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

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Abstract

Heavy liquid fuels, such as crude oil or heavy fuel oil can be used for power generation, but these ash-bearing fuels are traditionally only used on E-class turbines, in part because of the high levels of metal contaminants. However, some crude oils have the potential to be used in F-class turbines. One particular crude oil, Arabian Super Light (ASL), has the potential to be used as a fuel on a heavy-duty gas turbine as ASL has unique properties relative to other crude oils, including low levels of vanadium. This paper presents a case study in GE’s fuel evaluation process using the ASL as an example of 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, and concluded with a successful field demonstration on a GE 7F gas turbine in Saudi Arabia. This was a significant milestone as it was the first time that a crude oil was operated in an F-class gas turbine.

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 [1]. Even though gas turbines have broad fuel flexibility 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. For example, in the Middle East there is an increased interest in using crude oil as power generation fuel. Specifically, in Saudi Arabia there is interest in using Arabian Super Light (ASL) as a fuel in advanced F-class turbines configured with Dry Low NOx (DLN) combustion systems.

Crude oils have been successfully used as fuel in E-class gas turbines for power generation applications for many years. To date, GE has more than 190 E-class turbines that have operated on crude oil or heavy fuel oil, accumulating over 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 constituents that can cause 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 could 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 0.5ppm of vanadium without treatment; above 0.5ppm vanadium GE requires the use of an inhibitor (that is added to the fuel) to prevent corrosive ash from forming [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.

![Figure 2 - Examples of coking, corrosion, and fouling](image)

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 on constituents that could 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, and uses 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 is a multi-step process to determine specific fuel characteristics and properties related to combustion and fuel handling. There are typically four major steps as shown in Figure 3: determine 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 could 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.
Step 1 – Determine fuel source

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? These questions are important as they can provide insights into answers for the next steps.

Step 2 – Analytical fuel characterization

In order to be able to use a new fuel in a gas turbine, it is important to understand fuel composition and key properties. 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 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].

This process is more complicated when evaluating a liquid fuel, as a list of individual components is not always readily available. For liquid fuel evaluation, typically the information that is readily available includes the fuel’s heating value, density (specific gravity), and kinematic viscosity. Additional information that is required, but not always initially available includes the flash point, carbon residue, distillation curve, as well as specific information on the content of hydrogen, H2S, ash, and wax.
The distillation curve helps to 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 will also be necessary to perform detailed analyses to determine if there are any metals (sodium, potassium, vanadium, calcium, or lead) in the fuel, as these can lead to erosion, corrosion, and/or fouling of turbine components.

As part of this process, an OEM may require small samples of the fuel to be collected to allow for detailed physical and chemical analyses. In many cases, the samples can be sent to 3rd 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 viable, testing of specific fuel characteristics can proceed. If the fuel is viewed as being potentially viable, 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: diffusion flame combustor or premixed (Dry Low NOx) combustor. GE offers a variety of combustion systems, some of which are highlighted in Figure 5.

Figure 4 - GE fuel analysis data sheets for gas and liquid fuels
Step 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 that are focused to determine emissions, combustion dynamics (combustion acoustics), and/or overall operability. These tests can also be run in a variety of facilities, each with a different scale as shown in Figure 6. A single nozzle combustion test facility is typically 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, these tests require larger volumes of fuel, more time to set-up, and are therefore inherently more expensive to perform.
The discussion in this section has focused combustion tests, but 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.

Once the fuel tests have been completed, the data will be reviewed along with the results of the analytical fuel characterization. From this data, a decision can be made on 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 site, and to avoid disturbing power generation during peak periods or maintenance cycles.

In planning for a field demonstration there are a number of elements that must be considered, which include: 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, as well as logistics for the OEM team supporting the field activities. The total time of operation on the new fuel will be dependent 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 – Determine fuel source**

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 characterization**

The first step in evaluating ASL was to generate a detailed understanding of the physical and chemical properties of the oil. This was an important step for ASL, as it is a whole crude oil and not a refinery product. This 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 this 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, it will be a narrow curve with a small range of temperatures. If the liquid contains components with varying molecular weights and boiling temperatures (such as crude oil), this will yield a distillation curve with a broad distribution. The distillation curves for distillate oil and ASL are shown in Figure 8.

![Figure 8 - Comparison of ASL and Distillate Oil #2 distillation curves](image)

Typical liquid fuels used in a heavy duty gas turbine 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 ~ 170°C (300°F). This limits lower molecular weight components, as well as the amount of higher boiling point crude oil components. This 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 higher boiling point hydrocarbons are also more difficult to burn completely, and could impact gas turbine combustion operability.

ASL’s distillation curve is very different from distillate oil’s curve as it spans nearly 700°C. ASL’s initial boiling is less than 50°C (122°F), which is less than the boiling point of distillate (180°C, 356°F); this means that ASL will start to boil much lower temperatures than distillate, and hence it is considered more volatile. 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 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 due to the negative impact it can have on performance and/or combustion component durability.
Knowing that ASL has a distillation curve more like a traditional crude oil indicated that a more detailed analytical characterization was necessary. Table 1 shows some of the results from this characterization relative to distillate oil.

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

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 the GE specification limit (0.5ppm), and therefore a vanadium inhibitor would not be required. Fuels with vanadium concentrations greater than 0.5ppm 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, and which could indicate that the fuel might coke up fuel lines or fuel nozzle tips. 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”.
To properly assess the viability of using ASL in an F-class turbine, given that fuel characterization study resulted in both positive and potentially negative indicators, a series of lab tests were defined and performed.

**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**

Since ASL’s distillation curve is much broader than a traditional distillate fuel, ASL has could have a very different vaporization profile as compared to distillate oil #2, there was a concern on 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**

Since the RCR for ASL was 10 times larger 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 conditions that could represent worse case conditions for coking. Flow rates up to 0.162 kg/s (0.36 lbm/s) and temperatures up to 150°C (300°F) could be accommodated.

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. Any changes in the pressure-drop could indicate a potential accumulation of coke deposits in these small flow passageways. The pressure transducers were calibrated to better than 0.1% accuracy to be able monitor for small pressure changes.

Both distillate and ASL crude oil were tested; distillate was tested to provide a baseline data set. The emphasis of these tests was a high temperature low flow condition expected to be the most challenging conditions 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 any 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.

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**Figure 11 - 3D rendering of the coking test facility**

**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 the state-of-the-art single nozzle combustion test facility at GE’s Global Research Center shown in Figure 13.

![Figure 13 - Single nozzle combustion test facility](image)

The combustor assembly shown in Figure 14 included a GE 7F gas turbine DLN fuel nozzle. This fuel nozzle assembly was mounted to the American Association of Mechanical Engineers (ASME)-stamped pressure vessels (shown in Figure 13). The vessels are 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 base line for comparison. Real-time pressure, temperature, emissions and combustion dynamics data was collected.

![Figure 14 - Single nozzle combustor cross-section](image)
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. Tests were also performed at part load conditions, and they 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. This facility is equipped with multiple combustion test cells and a fuel system capable of handling a wide variety of gas and liquid fuels. This test did not indicate any 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 less than 660 gallons of ASL. The full combustion chamber test was performed in a single day, used roughly an order of magnitude more fuel than was used in the single nozzle testing.

After the analytical and combustion evaluation steps were completed, the data 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 in real operating conditions. For ASL, the field demonstration test was performed at the PP11 power plant in Saudi Arabia in December 2013. The plant, which has seven GE 7F.04 gas turbines, is shown in Figure 17. For this test, a single gas turbine operating in simple cycle configuration was utilized.

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 17 shows the transfer to ASL and the ramping up of load until the unit reached approximately 38% 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 operation on ASL for signs of fuel filter clogging that could be caused by fuel contaminants, wax, etc. While monitoring these systems the teams identified a pressure reduction in the ASL fuel system (as shown in Figure 18), and took the appropriate actions without impacting plant output. In this case, the action was changing of the fuel line filter; GE’s liquid fuel system is configured to allow on the fly filter changes that allowed the plant to continue generating power without interruption.
Figure 18 - Part load operation on ASL

In the second part of the test, 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. This figure only shows the first 30 hours out of the 90-hour test. The sinusoidal variation is 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. This 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 fuels these systems are able to operate on 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.

As new fuels become available for power generation, to ensure they can be used without harming equipment that represents a large capital investment it is necessary to perform a detailed evaluation. There are multiple steps in this process, which in the end provide a detailed response on the applicability of the fuel, and any potential restrictions.

In the case of ASL, the 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 be able to operate on a crude oil. This evaluation of ASL was an important step for power generation in Saudi Arabia as this fuel has been selected as the back-up fuel for multiple combined cycle power plants.
which include 27 GE 7F gas turbines. Once all of these units are fully commissioned, they will provide more than 4.4 GW of power for Saudi Arabia.

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References