Siloxanes				
Other (Please specify)				

GEI 41047m *Heavy Duty Gas Turbine Liquid Fuel Specifications*

Table 4. Fuel Analysis Data

Property	ASTM Method[1]	Measured Value
Gross Heat of Combustion, Btu/lb	D 4809/D 240	
Kin. Viscosity, cSt, 100°F (37.8°C)	D 445	
Kin. Viscosity, cSt, 122°F (50.0°C)	D 445	
Kin. Viscosity, cSt, 210°F (98.9°C)	D 445	
Specific Gravity, 60°F (15.6°C)	D 1298	
Specific Gravity, 100°F (37.8°C)	D 1298	
Pour Point, °F (°C)	D 97	
Flash Point, °F (°C)	D 93	
Distillation Range (Not on Residuals)	D 86	
		IBP
		10%
		20%
		30%
		40%
		50%
		60%
		70%
		80%
		90%
		EP
Carbon Residue, Wt. %	D 524	
Sulfur, Wt. % (Very Light Distillates)	D 1266	
Sulfur, Wt. % (All Other Fuels)	D 4294/D 129	
Hydrogen, Wt. %	D 5291	
Nitrogen, Wt. %	D 5291	
Total Ash[2], ppmw	D 482	
Trace Metals[2], ppmw		
Sodium		
Potassium		
Vanadium		
Calcium		
Lead		
Other Metals over 5 ppmw		
Sediment & Water Vol. %	D 2709/D 1796	
Water, Vol. %	D 95	
Filterable Dirt, mg/100ml	D 5452/D 2276	
Cold Filter Plugging Point, °F	D 6371	
Wax[3], Wt.%		
Wax Melting Point, °F		
Cetane No. (Diesel Engine Start Only)	D 975	

(1) Refer to applicable ASTM Standards
(2) A total ash less than 3 ppm is acceptable in place of trace metal analysis
(3) Wax data only on crudes and heavy distillates

Figure 4 - GE's fuel analysis data sheets for gas and liquid fuels

Multi nozzle quiet combustor

DLN1 combustor

DLN2.6+ combustor

Figure 5 - GE's gas turbine combustion systems

3. Fuel testing

The analytical examination of the fuel provides insights into combustion and/or fuel handling properties, which can determine the types of tests needed to evaluate the risk of using a new fuel. For example:

- A liquid fuel with a large carbon residue might be prone to coking, which could result in a blocked fuel line or a blocked fuel injector
- A gaseous fuel with a large percentage of a highly reactive fuel component might create a flashback risk

These examples illustrate that gathering information on the properties of a new fuel allows for an intelligent selection of tests to examine specific fuel characteristics to determine the potential risk if used in a gas turbine. Typically, these are combustion tests focused on determining emissions, combustion dynamics (combustion acoustics), and/or overall operability.

These tests can be run in a variety of facilities, each with a different scale as shown in Figure 6. A single nozzle combustion test typically makes use of a simpler combustion system, requiring significantly less fuel, and allowing for additional instrumentation and more rapid testing.

The next step up in scale requires a combustion chamber (for a can-annular combustor) or an annular combustor to provide insights on the behavior of the fuel in the full combustor geometry. Although these tests can provide a more complete understanding of combustor behavior on a new fuel, they require larger volumes of fuel and more time to set up, making them inherently more expensive to perform.

In addition to the important combustion tests already described, there are non-combustion fuel characteristics that sometimes require evaluation. Examples include the impact of fuel lubricity (or lack of lubricity) on seals, and the potential for fuel line coking.

Single Nozzle

- Full pressure, temperature
- Rapid concept evaluation
- Parameters monitored:
  emissions, combustion dynamics, gas and liner temperatures, etc.

Combustion Chamber

- Full pressure, temperature
- Full scale combustion fuel nozzle and chamber configuration
- Parameters monitored:
  emissions, combustion dynamics, gas and liner temperatures, etc.

Field Test

- Site conditions and "real" fuel
- Interaction of fuel accessories and control systems
- Gas turbine/combined cycle performance, emissions and operability

Liquid fuel volume required at each evalution step

500 – 2,000 gallons	8,000 – 30,000 gallons	80,000 – 800,000 gallons

Figure 6 - Gas turbine fuel evaluation facility scaling

After completing the fuel tests, the data is reviewed along with the results of the analytical fuel characterization. Based on the data analysis, a decision can be made regarding the general viability of the fuel and applicability of the fuel to specific gas turbine platforms. Assuming that the fuel is considered acceptable, a field demonstration test may be required to examine overall system operation in the field.

Step 4 – Field demonstration

Once the first three steps have been completed, a new power generation fuel may require a dedicated field demonstration to evaluate operation in a full gas turbine and power plant system. This type of test requires detailed coordination between the gas turbine OEM and the power plant owner, and potentially the plant operator if this is a separate entity from the plant owner. Typically, a field test or field demonstration is planned months in advance to ensure that all long lead items (including fuel) will be at the site, and to avoid disturbing power generation during peak periods or maintenance cycles.

A number of elements must be considered when planning for a field demonstration, including: procuring an adequate supply of the fuel to be tested; any special instrumentation required to validate the performance or operation on the new fuel; spare parts for any unusual or long lead time equipment or consumables critical for the demonstration; and logistics for the OEM team supporting the field activities. The total time of operation on the new fuel depends on the fuel, and the results of the previous steps.

Evaluation of Arabian Super Light (ASL) crude oil

The evaluation of ASL followed the process outlined in the previous section, with each step providing new information and insights into the fuel and its properties.

Step 1. Fuel source determination

A first step in evaluating ASL was to determine the source of the fuel, and if there would be any pre-treatment applied before being supplied to a power plant. Based on information gathered from multiple sources, it was determined that ASL was discovered in the mid-80s in central Saudi Arabia, and is produced from crude oil fields south of Riyadh [4,5]. As a crude oil, it is minimally processed, with only a stabilization process that removes gases with very low boiling temperatures to allow for safe transport.

Step 2. Analytic fuel characterization

The next step in the evaluation of ASL was to generate a detailed understanding of the physical and chemical properties of the oil. This is a particularly important step because ASL is a whole crude oil and not a refinery product. The step was completed using existing crude oil assays as well as a series of ASL samples that were analyzed by an independent, third-party laboratory using standard American Society for Testing and Materials (ASTM) analytical tests.

As part of this process, an important step in understanding a liquid fuel is a very simple visual inspection. Figure 7 shows a comparison between samples of distillate oil #2 and ASL. Clearly, the visual appearance of ASL is very different from distillate; the ASL looks more like a crude oil than a light refined liquid fuel that is typically used in F-class gas turbines. As one might expect from a crude oil, the ASL is completely opaque (as tested by shining a flashlight at the sample), but at the same time the ASL seemed to have similar viscosity as one might expect from a refined liquid fuel, such as distillate oil #2.

Given that ASL is a crude oil, another step in understanding physical and combustion properties is to determine the distillation curve. In the test, a liquid sample is carefully heated and the liquid volume and liquid temperature are recorded. The distillation curve represents the volume of liquid that will boil off at a given temperature. If the liquid is made up of a small number of components with similar boiling points (such as distillate oil #2), the resulting curve is narrow with a small range of temperatures. If the liquid contains components with varying molecular weights and boiling temperatures (such as crude oil), the resulting distillation curve will show a broad distribution. The distillation curves for distillate oil and ASL are shown in Figure 8.

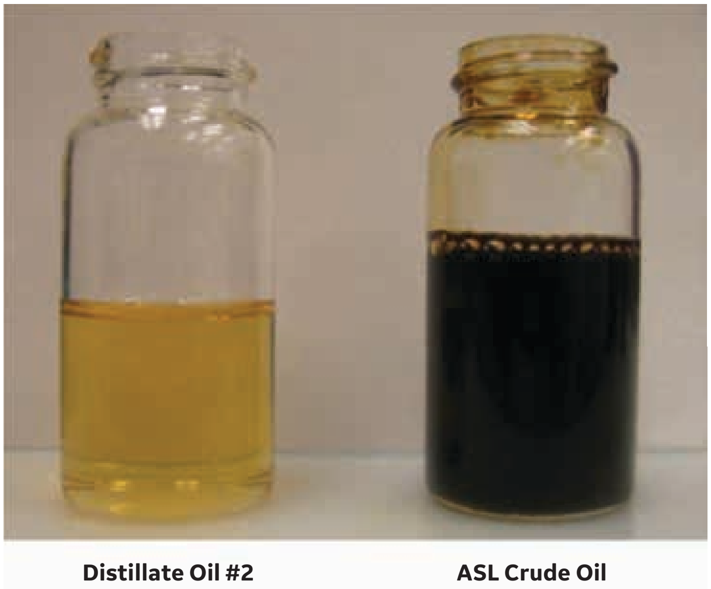


Figure 7 - Visual comparison of distillate oil and ASL crude oil

Typical liquid fuels used in heavy-duty gas turbines are the product of a distillation process, and have controlled initial and final boiling points with a narrow temperature difference between these points; the temperature difference between the initial and final recovery points for distillate as shown in Figure 8 is approximately 170°C (300°F). This limits lower molecular weight components, as well as the amount of higher boiling point crude oil components. The process naturally restricts ash-forming and organic-metallic compounds, some of which tend to be present in the higher boiling point hydrocarbons components of crude oil. These

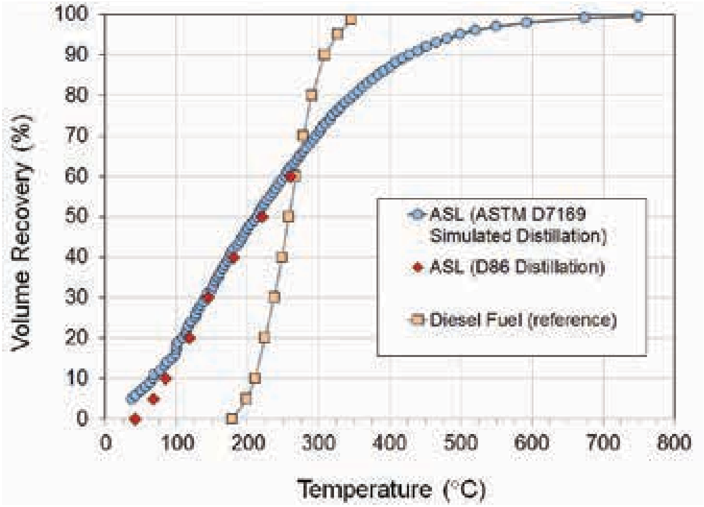


Figure 8 - Comparison of ASL and Distillate Oil #2 distillation curves

higher boiling point hydrocarbons are also more difficult to burn completely, and can impact gas turbine combustion operability.

Spanning nearly 700°C, ASL's distillation curve is very different from that of distillate oil. With an initial boiling point below 50° (122°F), ASL is considered more volatile than distillate because it starts to boil at much lower temperatures than distillate (which boils at 180°C or 356°F). The final boiling point of the ASL is about 750 °C (1380 °F), which is roughly 400 °C (540°F) higher than the final boiling point of distillate. From a combustion perspective, these differences could mean the vaporization characteristics of ASL are different from distillate, and could potentially impact combustor operability. In addition, the wide span of boiling points means that the fuel could contain contaminants (such as vanadium) that tend to be found in the higher boiling point hydrocarbons in crude oil. Depending on the type and level of the contaminant, a mitigation action might be required to reduce potential negative impacts to performance and/or combustion component durability.

Because ASL's distillation curve resembled that of traditional crude oil, a more detailed analytical characterization was deemed necessary. Table 1 shows some of the results from this characterization relative to distillate oil.

Table 1 – Comparison of ASL and distillate properties

PROPERTIES	Unit	ASL	Distillate
Heating Value Gross	BTU/lbm	19329	19420
Density	g/cc	0.778	0.83
Viscosity @100 °F	cSt	1.76	2.6
Carbon	Weight %	86.36	85
Hydrogen (calculated)	%	13.6	13
Carbon / Hydrogen	ratio	6.35	6.5
Ash	ppm mass	3	100
Ramsbottom Carbon Residue	Weight %	0.32	0.035

From the perspective of being able to use ASL in an F-class gas turbine with a DLN combustion system, the heating value, density, percent hydrogen, and the carbon/hydrogen ratio of ASL and distillate are very similar. This indicates that the fuel could potentially be used instead of distillate. To highlight the importance of detailed fuel property understanding, Figure 9 compares the specific gravity and kinematic viscosity of ASL to other liquid fuels and some common liquids.

In addition, the vanadium content of the ASL was found to be below GE's specification limit (0.5 ppm), and therefore precluding the need for a vanadium inhibitor. Fuels with vanadium concentrations greater than 0.5 ppm are currently limited to B- and E-class turbines. The ash formed by the reaction of vanadium and the inhibitor has the potential to block cooling holes on the turbine buckets, which could significantly impact hot gas path component durability.

The largest disparity between these two fuels was the ASL carbon residue, which was 10 times larger than distillate. This could indicate the potential for coke up of fuel lines or fuel nozzle tips when operating on ASL. 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

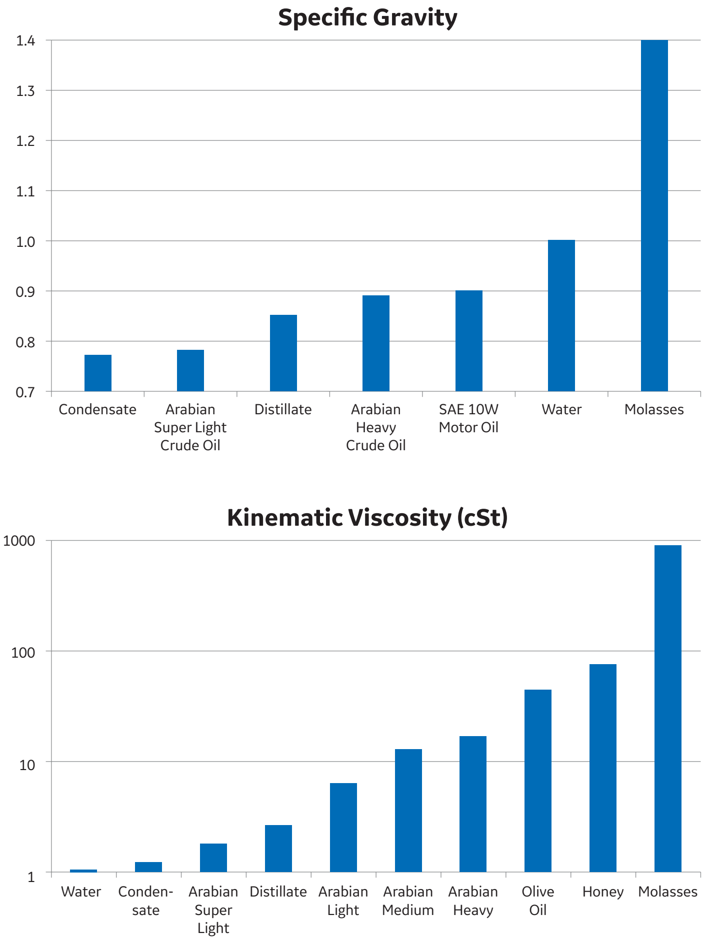


Figure 9 - Comparison of ASL properties to other fuels and common liquids

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."

Given that the fuel characterization study resulted in both positive and potentially negative indicators for the viability of using ASL in F-class turbines, a series of lab tests was defined and performed to ensure proper assessment.

Step 3. Fuel testing

Based on the results of the fuel characterization, as well as customer requests on the potential applications of ASL, three distinct types of tests were defined: ignition, coking, and overall combustion characteristics.

ASL ignition testing

Because its distillation curve is much broader than a traditional distillate fuel, ASL could have a very different vaporization profile compared to distillate oil #2. This finding led to a concern about the ability to easily and regularly ignite ASL. Using a modified combustion test facility, a series of ignition tests were performed on a single nozzle configuration to examine the ability to ignite ASL. Although qualitative in nature, these tests did not provide any indication that ASL would be more difficult to ignite than distillate. Figure 10 shows a picture of an ASL flame (looking upstream at the fuel nozzle) taken during this series of ignition tests.

ASL coking testing

Because the RCR value for ASL was 10 times greater than that of distillate oil, a special test facility was built to examine the potential for ASL to build-up carbon deposits on the interior liquid fuel passages of a DLN combustor fuel nozzle. The test rig (as shown in Figure 11) was configured to allow a variety of liquid fuels to be heated and circulated under potentially worse-case conditions for coking. The test accommodated flow rates up to 0.162 kg/s (0.36 lbm/s) and temperatures up to 150°C (300°F). The test article was a modified GE DLN liquid fuel cartridge with a removable tip that permitted careful inspection upon completion of the test run. The system was instrumented with a variety of thermocouples and pressure transducers, which included differential pressure measurement across the liquid fuel cartridge. Changes in the pressure-drop could indicate a potential accumulation of coke deposits in these small flow passageways. To enable monitoring of small pressure changes, the pressure transducers were calibrated to better than 0.1 percent accuracy.

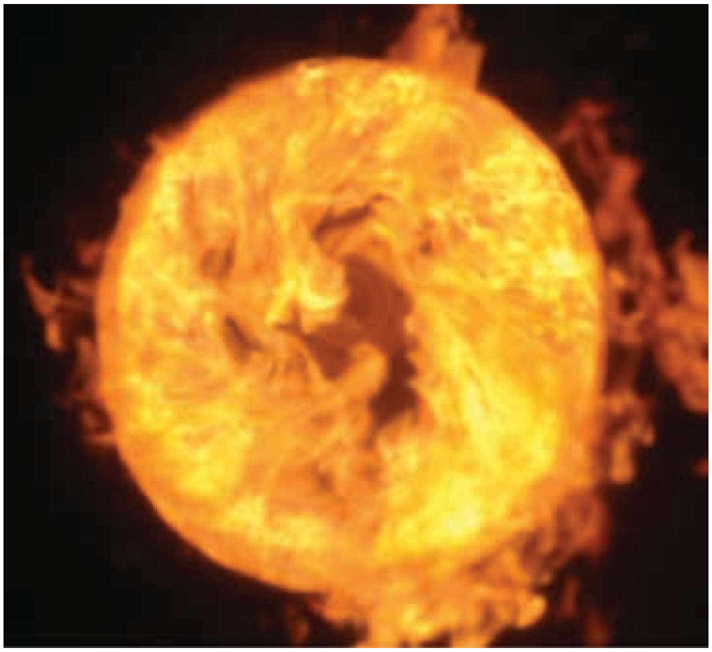


Figure 10 - ASL flame

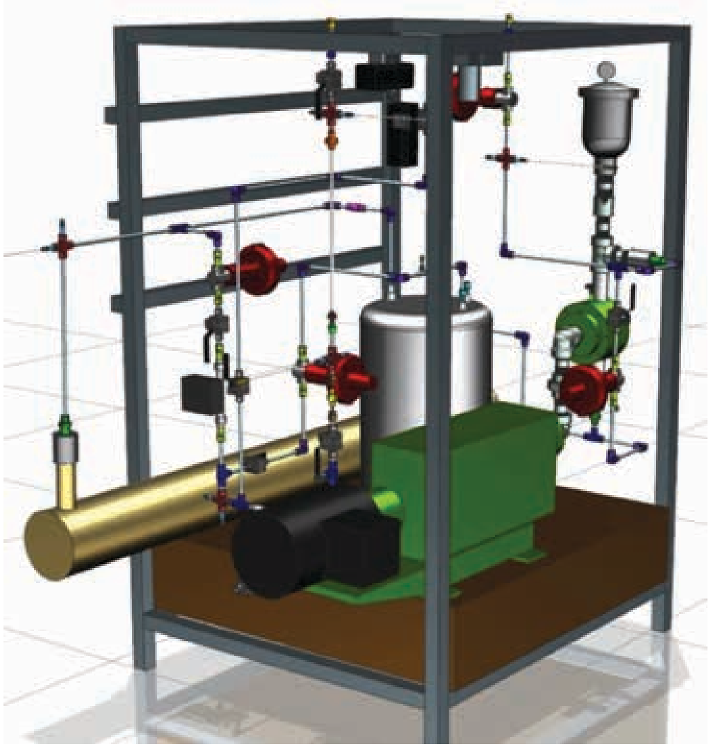


Figure 11 - 3D rendering of the coking test facility

Both distillate and ASL crude oil were tested; distillate was tested to provide a baseline data set. The emphasis of these tests was under high-temperature, low-flow conditions that were expected to offer the most challenges for the liquid fuel cartridge to resist coke formation. Figure 12 shows results from an ASL test conducted for 20 hours at 93.3°C (200°F) and 0.045 kg/s (0.1 lbm/s). Overall, there were no changes to the liquid flow rate or the differential pressure in the liquid fuel passages. Similar tests conducted with distillate also did not show changes in flow as a function of time. In addition, there were no visual difference in the liquid fuel cartridge between tests on distillate and ASL. Based on these experimental observations, for the conditions tested, ASL does not seem to be prone to coking the liquid fuel passage in the gas turbine fuel nozzle. Additional details on this portion of the ASL evaluation are available in a paper published by the ASME [6].

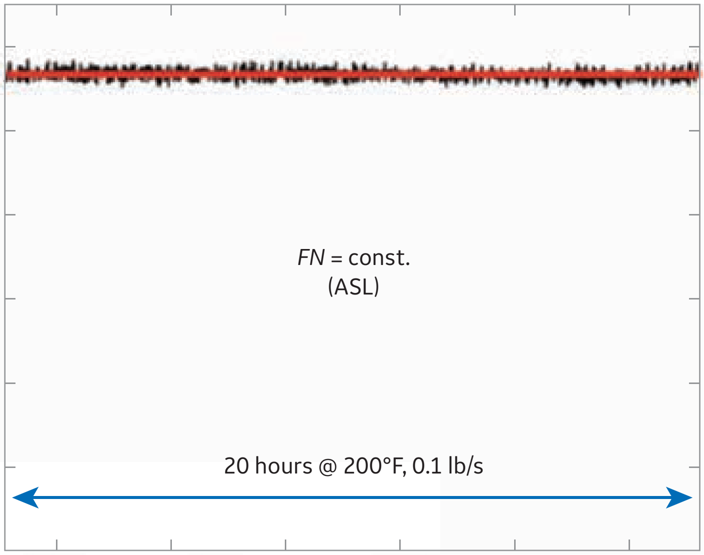


Figure 12 - Typical results from coking tests

ASL combustion characteristics

Although crude oil is routinely used in lower firing temperature gas turbines, it has not been used commercially in an F-class gas turbine. To alleviate potential concerns of the fuel's ability to operate in a modern DLN combustion system, a series of fuel screening combustion tests were performed using an advanced technology single nozzle combustion test facility at GE's Global Research Center shown in Figure 13.

The combustor assembly shown in Figure 14 included one of GE's 7F gas turbine DLN fuel nozzles. The fuel nozzle assembly was mounted to the American Society of Mechanical Engineers (ASME)-stamped pressure vessels (shown in Figure 13) rated to 25.5 bar (370 psia) and 922 K (1200°F). Tests were performed with both distillate and ASL; the distillate data provided a baseline comparison. Real-time pressure, temperature, emissions and combustion dynamics data was collected.

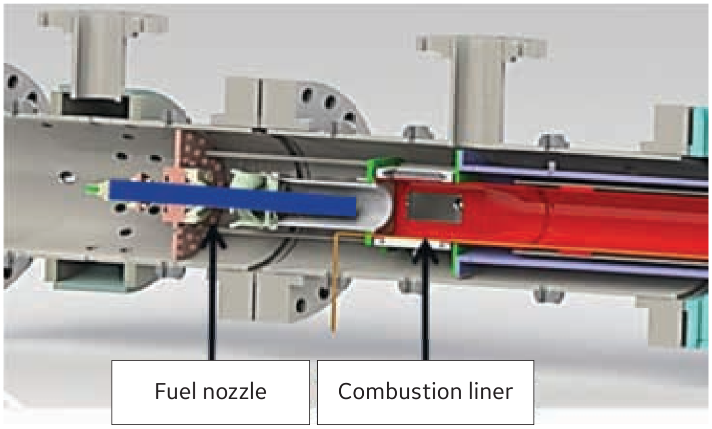


Figure 14 - Single nozzle combustor cross-section

The average non-dimensional NOx and CO emissions from ASL and distillate were plotted against (non-dimensional) combustor exit temperature as shown in Figure 15. Note that the ASL NOx and CO emissions were similar in magnitude to distillate, and followed the same trend. The combustion dynamics trends for both ASL and distillate are plotted in Figure 16; the peak amplitudes and frequencies observed for ASL were no different than observed for distillate. Additional test data examined the combustion liner temperatures and it was noted that the liner temperature for the ASL followed the same trend as distillate, but the absolute temperature of the liner was lower with ASL.

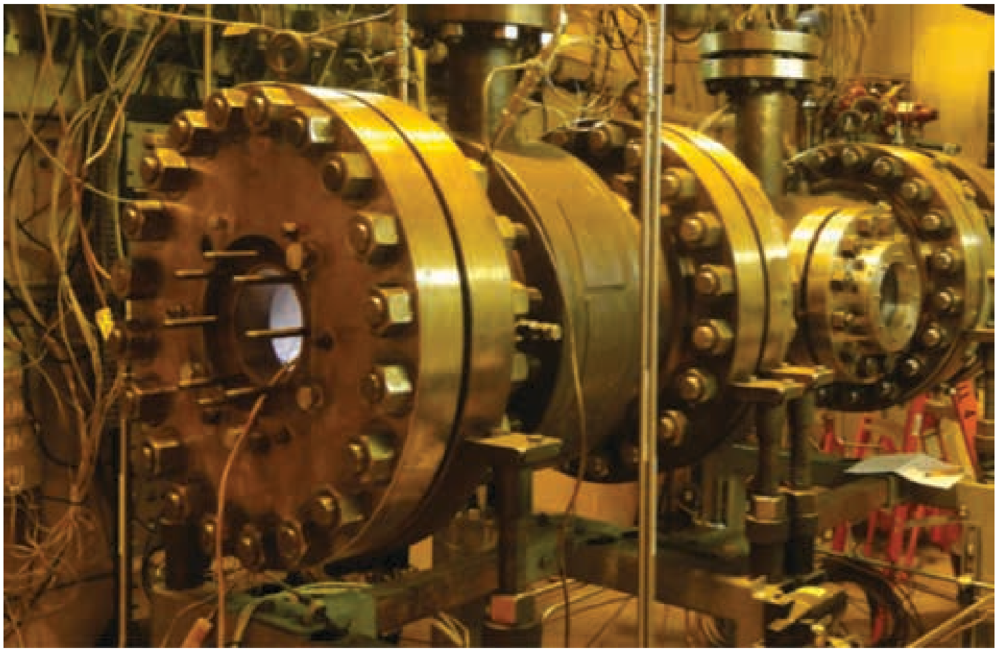


Figure 13 - Single nozzle combustion test facility

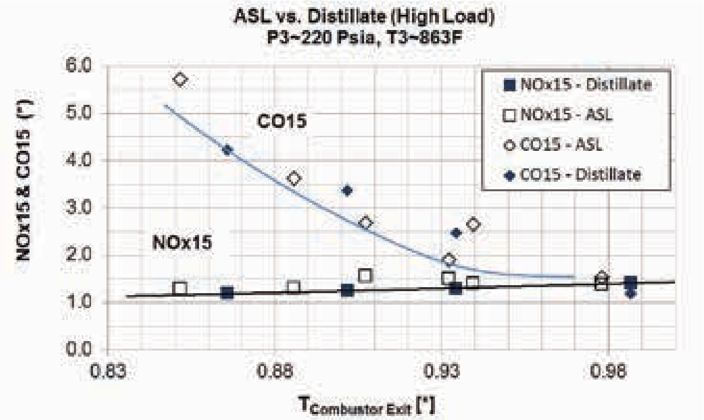


Figure 15 - Average non-dimensional NOx and CO emissions for ASL and distillate

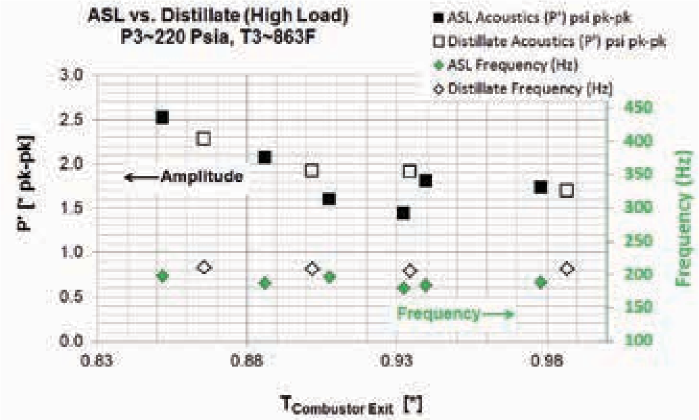


Figure 16 - Average peak frequencies and amplitude for ASL and distillate

Further tests performed at part load conditions yielded similar results. Additional details of this study are available in a paper published by the ASME [6].

In addition to the single nozzle tests, a full combustion chamber test (with a similar crude oil) was performed at GE's Gas Turbine Technology Lab in Greenville, SC. The facility is equipped with multiple combustion test cells and a fuel system capable of handling a wide variety of gas and liquid fuels. The test did not indicate major differences from the single nozzle combustion tests, and validated the ability to operate ASL on a 7F DLN combustion system.

The single nozzle fuel tests were performed in a period of just a few weeks using fewer than 660 gallons of ASL. The full combustion chamber test was performed in a single day, and roughly 10 times as much fuel as was used in the single nozzle testing.

The data that resulted from the analytical and combustion evaluations indicated that ASL could be used in an F-class DLN combustion system.

Step 4 – Field demonstration

The final step in the ASL evaluation process was a field demonstration, which examined the operation of the fuel and all of the related systems in a power plant operating under real conditions. The ASL field demonstration test was performed at the PP11 power plant in Saudi Arabia in December 2013. The plant, which has seven of GE's 7F.04 gas turbines, is shown in Figure 17. The test used a single gas turbine operating in simple cycle configuration.

In the first phase of the demonstration, the gas turbine was fired on ASL at part load. A plot of output (as a percent of base load) versus time in Figure 18 shows the transfer to ASL and the ramping up of load until the unit reached approximately 38 percent load. The unit was then allowed to operate for roughly 22 hours.

As described in previous sections, using crude oil as a fuel has certain operational challenges, and knowledge of these potential issues is critical when planning to operate an advanced gas turbine on a non-traditional fuel. As an example, the GE and plant operational teams monitored the fuel system during

Figure 17 - PP11 combined cycle power plant

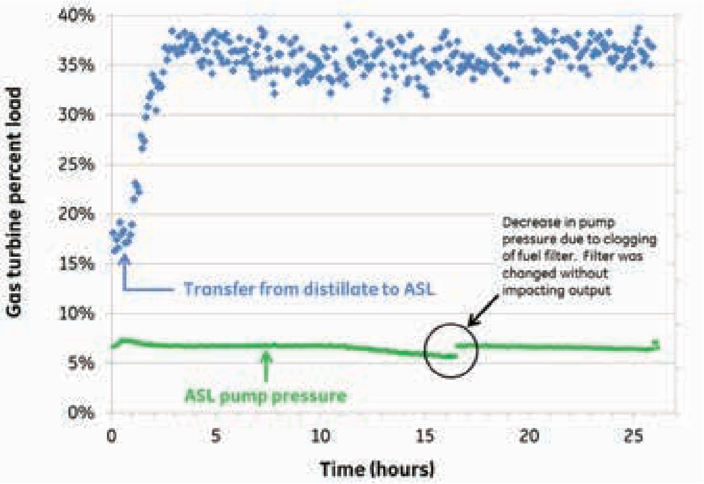


Figure 18 - Part load operation on ASL

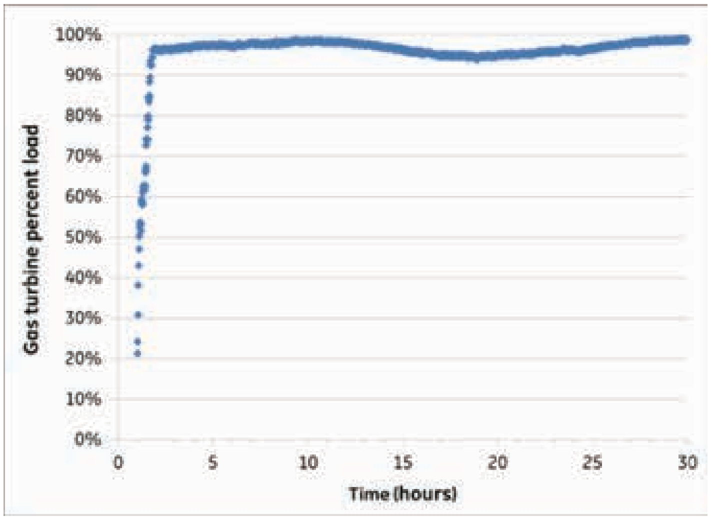


Figure 19 - Base load output on ASL

operation on ASL for signs of fuel filter clogging that could be caused by fuel contaminants, wax, and so on. While monitoring these systems the teams identified a pressure reduction in the ASL fuel system (as shown in Figure 18), and took action without impacting plant output. The appropriate action involved changing the fuel line filter; GE's liquid fuel system is configured to allow on the fly filter changes so that the plant can continue generating power without interruption.

In the second part of the test, the gas turbine was operated on ASL at base load. Figure 19 shows gas turbine output (as a percentage of output on liquid fuel) starting just after the transfer to ASL, including ramp up to base load. The figure only shows the first 30 hours of the 90-hour test. The sinusoidal variation in the load was a result of ambient (day/night) variation.

To provide perspective on fuel usage, the field demonstration used in excess of one million gallons of ASL, versus less than 30,000 gallons used in the combustion and characterization tests. Thus, it is very important to properly characterize the fuel before planning for a field demonstration.

The field demonstration clearly showed that ASL could be used as a fuel in a 7F gas turbine with a DLN combustion system. The test was a major milestone, as GE was the first OEM to operate crude oil in a Dry Low NOx combustion system in an F-class gas turbine.

Summary

Modern gas turbines are able to operate on a large range of gas and liquid fuels, and the number of viable fuels continues to expand. Power generation assets that are able to operate on a wide variety of fuels provide countries around the globe with extra tools for developing domestic energy security. The fuel flexibility provided by a gas turbine allows countries to determine how best to use their domestic natural resources. For some countries, this means using lower quality fuels for domestic power generation, while using higher quality fuels in domestic industries or selling the fuels internationally where they may have higher economic value.

To ensure that new fuels can used for power generation without harming equipment that represents a large capital investment, it is important to perform detailed evaluations. There are multiple steps in this process, which in the end provide a detailed response on the applicability of the fuel, as well as any potential restrictions.

In the case of ASL, GE's thorough evaluation process provided a positive result. Following the successful completion of the ASL demonstration testing in December 2013, the customer fully commissioned the plant on ASL, becoming the first F-class power plant to operate on a crude oil. The evaluation of ASL was an important step for power generation in Saudi Arabia, allowing this fuel to be selected as the back-up fuel for multiple combined cycle power plants, which include 27 of GE's 7F gas turbines. Once all of these units are fully commissioned, they will provide more than 4.4 GW of power for Saudi Arabia. In addition, as the 7HA and the 7F.05 both use the DLN2.6+ combustion system, ASL can also be used in the 7HA.

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