The Future of Gas Turbine Technology
9th International Gas Turbine Conference
10-11 October 2018, Brussels, Belgium

Paper ID Number: 61-IGTC18

THE CHALLENGE OF BURNING DIESEL FUEL IN AERO-DERIVATIVE GAS TURBINES OFF-SHORE

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ABSTRACT

Behind the common idea that diesel fuel is a standard and regular product which is easily available and used to run gas turbines, an Oil & Gas operator is well positioned to confirm that burning diesel fuel in aero-derivative gas turbine is, in fact, a real challenge. If the diesel fuel treatment system of a gas turbine is not properly designed, the life of a turbine running with diesel can be reduced to a few minutes. To avoid issues arising from burning diesel fuel, it is required to understand its nature, the fact that it is a “living substance”, and adopt specific designs and operation practices. The objective of this technical paper is to share the experience accumulated in this field by an Oil and Gas operator off-shore. Firstly, some parameters of fuels are discussed. Secondly, the liquid fuel specifications of aero derivative gas turbines are reviewed and the gap with respect to standard fuels available on the market is highlighted. Thirdly, different operational issues and symptoms that were observed when operating aero engines with diesel fuel are presented. These issues may come from the supply, storage, treatment, or turbine fuel system and its control. Finally, a set of guidelines to obtain a robust diesel fuel storage, treatment and overall turbine fuel system for dual fuel operation is proposed. These guidelines include design and operating rules based on the knowledge of the diesel fuel presented in section one, and that have proven to be effective in solving the issues described in section two.

1. INTRODUCTION

TOTAL operates a large fleet of more than 250 gas turbines whereas about 80 of them are aero-derivatives. This fleet includes:

- General Electric gas turbines like PGT 25 Base, PGT 25+ and LM2500+G4.
- Siemens gas turbines like SGT A35 RB, former RB211 6556, 6562, 6762 and 6761 and Siemens Avons.

The majority of these 80 turbines are dual fuel (gas and liquid), and run mainly in turbo-generators. A minority are single fuel (gas) used for mechanical drive coupled to centrifugal compressors. The dual fuel capability is especially required for field start-up or re-start when fuel gas is not available.

Additionally, some smaller aero derivative gas turbines like Bastan IV from Turbomeca (currently Safran Helicopter Engines) were operated by TOTAL, and have been running on diesel fuel since the 80s. Overall, TOTAL has cumulated more than 35 years of experience running aero-derivative gas turbines with diesel fuels.

Aero-derivative gas turbines are initially designed to burn kerosene grade fuel. However, for off shore operations, it is not possible to use kerosene due to the cost and logistic implications that it would represent. For example, a site with a power generation capacity of 120MW consumes approximately 30 m3/h of liquid fuel. In such cases, it is required to use diesel fuel instead, which could be automotive or marine fuel. Consequently, Original Equipment Manufacturers (OEMs) open their liquid fuel specifications to other liquids like Diesel fuel (distillate), which may get close to aviation fuel characteristics. However, according to the experience of TOTAL, the use of diesel oil off-shore in aero derivative gas turbines is not a simple operation. This paper presents some aspects of TOTALs experience on this subject.

ABBREVIATIONS

FPSO	Floating Production Storage and Offloading Vessel
O&G	Oil and Gas
OEM	Original Equipment Manufacturer

2. MAIN CHARACTERISTICS OF DIESEL FUEL

The objective of this paragraph is to review the key parameters defining the quality of Diesel fuels.

The characteristics of jet fuel (Jet A and Jet A1), are also presented because they are the reference for which the gas turbines were initially designed. Jet A and A1 are governed by the ASTM D1665-18a (Ref. 1) in the United States.
Three type of standardized diesels are considered:

- Automotive diesels, as defined by ASTM D975 for the US (Ref. 2) and EN590 for Europe (Ref. 3).
- Distillate marine diesels DMX, DMA, DMZ, DMB, as defined by ISO 8217 (Ref. 4).
  - Residual marine fuels (RMA,.RMB, RMD, RME, RMG, RMK) are not considered because they are not used in aero derivative gas turbines.
- Gas turbine fuel oils, as defined by ASTM D2880 (Ref. 5).

2.1 Specific Gravity

The specific gravity of a Diesel fuel is a very important value because it can be easily measured. This information is part of all Diesel fuel certificate. Even in cases where there is very limited information about the fuel, this parameter is at least always available to the gas turbine operator.
The Diesel fuel quality may vary a lot with the specific gravity. For a Diesel fuel, a low specific gravity value is a good sign of high grade distillate. Specific gravity usually refers to a temperature of 15°C or 60F. In case the specific gravity is not expressed at 15°C, it can be corrected for temperature variations as proposed by ASTM D1250 – 04 (Ref 6).
Relatively accurate correlations between the specific gravity (kg/m3) and the low heating value (kJ/kg) exist in the open literature. The low heating value increases with the specific gravity.

Discussions on Specific Gravity for Aero-derivative Engines

Table 1 summarizes the requirements imposed by the different standards. The specific gravity is one of the parameters reported systematically in the fuel certificates. This is the reason why it is important to have a good knowledge of its implication and the acceptable limits. Of course, all fuel quality cannot be judged by this single parameter.
According to experience on site, the maximum specific gravity at which a diesel fuel is fairly workable in aero-derivative gas turbines is 845 kg/m3 (at 15°C) and more hardly workable is 855 kg/m3 (at 15°C). These values are close to the N°1-GT grade of ASTM D2880 and close to the higher limit of EN590 and far below the DMA specific gravity of 890 kg/m3 @ 15°C. Specific gravities of 845-855 kg/m3 remain 8 to 10% higher than the maximum specific gravity specified for the Jet A1.
These values of 845 kg/m3 to 855 kg/m3 are typical from DMX, or good quality DMA delivered offshore in Guinea Gulf where TOTAL operates a large fleet of aero-derivative gas turbines.
An example of diesel fuel specification from a refinery in the Guinea Gulf targets a minimum specific gravity of 820 kg/m3 at 15°C without upper limits. This fuel was the only process delivering Diesel fuel to cars locally and to the offshore platforms operating gas turbines and specifically aero-derivative engines.
Higher specific gravity, close to 860 kg/m3 may illustrate a Diesel fuel rich in heavy ends or presence of improper residue for which decantation and high grade filtration is mandatory. Fuel oils with specific gravity above 855 kg/m3 are not convenient to use and generate issues on the liquid fuel network or on the gas turbine itself.

2.2 Color

Similarly to the specific gravity, fuel oil color is a precious piece of information relative to quality. Color is scaled from 0,5 to 8 in the ASTM D1500 (Ref. 7) as it can be seen in Figure 1. It is easy to measure but this information is not systematically reported in liquid fuel certificates.

Specifications	Title	Fuel Grade	Specific Gravity[(a)]
ASTM D1655	Aviation Turbine Fuels	Jet A or Jet A1	775 kg/m3 Minimum 780 kg/m3 Maximum
ASTM D975	Diesel Fuel Oils (Automotive)	All Grades	No References to SG
EN590	Diesel Fuel Oils (Automotive)	All Grades and Classes	820 kg/m3 Minimum 845 kg/m3 Maximum
ISO 8217	Marine Fuel Oils	DMX DMA, DMZ DMB	No References to SG 890 kg/m3 Maximum 900 kg/m3 Maximum
ASTM D2880	Gas Turbine Fuel Oils	N°0-GT N°1-GT N°2-GT N°3-GT N°4-GT	No Reference to SG 850 kg/m3 Maximum 876 kg/m3 Maximum No References to SG No References to SG

(a) Specific gravity is reported at 15°C.

Table 1 – Specific Gravity of Fuels according to their standards

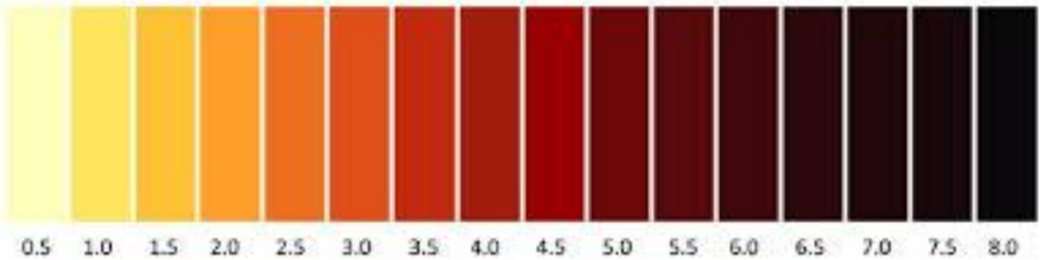

Figure 1: ASTM D1500 Color Scale for Fuel Oil

ASTM D1500 states that “the determination of the color of petroleum products is used for manufacturing control purposes and is an important quality characteristic, since color is readily observed by the user of the product.”. ASTM D1500 is right when they say that the final users pay a lot of attention to the color because, with experience color reveals how easy would be to operate the aero-derivative gas turbines at site.
ASTM D1655 states that “color can be a useful indicator of fuel quality and a change in fuel color may be the result of product contamination and may be an indicator that the fuel is off-specification.”

<u>Discussions on Color for Aero-derivative Engine</u>

ASTM D1655 states that for aviation kerosene “the fuel color ranges from colorless to straw/pale yellow. Despite the importance of this parameter on the quality of the product, none of the considered diesel specifications refer to the color. Color may be disregarded for being considered a more qualitative parameter instead of a quantitative quality criterion. But, this parameter reports directly the addition of residues, pollution happening during transfer and fuel oil degradation due to light or oxygen.
According to TOTALs experience having a fuel oil over 3.5 becomes an issue offshore for aero-derivative gas turbines.

2.3 Clear and Bright

Generally, fuel oil certificates refer to a clear and bright product. By putting a white paper sheet behind a sample of fuel oil (with a color index below 5) it is possible to check if the sample is clear and bright.
The ASTM D1655 mentions the “Clear and Bright Pass/Fail” requirement according to the test method D 4176 which provides a non-quantitative method for detecting contamination in a distillate fuel. None of the other considered diesel or fuel oil specification refer to a “clear and bright” criteria.
This criteria is systematically reported in the fuel oil certificates delivered with the product. However, the fact that the certificate states that the oil was bright and clear while being charged, does not guarantee that it is still bright and clear when delivered to the off-shore facility.

2.3 Cetane Number

The Cetane number provides an indication of the speed at which combustion of a given fuel takes place. Light and volatile fuels have relatively high Cetane numbers. In a gas turbine, variations in Cetane number have an impact on the temperature distribution and holding distance of the flame. Relatively low Cetane number fuels would lead to a hotter temperature close to the end of the combustion chamber and consequently metal temperatures higher than design values on the combustion chamber liner and first turbine nozzles. However, none of the Turbine Fuels specifications (ASTM D1655 and ASTM D2880) refer to the Cetane number. Only automotive standards do, as can be seen in Table 2. The spread of the Cetane number value is quite large from one specification to another. It may vary from 30 minimum to 51 minimum.

Specifications	Titles	Fuel Grade	CETANE NUMBER
ASTM D1655	Aviation Turbine Fuels	Jet A or Jet A1	No References
ASTM D975	Diesel Fuel Oils (Automotive)	Grades N°1 & N°2 Grade N°4	40 Minimum 30 Minimum
EN590	Diesel Fuel Oils (Automotive)	All Grades and Classes	51 Minimum(1)
ISO 8217	Marine Fuel Oils	DMX DMA, DMZ DMB	45 Minimum 40 Minimum 35 Minimum
ASTM D2880	Gas Turbine Fuel Oils	N°0-GT, N°1-GT N°2-GT, N°3-GT N°4-GT	No References

(1) Exception for Artic where the requested Cetane number may be lower.

Table 2 – Cetane Number of Fuels according to their standards

Although not required by gas turbine fuel standards, Cetane number is a good indicator of the diesel fuel quality and can be considered by an operator. For aero-derivative gas turbines, higher cetane number fuels will more likely lead to less operational issues. However, it is difficult to measure and obtain this figure.

3. OEM SPECIFICATIONS AND AVAILABLE PRODUCTS

3.1 OEM Specifications

The column "OEM requirements" of Table 3 summarises the main requirements for liquid fuel, as defined by the two most representative aero-derivative gas turbine manufacturers (named OEM 1 and OEM 2) for TOTAL. There are requirements for some physicochemical properties of the fuel, (such as density, acid number, etc.) and upper limits for some chemical species that can degrade turbine components (ashes that degrade the thermal barrier coatings; Sulphur, Calcium, Sodium, Potassium that may produce hot corrosion; etc.).

The two OEMs, also propose a list of the standard fuel grades (Table 4) available in the market that may comply with the requirements of Table 3. OEM 2, also mentions some specific military, automotive and fuel oil grades not included in Table 4. Military fuels are not considered by O&G operators. Automotive and fuel oils rarely used in off-shore operations and therefore are not covered in this chapter of the publication.

Parameter	OEM requirements	ASTM D1655 Jet A1	ASTM D2880 N°1-GT ASTM D2880 N°2-GT	ISO 8217 DMA	Reported in fuel Certificates(3)
Density at 15°C (kg/m3)	600 min(1) 880 max(1)	775 min 840 max	850 max N°1-GT 876 max N°2-GT	890 max	Always
Sulphur (% weight)	1 max(1)(2)	0,3 max		1,5 max	Always
Total Acid Number (mg KOH/g)	0,5 max(1)	0,1 max		0,5 max	Always
Aromatic Content (% volume)	5 min (1) 40 max(1)	25 max			***Not Reported***
Carbon Residue (100% sample)	1 max(2)				***Not Reported***
Carbon Residue on 10% bottoms	0,35 max(1) 0,25 max(2)		0,15 max N°1-GT 0,35 max N°2-GT	0,30 max	Always
Cloud Point	5°C below fuel temp.(1)				Always
Distillation 10% vol Recovery	250°C max(1)	205°C max			***Not Reported***
Distillation 90% vol Recovery	357°C max(1)	Report	282°C min 338°C max		Sometimes
Distillation Final Boiling Point	385°C max(1)	300°C max			Sometimes
Flash Point (°C)	10 above fuel temperature(1)	38 min	38 min	60 min	Always
Smoke Point (mm)	17 min(1)	25 min			***Not Reported***
Kinematic Viscosity (mm2/s or Centistoke)	1 min(1) 11 max(1)	8 max @-20°C	1,3 min @40°C N°1-GT 2,4 max @40°C N°1-GT 2,4 min @40°C N°2-GT 4,1 max @40°C N°2-GT	2 min@ 40°C 6 max @ 40°C	Always
Demulsification (min)	20 max(2)				***Not Reported***
Copper Corrosion	1 max(1)(2)	1 max			Sometimes
Hydrogen Content (% weight)	12 min(1) 12,7 min(2)				***Not Reported***
Olefin Content (% Vol)	5 max(1)				***Not Reported***
Free Water & Sediment (% Vol)	0,05 max(1) 0,10 max(2)		0,05 max		Sometimes

Ash (% Weight)	0,01 max(1)(2)	Always
Particulates	3 mg/l max(1) 2,6 mg/l max (2)	***Not Reported***
Particle Size	40 µm max(1)	***Not Reported***
Calcium (ppmw)	0,5 max(1) 2 max(2)	***Not Reported***
Sodium plus Potassium (ppmw)	0,6 max(1)	***Not Reported***
Sodium, Potassium & Lithium (ppmw)	0,2 max(2)	***Not Reported***
Lead (ppmw)	0,5 max(1) 1 max(2)	***Not Reported***
Vanadium (ppmw)	0,5 max(1) 0,2 max(2)	***Not Reported***

(1) = OEM 1 / (2) = OEM 2 / (3) Fuel quality certificates issued by the fuel provider at delivery

Table 3 – Liquid Fuel Requirements from OEMs vs Diesel specifications from international standards

Aero-derivative Gas Turbine Manufacturer	**ASTM D1655 Aviation Turbine Fuels**	**ASTM D2880 Gas Turbine Fuel Oils**	**ISO 8217 Marine Fuels**
OEM 1	Jet A Jet A-1 Jet B	None	None
OEM 2	Jet A Jet A-1 Jet B	No 0-GT No 1-GT No 2-GT	DMA

Table 4 –Fuel Grades Recommended by Gas Turbine OEMs 1 and 2.

3.2 Jet Fuels (ASTM D1655)

The different types of fuels from ASTM D1655, mentioned in API 616 Standard Code revision 05, 2011 are the following kerosene grade fuels:

- Jet A and Jet A-1 are relatively high flash point distillates of the kerosene type. They represent two grades of kerosene fuel that differ only in freezing point.
- Jet B is a blend of kerosene and gasoline resulting in a more volatile fuel with a lower freezing point. It is only used in extreme cold weathers or in some military applications.

3.3 Gas Turbine Fuel Oils (ASTM D2880)

The API 616 Standard Code revision 05, 2011 considers the different grades of fuel oil from ASTM D2880, principally fuel oils:

- Grade 0-GT includes naphtha, Jet B, and other light hydrocarbon liquids that characteristically have low flash points and low viscosities compared to those of kerosene grade fuel and fuel oils.
- Grade 1-GT is a light distillate fuel suitable for use in nearly all gas turbines.
- Grade 2-GT is a distillate that is heavier than Grade 1-GT, and it can be used by gas turbines not requiring the clean burning characteristics of Grade 1-GT. Fuel heating equipment may be required by the gas turbine depending on the fuel system design or the ambient temperature conditions or both.
- Grade 3-GT may be a distillate that is heavier than Grade 2-GT, a residual fuel oil that meets the low ash requirement, or a blend of a distillate and a residual fuel oil. If Grade 3-GT is specified, the gas turbine will require fuel heating in almost every installation.
- Grade 4-GT includes most residuals and some topped crude oils. Because of the wide variation and lack of control of properties, the gas turbine manufacturer should be consulted about acceptable limits on properties.

3.4 Marine Fuel (ISO 8217)

The ISO 8217 refers to marine fuels. Different grades are available and are named DMX, DMA, DMB, DMC. DMA is the only grade considered for aero derivative gas turbines. This widely used standard is not mentioned in API 616 revision 05, 2011.

3.5 Automotive Diesel Fuel (ASTM D975 AND EN 590)

In some remote countries, with relatively limited refining infrastructure, only automotive diesel can be found in the market. Consequently, these fuel grades are used to run gas turbines. In general terms, automotive diesel is of better quality than marine or some grades of gas turbine fuel oil, but it is more expensive. For this reason, it is potentially considered as a second choice for off-shore operations.

3.6 Comparison Between Requirements and Available Fuels

As it can be seen from Table 3 and Appendix 1, the requirements prescribed by the considered OEMs are closer to aviation fuel characteristics than to turbine fuel oils or marine diesel characteristics.

Additionally, none of the fuel grades defined by standards, satisfy all the OEMs liquid fuel requirements. Furthermore, not all the required parameters by OEMs are covered in diesel specifications, nor commonly reported in fuel certificates (details in Table 3). As a consequence, it is not possible to order fuel according to the gas turbine manufacturer specifications, nor to verify its compliance from a fuel certificate.

According to TOTALs experience, it is only possible to order kerosene or marine or automotive diesel fuels, and verify the compliance of the OEM specifications with a detailed customized series of laboratory test, which are commonly difficult to obtain because it is not a standard set of analyses.

The refueling of the offshore facilities in the O&G sector refers to marine practices. The fuel logistics of an oil and gas operator encompasses the refueling of supply boats and diesel engines in use on drilling and production units. Consequently, for a large portion of the offshore facilities operated by TOTAL, the only available diesel would be as per ISO-8217 (Marine Fuels). As it can be seen in Table 3, there is a large gap between DMA marine fuel and the required liquid fuel by OEMs. In consequence, running aero-derivative with diesel fuel in offshore environment necessitates to cover a large gap between the required and the available fuel. An adequate fuel treatment and operations may potentially cover part of this gap.

However, it is important to say that the fact that some parameters are not required by diesel/fuel oil standards, does necessarily mean that a given load of diesel does not meet the requirements of aero derivative turbines. For example, Table 5 summarises the metal and alkali verification performed to a diesel load at the exit of the refinery and at the tanks of the off-shore facility. It can be seen that all parameters are within acceptable limits. Note that from an operating point of view, it is not possible to carry out this type of analysis when a diesel fuel loading is achieved, and therefore there is always an uncertainty about the compliance to OEM criteria.

Property	Test Method	OEM Specification	At Refinery	At Off-shore Facility
Flash Point	ISO 2719	<93° c	84° C	85° C
Water	ISO 6296	<0,1 % Vol	54 ppm	46 ppm
Calcium	ISO 11885	<2 ppm	0,49 ppm	0,38 ppm
Copper	ISO 11885		<0,01 ppm	0,01 ppm
Potassium	ISO 11885	<0,2 ppm	0,09 ppm	0,12 ppm
Lithium	ISO 11885	<0,2 ppm	<0,03 ppm	<0,03 ppm
Sodium	ISO 11885	<0,2 ppm	0,26 ppm	0,14 ppm
Lead	ISO 11885	<1,0 ppm	<0,01 ppm	0,015 ppm
Vanadium	ISO 11885	<0,5 ppm	<0,01 ppm	<0,01 ppm
Total Sulphur	ISO 8754	<1 % pds	0,15 % pds	0,18 % pds
Residue at 500° C		<0,01 % pds	<0,01 % pds	<0,01 % pds

Table 5 – Analysis of Contaminants in two Diesel Fuels, One Operated at Site

4. OPERATIONAL ISSUES

This paragraph presents some operational difficulties encountered when running turbines with diesel oil, mainly related to the diesel fuel quality. They all happened in Africa, where most of the time diesel is issued from a simple “topping” operation, as compared with a process based on hydrosulfuration and fuel catalytic cracking. As a consequence, such diesel is less stable and may contain more sulfur.

The four presented cases took place in offshore facilities, such as FPSOs (Floating Production Storage Off-loading) and conventional platforms. These production facilities have their diesel storage and treatment systems (some details presented in section 5). The aero derivative engines on these sites, either from Siemens, model SGT A35 RB or General Electric LM 2500 + are equipped with a diesel HP pump skid, running when turbines are operated on diesel. The skids are equipped with fine filter cartridges (generally duplex) of 3 to 5 micron filtration degree, and an area of approximately 0,5 m^2. These filters are only last chance filters, which are not supposed to do any active fuel treatment.

4.1 Heavy Pollution on a Production Facility

The loading of diesel consisted of two batches of fuels performed during the tow of an FPSO. Tables 6 and 7 present the certificates of both batches as they were provided on the facility. The format has not been modified on purpose to highlight the fact that that certificates do not provide the same information. From numerous certificates that were analyzed, the parameters reported in the certificate depend on the certification company and the provider.

Batch N°1 was delivered with the name “Resample Bunker Gasoil BA7 ex JBS”. This product is not qualified as DMA according to IS8217 nor GT-N°2 as ASTM D2880. Cetane index, sulfur, hydrogen sulfide, acid number, cloud point and pour point are not reported.

Batch N°2 was delivered as “Bunker Gas Oil (DMA)”. This diesel fuel seems close to distillate Marine Fuel, DMA according to ISO8217. Nevertheless, the acid number, hydrogen sulfide and the oxidation stability are not reported.

It is difficult from these two certificates to anticipate a pollution. However, the use of this fuel gave place to a series of issues due to the presence of black colloids formed from hydrocarbon heavy ends. Figure 2 shows a sample taken from a sampling point close to the lower side of the tank, and its visual appearance when it is fully settled (after six weeks) and when it is mixed.

Property	Test Method	Limits	Results
Density @ 15°C, kg/l	D 1298	0,8195min	0,8780
Density @ 20°C, kg/l	D 1298	0,816min	0,8747
Specific Gravity @ 60°F/60°F			0,8785
API Gravity			30
Distillation: 90% Vol Rec, °C	D 86	367max	330
Flash Point PMCC Composite	D 93	62min	88
Flash Point PMCC Top	D 93	62min	88
Flash Point PMCC Middle	D 93	62min	87
Flash Point PMCC Bottom	D 93	62min	88
Kinetic Viscosity @ 40°C, cSt	D 445	2,2min - 6,0max	2,84
Redwood Viscosity @ 100°F, Sec's	Calc.		34
Water Content: Karl Fisher ppm	D 1744	500max	58
ASTM Color	D 1500	3,0max	<1,0
Appearance	D 1476	Pass	Pass
Odor		Marketable	m/a

Table 6 - Diesel Fuel Batch N°1

Property	Test Method	Specification	Results
Appearance - Haze Test	ASTM D.4176 – Procedure 2	2max	N°1
Ash Content – Petroleum Products, mass%	ASTM D.482	0,01max	<0,01
Ransbottom Carbon Residue, %m/m	ASTM D.524	0,30max	0,05
Calculated Cetane Index	ASTM D.4737	40min	43
Density @ 15°C, kg/l	ASTM D.4052	0,890max	0,8693
Density @ 20°C, kg/l	ASTM D.4052	Report	0,8657
Pour Point, °C	ASTM D.97	0max	-6
Sulphur – X-ray Method, % m/m	IP 336/ASTM D.4294	1,50max	1,3320
Viscosity @ 40°C, cSt (mm2/s)	ASTM D.445	1,50-6,00max	3,374
Water – Coulometer Karl Fisher, mg/kg	ASTM D.4928	250max	214,5
Flash Point Pensky-Martens, °C	ASTM D.93 – Proc.A	62min	87

Table 7 – Diesel Fuel Batch N°2

For the batch N°1, the ASTM color is reported below 1, meaning yellow which is an indication of excellent quality. The limited number of criteria selected from ISO 8217 DMA specification are met. After analyzing the consequence of the pollution, the drawback of the batch N°1 is clearly a lack of reference to DMA.

It was difficult to identify if the long hydrocarbon chains obesrved in Figure 2 were a residue or a recombination of unsaturated hydrocarbons. It is important to keep in mind that Diesel fuel is a “living” product and some diesel fuel from emerging countries are not treated with hydrogen. This treatment saturates with hydrogen the free radicals of unsaturated chains, to prevent the recombination of molecules.

		
State 1 - 2 Liquid Phases - Colloids generate a black deposit in the bottom of the sample. The red top layer remain a conventional diesel fuel.	State 2 - Mixed of 2 Phases - Colloids can move in the red phase.	State 3 - 1 Dark Liquid Phase - After mixing, diesel fuel is homogeneous, dark and requests few days of decantation

Figure 2 – Diesel Fuel Samples

The paragraphs below provide some details about the difficulties faced with these diesel batches.

Plugging of Last Chance Filter
Last chance filters are installed along or on the gas turbine main skid. The 10 micron absolute filtration was plugged in few minutes. Black colloids were found in the filter cartridge. This black deposit was found floating in the fuel oil.

Fouling of Centrifugal Separators
Diesel fuel oil are treated through a complex process of filters and centrifugal separators. The purpose of centrifugal separators is to remove particulates and water from the fuel, thanks to the difference in their specific gravity.
Fouling of centrifugal separators have been observed in the chamber bowl. The fouling was made of a sticky black deposit of colloids. The issue with the colloids is that their specific gravity is very similar to that of the diesel fuel, and therefore not removed by the centrifugal separators. In the chamber bowl, the hydrocarbon re-combination continued until forming sticky deposits.

Distress on liquid fuel valve
Dosing valves were unable to operate properly. It is highly difficult to understand the fine details of this issue, because it is not possible to dismantle this type of valve at site. However, it is very likely that the long hydrocarbon chains have affected the operation of the numerous balancing cavities of the valve.

Pollution of the tanks
The diesel fuel storage capacity on this production facility is of 7720 m^3 with the following arrangement:

- Diesel fuel tank (Port side) : 3330 m3
- Diesel fuel tank (Starboard side) : 3330 m3
- Diesel fuel settling tank (Port side) : 530 m3
- Diesel fuel service tank (Starboard side) : 530 m3

All tanks were polluted with the black deposit made of colloids. The contaminated bottom layer of the diesel tanks were drained and recycled into the crude oil production treatment. The settling and service tanks were totally drained until emptying them so as to allow the entrance of operators which performed a manual cleaning. The cleaning was facilitated because the colloids were settling down on the bottom of these two tanks, and a simple wiping of the tank bottoms has been carried out. The walls of the two tanks were free of colloids.

4.2 Inability to Run a Gas Turbine with regular DMA Diesel Fuel with a 20 Micron Filtration
This case shows that it is not simple to operate aero-derivative gas turbine with diesel fuel even though it is filtered at 20 micron.
A representative selection of certificates of different diesel loads taken on this site is presented in Table8. The certificates provided by the fuel suppliers in this country do not necessarily report the same parameters. Additionally, they do not report all the parameters requested by ISO 8217 for a DMA. Moreover, some of them do not contain important information like appearance. Nevertheless, the key available parameters

are presented in Table 8 and are acceptable according to the ISO 8217 DMA fuel grade.

The paragraphs below provide some details about the difficulties faced with these diesel batches.

Parameters	Units	Certificate 1	Certificate 2	Certificate 3	Certificate 4	Certificate 5	Certificate 6
Specific Gravity @ 15°C	(kg/m3)	863,7	858,0	858,0	858,1	841,1	848,7
Color	/	1,5	1,0	2,5	2,5	L1,0	L1,0
Appearance	/	Clear and Bright	Clear	Not Reported	Not Reported	Not Reported	Not Reported
Cetane Index	/	46,7	49,1	47,5	47,3	52,8	54,3
Sulfur	%	0,147	0,1795	0,2372	0,2852	0,1565	0,16
Water	ppm	208	115	240	115	151	Not Reported
Cloud Point	°C	-2	-0,9	4,5	-2	1,5	Not Reported
Pour Point	°C	-6	-4	-3	-6	-19	+3

Table 8 – Diesel Fuel Certificates

Plug-in of large filter

The presence of colloids made of heavy ends plug a large filter in a few days of operation. These filters have an effective filtering surface of 20 m^2 and an absolute filtration grade of 20 micron.

Fouling of splash plate and injector

After a few days of operation, the splash plates were covered by carbon residues (asphaltenes) as shown in Figure 3. This deposit plugs holes and modifies the flows in the injector area, and this impacts the combustion with liquid fuel generating a higher temperature spread which is detected by the turbine thermocouples. Additionally, after a few days of operation with liquid fuel, the unit may be unable to re-start. In these cases, the OEM recommended to remove the engine and dispatch it to its warehouse. However, it is not realistic to do an engine change over every few weeks of liquid fuel operation due to the cost and all the implications of such activity. Instead, the splash plate and injectors can be cleaned manually, and this operation allows the engine to restart.

Fouling of Gas Manifold

In this site, fouling of the gas manifold was also observed as shown in Figure 4. The details of such an issue are discussed in section 4.4.

Figure 3 – Splash Pate of Aero-derivative Gas Turbine after Running with Diesel Fuel

Figure 4 – Hydrocarbon Deposit in Gas Manifold

Parameters	Method	Units	Laboratory Analysis of Fuel in Operation
Specific Gravity @ 15°C	ISO 12185	(kg/m3)	855
Color	ASTM D1500	/	L3,5
Sulfur	ASTM D2622	%	0,267
Water	Proprietary	ppm	67
Cloud Point	EN 23015	°C	4,1
90% Distillation	ISO 3405	°C	362,6

Table 9– Analysis of Diesel Fuel upstream the last chance fuel filter

Diesel Fuel Analysis

Table 9 presents the analysis of a sample taken downstream the filtration treatment of the offshore facility and upstream the last chance diesel fuel filter.

Figure 5 shows the particle size distribution for this same sampling location. Compared to a typical European automotive diesel (EN-590 grade B), the fuel running in these turbines has up to 200 times more particles.

Figure 5 shows that a large number of particles are between 4 and 14 micron. This explains why a last chance filter of an area of 0,5 m2, filtering at 3, 5 or 10 micron can be plugged very rapidly. In this particular site, the filters are plugged in approximately ten minutes.

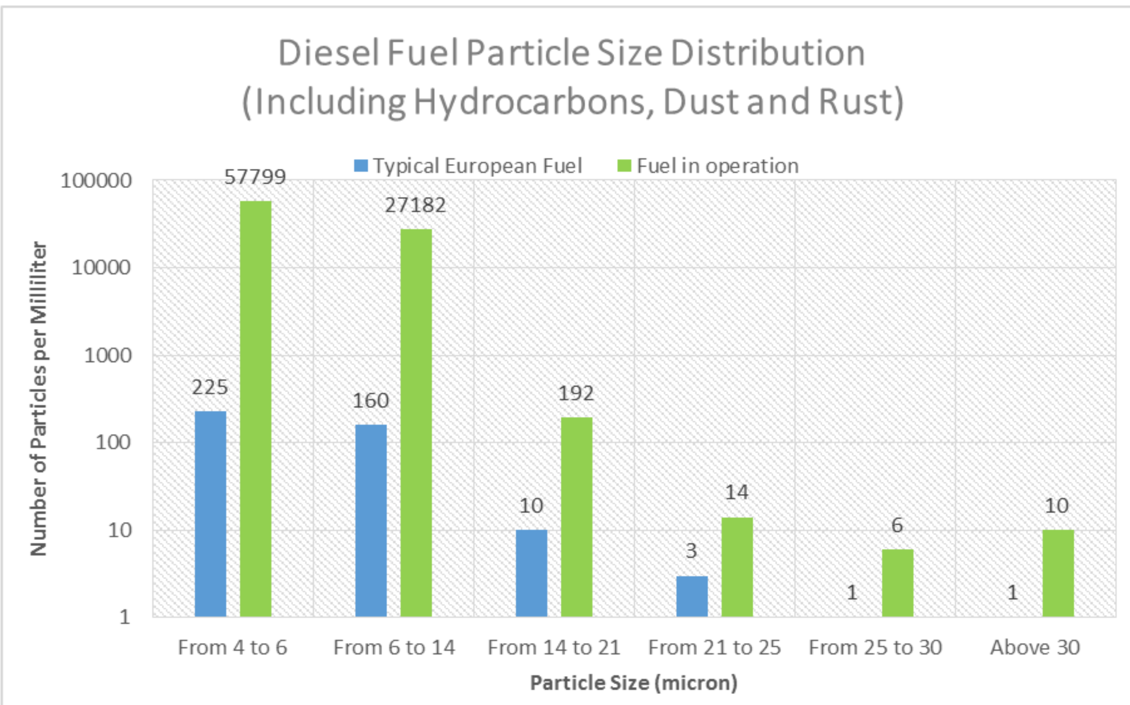

Figure 5 – Diesel Fuel Particle Size Distribution upstream the last chance fuel filter

Particles are made of long chain hydrocarbons of different compositions as well as other particles commonly named “dust and rust”. The long chain hydrocarbons have been analyzed by a Gas Chromatograph – Mass Spectrometry method and paraffin’s were identified. Figure 6 shows the result of this analysis. Each peak of retention corresponds to an n-paraffin component. For instance the peak rising at 27,23 minutes corresponds to the n-C18 paraffin and the peak at 43,76 minutes corresponds to the n-C30 paraffin.

The diesel fuel in operation contains up to n-C35 paraffin whereas European automotive diesel fuel display up to n-C24 or n-C26 paraffin components.

The paraffinic components have not been weighed, which would be very valuable in order to size the filtration area and the associated filter load capability. Nevertheless, it was possible to weigh the dust and rust by size. Dust and rust represents 11 to 14 ppmw at different filtration grades as shown in Figure 7. These quantities may represent more than 60 grams per hour of “dust and rust” particles for a 30-MW gas turbine.

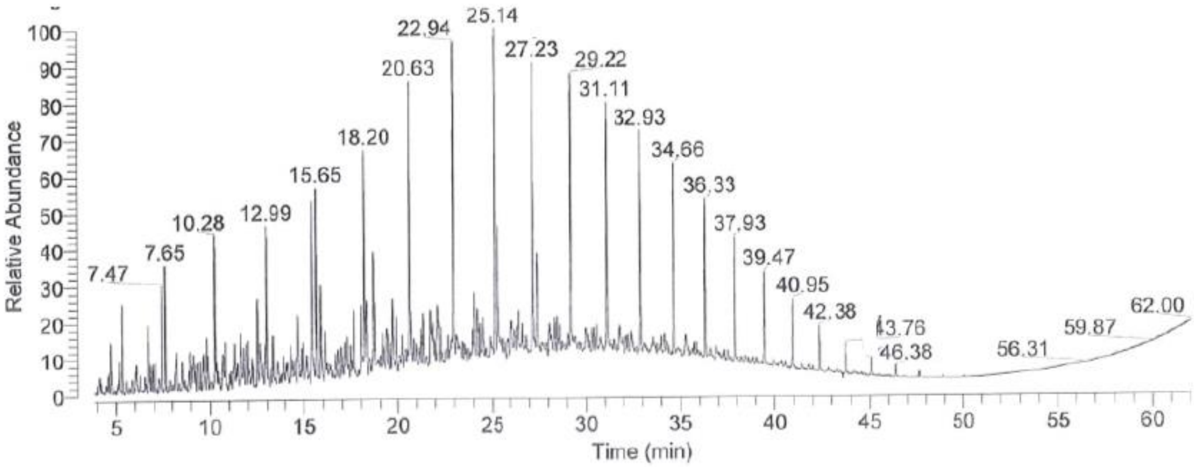

Figure 6 – Gas Chromatography – Mass Spectrometry of Diesel Fuel upstream the last chance fuel filter

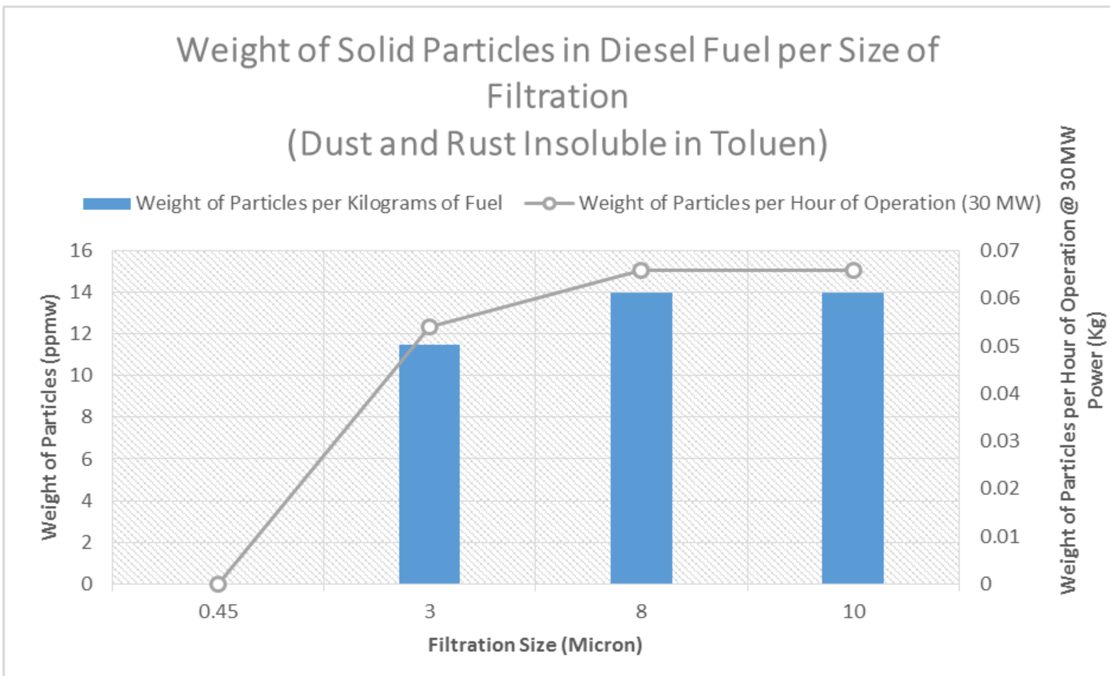

Figure 7 – Mass of Dust and Rust in the Diesel upstream the last chance fuel filter

Conclusions

The aero-derivative gas turbines are not tolerant to paraffinic components and require in consequence of high grade of filtration on the fuel treatment of the site, close to the last chance filters which are provided by OEM (3 to 5 micorn). The issue with this level of filtration is the plugging of the filter which occurs very rapidly in few days. Operating aero-derivative gas turbine offshore with diesel fuel is a tradeoff between gas turbine operability and filter life cycle.

4.3 Impact of Calcium Sterate

The start-up phase of a new facility is always critical. Aero-derivative gas turbine shall run for weeks with diesel fuel only because the gas fuel is not yet available.

Last Chance Filter Plug in

During a plant start-up, TOTAL faced the plugging of the last chance filters. Calcium stearate was found in diesel fuel with a concentration of 2,3 micrograms per milliliter (approximately 2,7 ppmw). This amount may represent 300 grams per day for an aero-derivative gas turbine of 30 MW. The carbon content was spread between C15 and C26. This type of components comes from some crude oil used for diesel oil production, which are rich in naphthenic acids, having a cycloaliphatic hydrocarbon arrangement as opposed to an aromatic hydrocarbon arrangement. In this case, the last chance filter was plugged after only twelve minutes of operation and the gas turbine was stopped. Filter surface area and loading capacity become a major area of concern. The presence of calcium stearate impacted the production of the asset by delaying its start-up. In that case, TOTAL together with the manufacturer decided to enlarge the last chance filter grade from 5 to 20 micron. This change was in line with the OEM particles requirement of 40 micron maximum. The OEM requirement of 40 micron is quite surprising, considering that a 5 micron filter is supplied. According to the previous example, it is likely that operating with a 40 micron filtration system would rapidly lead gas turbine to operational issues.

After this experience, TOTAL installs an additional large fine duplex filters of 10 micron upstream the last chance duplex filters for the design of new facilities.

4.4 Gas Manifold Contamination

In this case, a high temperature spread at the exit of the gas generator was observed when changing over from liquid to gas fuel, as shown in Figure 8. The temperature spread reached up to 120°C when the engine was transferred to gas, whereas the temperature spread was limited to 22°C when running with diesel fuel (refer to Figure 8). A common spread on any fuel is between 40 and 70°C.

Figure 8 – Gas Generator Exhaust Temperature at fuel change over liquid to gas.

The unit was not stopped because no trips are associated to this parameter, even though a high spread remains detrimental for an engine. After a borescope inspection, it was concluded that this temperature spread was caused by coking build-up in the fuel nozzles (see Figure 9). Contamination in the form of long chain hydrocarbons was also found on the fuel gas manifold (see figure 10).

These observations call for three comments:

- Liquid fuel migrates into the fuel gas manifold.
- After running with liquid fuel, the drainage of the gas and liquid manifolds are not necessarily properly achieved.
- Diesel fuel contents long hydrocarbon chains in the form of colloids.

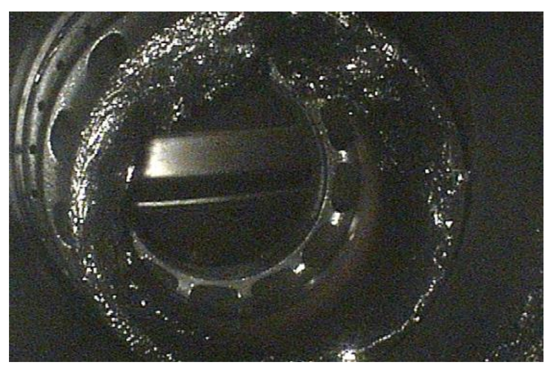

Figure 9 – Coke Built up on Combustor Venturi

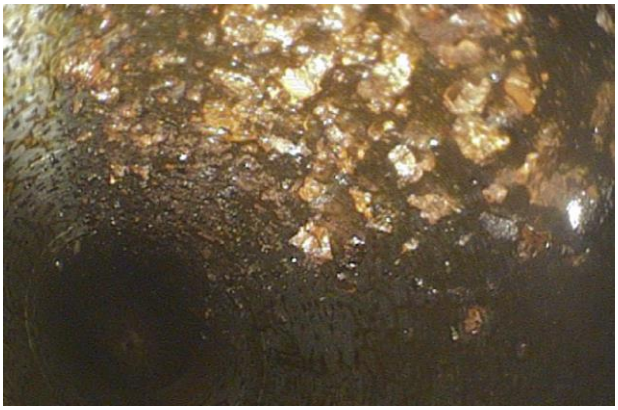

Figure 10 – Varnish Deposit in Gas Manifold

Figure 11 – Black Deposit in Fuel Gas Nozzle

For this asset, the large fine filter upstream the turbine last chance filter had an inorganic micro-glass fiber filtration media with a filtration grade of 14 micron and an efficiency of 99.9%. This filtration grade is equivalent to 16 micron absolute. The last chance filter grade for this application was 12 micron with an associated efficiency of 99.9%. Assuming that figure 5 is a representative particle distribution for a diesel offshore, the filtration level of 14 micron does not stop the largest amount of particles that exist between 4 and 14 microns. Theoretically, 99.74% of the particles above 4 microns are not stopped by any of the two filters.

After an investigation, it was found that the original design of the asset considered a micro-glass filter cartridge with a filtration grade of 5 microns associated to an efficiency of 99.9% meaning an absolute rating of 3 micron.

Subsequently, it was decided to install the original design cartridges with a 3 micron absolute filtration grade. This change has not yet been implemented. An improvement in the operability of the gas turbine is expected, however it is not certain that the duration of the filters may be workable. In parallel, improvements of the manifold draining system are under study.

5. GUIDELINES FOR DIESEL FUEL TREATMENT

This paragraph presents some guidelines used by TOTAL for the design of the diesel fuel storage and treatment of the production site.

5.1. Storage

O&G offshore facilities can be conventional platforms equipped with jackets, FPSO, Floating Production Unit Vessel or Floating Storage and Offloading Vessel. The diesel fuel storage arrangement can be different between fixed leg platforms and floating units.

<u>Fixed Legs Platforms</u>

It is common to store the diesel fuel inside one of the legs of the fixed platforms. This solution, commonly used in the 80's offers the possibility of an uninterrupted settling process of the water and sediments of the fuel. After days, the sediment locates on the sea bed at the bottom of the fixed leg. Therefore, this type of tanks are easy to operate and offer a good quality diesel fuel at the gas turbine connection.

TOTAL used to operate small aero-derivative gas turbine on fixed legs platforms without any real issue because, as it is reported, particulates, water and long hydrocarbon chains generating colloids are efficiently separated from the clean diesel fuel.

<u>Floating Units</u>

Capacity: For floating units, the tank arrangement is comparable to that of the marine sector:

- 2 raw diesel fuel storage tanks.
- 2 treated diesel fuel storage tanks.

These tanks are multiple and redundant. In O&G floating production facilities the storage capacity may reach 3000 m^3 for the raw diesel fuel tank and 500 m^3 for the treated diesel fuel tank. The objective of separating the raw diesel fuel tanks and treated diesel fuel tanks is to prepare and store a batch of clean diesel fuel for operations. Table 10 presents the autonomy of an FPSO of 200 000 bbl/d, with the previously mentioned diesel tanks.

Gas Turbine Running (30 Mw Range Each)	Raw Diesel Fuel Tank (3000 m3)	Treated Diesel Fuel Tank (500 m3)
1	20 days	3 days
2	10 days	1,5 days

Table 10 – Autonomy of an FPSO on Diesel Fuel Tanks

Settling: The settling phase in the tank is of a paramount importance because it is the most efficient way to eliminate water and particles. For that, some gas turbine manufacturers recommend to settle the fuel during 24 hours before using it in aero-derivative gas turbines. A rule of a thumb for a proper settling time is 1 hour per foot of liquid height. Experience shows that undesirable long chains of hydrocarbons may necessitates several weeks for a proper separation from the clean fuel.

Drainage: The tanks need to be designed for a proper drainage of water, sediment, bacteria and poor or polluted diesel fuels as necessary. For this, it is necessary to position the drain point at the lower location of the tank and to equip the tanks with conical drainage tie in points from where all inappropriate liquids and particulates could be collected. The drained liquids are typically sent into the main production flow.

Suction: Commonly, the suction line is located near the bottom of the tanks because a floating suction, as recommended by some gas turbine manufacturers for the treated diesel fuel tank, is not a kind of design adopted by the shipyards building such floating units.

Vent: In order to limit the quantity of water in the tanks, vents should be equipped with 4-micron coalescer breather in addition to the flame arrester. This will reduce the amount of water entering the tank through the vent.

Painting: The tank internal surface are sensitive to corrosion. Consequently, it is recommended to cover them with epoxy painting. Zinc painting has to be avoided because in presence of diesel, zinc gel is developed, which plugs the filters, and can also damage the gas turbine due to its low melting point.

5.2 Filtration

The settling remains the best separation system to remove particles and water from fuel. This shall be carefully considered for design and operation. Nevertheless, it is important to have another means of separation through filter element and centrifugal separator. Centrifugal separators present the great advantage to run with no consumable and to remove water and all other substance or particle with a specific gravity different than that of the fuel. Static filters are able to remove particles having a specific gravity close to the diesel fuel. Therefore, the two methods are complementary.

In order to be efficient and operational, filtration must be achieved with different steps which ensure the duration of the fine filters.

Five different stages are recommended:

1. The diesel fuel loading is achieved through static filters with a grade of 100 micron and an efficiency of 99%. They are installed at the inlet of the raw diesel fuel tanks.
2. A second static filtration is located between the raw diesel fuel tanks and the treated diesel fuel tanks, upstream the centrifuge separators. Its filtration level is 70 micron and an efficiency of 99.5%. The surface of this filter follows the rule: 1 m^3/h requires 0.5 m^2 of filtration media area.
3. A centrifugal separator is installed between the raw diesel fuel tanks and the treated diesel fuel tanks, downstream the 70 micron static filter. The associated filtration grade is 15 micron.
4. The third static filtration is in front of each aero-derivative gas turbine. The filtration level is 10 micron with an efficiency of 99.5%. This filter is commonly sized at 4 m^2 of filtration media area for every m^3/h of fuel.
5. The fourth and last static filter is that provided by the gas turbine manufacturer which acts as a last chance filter. The manufacturers' design is based on a fine filtration grade (10 to 3 micron) with approximately 0.08 m^2 of filtration media area per m^3/h of fuel.

Filter media should be made of inorganic fiber of micro-glass, compatible with diesel fuel.

From an operational point of view, the last chance filter cannot be of a higher filtration grade than the third static filter, otherwise it will be rapidly plugged. Two possibilities can be considered in order to have the third static filter doing the active filtration and the last chance remaining as a backup:

- Third static filter of 5-3 micron filtration grade with 99,5% efficiency.
- Last chance filter of 10 micron filtration grade with 90% efficiency.

According to TOTALs experience, the preferred solution is to start running the fuel treatment with a third stage filter of 10micron (99.5% efficiency), and a 10 micron (90% efficiency) last chance filter. This, together with good operational practices (as recommended in paragraph 6) should be enough to provide a good balance between operability and filter maintenance. If this is not achieved, the filtration system can be then upgraded to a 5-3 micron for third and last chance filters.

5.3 Piping

The piping between the fine filters and the gas turbine manifold should be made off 316L stainless steel. The same design is considered for the liquid fuel piping of the gas turbine. Other piping are made of carbon steel.

6 OPERATIONAL RECOMMENDATIONS

The diesel fuel is a "living" product and it is important to remind the three basic mechanisms of degradation:

- The presence of water in the fuel may lead to bacterial growth and emulsification.
- The contact of air and light with diesel fuel forms peroxides, organic acids and gums, sludge, varnish.
- Diesel not treated with hydrogen are prone to form, with time, long chain hydrocarbons that may create colloids in the fuel.
- In cold conditions, the wax may precipitate and increase viscosity.

For this reason, the adequate handling of the diesel is as important as the design of the fuel system

Delivery at Site

Diesel fuel is delivered at site by supply boats. It is wise to verify that the tanks of the supply boats are only used for diesel fuel delivery. It is good to understand the supply boat tank management in place by the shipping company and to carry out random diesel fuel analysis directly on the supply boat in order to verify that the diesel fuel delivered at site is similar to the provided certificate.

Tanks

The main recommendation is to separate efficiently the particles, water and colloids present in the diesel fuel. Settling mechanism is surely the most efficient and less expensive available on an offshore asset. In consequence, the unnecessary diesel fuel recirculation needs to be avoided. By the same, the tank recently loaded shall be kept unused during few days.

Contaminants like water, bacteria, particulates, colloids collected in the bottom of the tank shall be regularly drained through a rigorous tank housekeeping because diesel fuel is a “live product” and mutes constantly.

Regular diesel fuel analysis shall be carried out. Samples can be taken at the drain location and at the tank delivery connection. Simple parameters needs to be verified directly at site:

- Appearance.
- Water content.
- Color against ASTM D1500.
- Density.

To limit the water ingress, the coalescing breather that equipped the tank vent needs to be regularly inspected and changed as necessary.

The tank major inspection shall be an opportunity for a complete tank cleaning.

Filtration

The maximum differential pressure to operate the third static filter is about 3.4 bar. The typical value to change the filter is 2 bar. When gas turbines are operated with diesel fuel, the demand of filter cartridge is very important because a set may last few days only. It is highly recommended to store locally sufficient quantities of filter cartridges. Usually, in oil and gas production, long period of time running gas turbines with diesel fuel exclusively can be anticipated. The housing gasket of the blind flange must be renewed when filter elements are changed.

7 CONCLUSIONS

The main conclusions of this paper, coming from TOTALs operational experience offshore are:

- Aero-derivative gas turbines were originally designed to burn aviation kerosene. Burning aviation kerosene is impractical for industrial applications and consequently OEMs provide specifications for liquid fuels, which theoretically may be met by some diesel or fuel oils. However, in practice none of the diesel or fuel oil grades as defined by standards satisfy all the requirements set by the OEMS. As a consequence, it is not possible to order fuel according to the gas turbine manufacturer specifications, nor to verify its compliance from a fuel certificate.
- According to TOTALs experience, the most workable fuels offshore are the good quality marine distillate DMA and automotive diesel. A Straw/pale yellow color fuel is likely to give good operational results on aero derivative gas turbines. However, it is only possible to verify the compliance of the OEM specifications with a detailed customized series of laboratory test, which are commonly difficult to obtain because it is not a standard set of analyses.
- The diesel fuel is a “living substance”. Even though it is stored in clean tanks, water, light, oxygen, free radicals, etc. alter its composition throughout time. Additionally, its elaboration in refineries is not necessarily equal from one location to another. H_2 treatment for fixing the free radicals is not always carried out. Moreover, during regional transportation fuel quality may be degraded.
- Burning diesel fuel in aero-derivative gas turbine, specially offshore, shall be strictly limited to transient phase like asset start-up or facility re-start in order to avoid major production disruption.
- Operating aero-derivative gas turbine offshore with diesel fuel is a tradeoff between gas turbine operability and filter life cycle.
- Recommendations for the design and operation of liquid fuel systems, according to TOTALs experience, have been presented. Settling mechanism is surely the most efficient and less expensive available on an offshore asset. In consequence, the unnecessary diesel fuel recirculation needs to be avoided. Applying an adequate settling combined with a regular drainage of the tanks can achieve a good conditioning of the fuel; which implies a less stringent filtration as well as an increased life of the filter elements. In this scenario, a 10 micron filtration grade treatment system becomes a good compromise between gas turbine operability and filter life cycle.

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