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Development and Testing of an Anti-wear Gas Turbine Lubricant in a Challenging Offshore Environment

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Development and Testing of an Anti-wear Gas Turbine

Lubricant in a Challenging Offshore Environment

Abstract: This paper will focus on the development and testing of an anti-wear gas turbine lubricant for geared industrial turbine applications. The lubricant was designed around severely hydrocracked/hydrotreated Group II basestock technology, which offers enhanced thermal and oxidative stability over traditional turbine oils formulated with Group I (solvent refined) basestocks. Combined with a high performance, well balanced additive system, this formulation met the requirements outlined in General Electric's specification for extreme pressure / anti-wear (EP/AW) turbine fluids, GEK 101941A. This lubricant has been on field trial in two GE Frame 6B turbines on board the Terra Nova FPSO (Floating Production Storage and Offloading) vessel. During the past 4 years the turbines have accumulated over 25,000 fired hours of operation in a demanding offshore environment, located in the North Sea, 350 km off the east coast of Canada.

In this field trial, the lubricant must allow the turbines to provide reliable power output and avoid costly downtime while coping with unique and severe operating conditions. These include unpredictable environmental conditions, dynamic movements causing air entrainment, undersized oil reservoirs, reduced oil dwell times, long maintenance intervals and low oil make-up rates. Coupled with undersized oil coolers, this lubricant was continuously subjected to higher than recommended operating temperatures. All of these factors can have a significant impact on turbine oil longevity. Despite this, the fluid showed no significant signs of oxidative or thermal degradation, additive depletion, or change in other physical and chemical properties and continues to maintain performance and provide reliable service.

Introduction

Gas turbines are popular for generating electrical power, as well as gas transmission and compression due to their relative compact size and weight [1]. The successful operation of a gas turbine is vitally dependent upon the lubrication system. The role and primary functions of turbine oil are to:

- Lubricate contacting surfaces (i.e. bearings, shaft, reduction gears and flexible couplings in geared turbines, pumps, other auxiliary equipment, etc.), providing a continuous oil film separating moving parts, minimizing wear, and ensuring that all components can carry load.
- Act as a hydraulic fluid for control systems or speed governors.
- Act as a coolant to dissipate heat (heat transfer) from bearings and other components.
- Act as a medium for providing sealing force (labyrinth seals, etc.).
- Remove particulate debris from sensitive areas (bearings, cavities) to collecting filters.
- Prevent rust and corrosion.
- Provide good air and water separation.

In order for a turbine oil to perform its functions, the lubricant must possess key chemical and physical features. It must have adequate viscosity, low volatility, excellent thermal and oxidative stability, be non-corrosive, and able to resist air, water, and solid contaminant entrainment. Historically, turbine lubricants have been simple rust and oxidation inhibited (R&O), general purpose products suitable for steam turbines and light duty gas turbine applications. Over the

past few decades there have been steadily increasing demands placed on turbine lubricants due to major advances in output power-to-weight ratios, hotter operating temperatures and very low oil make-up rates. As the demands rise, basestock and additive selection are becoming increasingly more important to impart desired key features. Successful formulation balance is also required to design a robust product that can meet the challenges of a harsh operating environment. In addition, extra requirements such as load carrying ability and gear protection, without added corrosive or sludge forming tendencies, must be met when formulating turbine oil for geared turbines. All of these requirements have resulted in the development of lubricants specifically designed with anti-wear / extreme pressure additives [2].

Turbine Formulation Design

Design Input – Requirements for an Anti-wear Gas Turbine Lubricant

There are many considerations when developing and formulating turbine fluids for a particular application. Turbines employing a speed reduction gear system that is lubricated from a sump common with the turbine bearings require an extreme pressure / anti-wear (EP/AW) lubricant. One of the most common specifications for EP/AW turbine fluids is General Electric's GEK 101941A "Lubricating oil Recommendations with Anti-wear Additives for Gas Turbines with Bearing Ambients Above 500°F (260°C)" [2]. The physical and chemical properties for the lubricant specified in GEK 101941A are shown below in Table 1.

Table 1: Recommended Properties of Lubricating oils According to GEK 101941A

ASTM Test Method No.	Test	GEK 101941A Recommended Value
D-287	Gravity (°API)	29-33.5
D-1500	Color	2.0 (max.)
D-445	Viscosity - 40°C (cSt)	28.8-35.2
D-2270	Viscosity Index	95 (min.)
D-97	Pour Point (°F/°C)	+10 /-12 (max.)
D-92	Flash Point COC (°F/°C)	420/215 (min.)
D-665	Rust Prevention - B (24 hrs)	Pass
D-130	Copper Corrosion	1B (max.)
D-892	Foam - Seq. I (mL)	50/0 (max.)
	Foam - Seq. II (mL)	50/0 (max.)
	Foam - Seq. III (mL)	50/0 (max.)
D-3427	Air Release (minutes)	5 (max.)
D-524	Carbon Residue Ramsbottom (%)	0.10 (max.)
D-974	Neutralization No. or TAN (mg KOH/g)	0.20 (max.)
D-943	Turbine Oil Oxidation Test (TOST) (hrs.)	3000 (min.)
D-2272	Rotary Pressure Vessel Oxidation Test (RPVOT) (minutes)	500 (min.)
D-2272	Modified RPVOT (%)	85% (min.) of time in unmodified test
D-5182 (or DIN 51354)	FZG Gear Rig Test Failure Load Stage	8 (min.)
D-4951	Atomic Emission Spectroscopy	Zinc Content < 5ppm


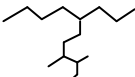
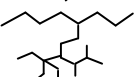
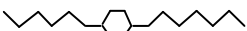
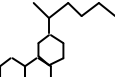
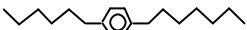

The wear, scuffing protection and load stage capability of such EP/AW turbine fluids is normally measured via the FZG gear rig test (DIN 51354/ ASTM D5182), otherwise known as the Four

Square Gear Oil Test. It employs a step-type loading method approach until a predetermined level of wear or gear scuffing appears. GEK 101941A specifies a failure on load stage 8 being the minimum performance level required, in addition to the more common test requirements as outlined in Table 1. There are several other OEMs that include additional requirements for geared turbine lubricants within their specifications such as Siemens TLV 9013-04, Solar ES 9-224V, Alstom HTGD 90 117, etc. All these specifications use FZG to measure load carrying ability with requirements ranging from a minimum failure stage load of 6 to ≥ 8 . Focus was placed on the General Electric specification as it was required for the turbines used in the field trial.

Design Input- Base Oils

Typically, turbine lubricant formulations consist of approximately 95 – 99.5% base oil plus 0.5 – 5 % additives [14]. The quality and performance effectiveness of turbine lubricants is a function of the type and quality of base oil used in their formulations. Base oils are composed of complex mixtures of various hydrocarbon structures and the type and degree of processing used to manufacture them will cause variations in their composition [3]. Base oil chemical composition can impact product properties such as: oxidation stability, viscosity index, pour point, volatility, solubility, response to additives and seal swell characteristics. Table 2 [3] gives a more detailed overview of the impact of hydrocarbon structure on some of these properties.

Table 2: Effect of Hydrocarbon Structure on Selected Lubricant Properties

Chemical Type	Structure	Viscosity Index	Pour Point	Oxidation Resistance
n-Paraffin (Wax)		Very High ~175	Solid @ 50°C	Excellent
iso-Paraffins with branched chains		High ~150	Good	Excellent
iso-Paraffins with highly branched chains (PAO's)		Good ~130	Good	Excellent
cyclo-Paraffin - single ring with long chains		Good ~130	Good	Good
Naphthenes, polycondensed		Poor ~60	Good	Medium
Monoaromatics, long chains		Poor ~60	Good	Medium
Polyaromatics		Very Poor <0	Good	Very Poor

Desirable paraffins and cycloparaffins yield high viscosity indexes and good oxidative stability, while undesirable aromatics and hetero-atoms lead to instability and deposit formation [3]. Careful tailoring in the refining process can optimize performance by selective removal or transformation of undesirable components such as sulfur, nitrogen, oxygen and aromatic

components. The American Petroleum Institute [4] classifies base oils according to sulfur content, saturates and viscosity index as shown in Table 3.

Table 3: API Base Oil Categories

Base Oil Category	Sulfur (%)		Saturates (%)	Viscosity Index
Group I	> 0.03	and/or	< 90	80 to 119
Group II	≤ 0.03		≥ 90	80 to 119
Group III	≤ 0.03		≥ 90	≥ 120
Group IV	All polyalphaolefins (PAOs)			
Group V	All basestocks not included in Groups I, II, III, or IV			

Much work has been done to correlate base oil properties with turbine lubricant performance. The performance advantages of Group II, III and higher quality basestocks over older generation Group I oils has been noted by several researchers, and the general conclusions arising from this work can be summarized as follows:

Solvent refined Group I base oils cannot meet today's heavy-duty high temperature gas turbine performance requirements. Mobil [5] notes that they have used high-quality hydrotreated basestocks in their premium turbine oils worldwide since the mid 80's. They comment that the low sulfur and aromatic levels provide excellent oxidation and colour stability. Rasberger [6] also noted that the oxidative stability and sludge forming tendency of additized hydrotreated basestocks, with low aromatic and sulfur content, is clearly superior to that of solvent refined oils.

Gatto and Grina [7] noted large differences in the response of different hydrocracked basestocks to an optimized hindered phenol/alkylated diphenylamine additive ratio. A very high viscosity index Group II basestock significantly outperformed other Group I and II basestocks tested. Galiano-Roth and Page [8] also show the superior response of two-stage hydroprocessed oils to antioxidants, in that oxidative performance increased as total and polynuclear aromatics decreased. Galiano-Roth and Page noted that although oxidation stability is increased by hydroprocessing, solvency of additives and oxidation products is decreased. It is important to note that these solubility problems were observed when an additive system typically employed in solvent refined basestocks was used in hydroprocessed basestocks.

Irvine [3] concluded that among highly refined Group II and Group III basestocks, with very low hetero-atom and aromatic content, poly-cycloparaffin content is a key indicator of oxidative performance. Oxidative stability of additized basestocks increases as poly-cycloparaffin content decreases. Group III basestocks with low poly-cycloparaffin content offer oxidative stability on par with PAOs.

Hannon [9] noted that most hydroprocessed turbine oils will have better initial RPVOT and TOST performance over conventional turbine oils, which is an oxidative stability performance advantage.

In short, the limitations of the basestocks being employed must be considered when designing turbine oils to meet particular applications or 'oil life' requirements. Group I basestocks can still be employed, although this will result in a much more limited oil life. The excellent properties

resulting from the use of highly refined, severely hydrocracked/ hydrotreated Group II, and higher quality basestocks, such as high purity and viscosity index, low volatility, superior oxidative resistance, and thermal stability make them ideally suited for modern heavy-duty gas turbine oil applications. It is for this reason that these basestocks were employed in a formulation designed to meet the requirements of GEK 101941A and to provide reliable, extended service life.

Design Input - Additives

Additives can be used to ‘boost’ the inherent properties of basestocks; however, lower additive treat rates are required to meet desired product specifications if high quality basestocks are employed. The additive system must be carefully balanced and have low volatility, good thermal stability and adequate solubility in the basestocks used in the turbine oil formulation [3]. Formulation balance also requires the selection of additives with synergistic effects, and multi-functional additives, where possible, to reduce overall additive treat rates. Low treat rates help to alleviate additive solubility concerns with highly non-polar basestocks, including problems with additive ‘fall out’, sludge and deposit formation [3]. Depending on the performance level desired, additives such as corrosion/rust inhibitors, foam suppressants, demulsifiers, pour point depressants, antioxidants and extreme pressure / anti-wear additives can be incorporated in turbine oil formulations.

In simple terms, corrosion/rust inhibitors are required to protect metal surfaces from rust and corrosion. Pour point depressants are added to impart good low temperature properties, and demulsifiers and anti-foam additives are employed to improve water and air separation properties, respectively.

Antioxidants are required to inhibit lubricant oxidation and prevent deterioration associated with oxygen attack. Antioxidants can be lost to vapourization or become ineffective as a result of high temperatures [10]. Without an effective antioxidant, which is non-volatile and thermally stable, the mineral oil will oxidize quite rapidly. OEM specification GEK 101941A specifically warns against the use of certain additives, “operating experience has shown that antioxidant of the di-tertiary butyl-para-cresol (DPBC) type is not adequate for this service” since bearing temperatures are hot enough to strip it from the lubricant [2]. It has been proven that a significant decrease in RPVOT test results will occur due to antioxidant vapourization, resulting in a loss of oxidation stability. As such, GEK 101941A includes a modified RPVOT test where the lubricant is stripped of any volatile additives by heating to 121°C and blowing it with nitrogen for 48 hours prior to testing.

In terms of antioxidant types, strong synergies have been noted when an optimal ratio of primary antioxidants or free radical scavengers are added to a formulation. Several formulations contain combinations of hindered phenols and alkylated diphenylamine antioxidants [14]. Also, the oxidation stability of base oils can be further optimized with the inclusion of phosphorus or sulfur type secondary antioxidants or peroxide decomposers [3, 11]. This synergistic antioxidant

effect differs from base oil to base oil, thus, finding the optimal ratio or combination is key to reducing additive treat rates.

The antioxidant system used for the prototype EP/AW turbine fluid (RDF-9908) is based upon a unique, synergistic combination of primary and secondary antioxidants which exhibit good solubility and allow the use of lower treat rates.

Finally, extreme pressure / anti-wear additives (EP/AW) are required for applications with load carrying equipment employing high speeds and highly loaded gearing. EP/AW additives bond to metal surfaces to create a strong lubricant film between moving metal parts. This film can withstand extreme heat and mechanical pressure to keep metal parts separated, protecting them from scoring and seizing. However, the acidity or TAN of EP/AW additives can have a detrimental effect on lubricant performance. Smith [10] noted that these additives can be corrosive and conducive to sludge formation. Therefore, formulation treat rates must be optimized and they should only be employed when a real need exists.

Many older EP/AW turbine oil formulations contained extreme pressure and anti-wear additives such as TCP (Tri-Cresyl Phosphate) or ZDDP (Zinc Dialkyl Dithiophosphate), which made significant improvements in gear wear [10]. In spite of this, oil formulators are moving away from TCP because it contains TOCP (Tri-Ortho-Cresyl Phosphate), which is a known neurotoxin. Also, ZDDP when used in turbine systems can become corrosive, bringing catalytic metals into the oil. OEM specification GEK 101941A specifically limits the amount of zinc in turbine oils to a maximum of 5.0 ppm to preclude the use of zinc based anti-wear additives and safeguard from this phenomenon [2].

The EP/AW additive chosen for RDF-9908 delivers excellent wear and scuffing protection, is thermally stable, ash free, resists deposit formation and boosts the load carrying capability of the oil without TCP, ZDDP or increasing the TAN significantly. The additive system is also multifunctional with additional benefits including excellent rust and corrosion protection as well as good oxidation stability.

Prototype EP/AW Turbine Oil (RDF-9908)

Considering all the design inputs and factors mentioned in the previous sections, a prototype EP/AW turbine oil (RDF-9908) was designed using highly refined, high purity Group II basestocks, combined with a thermally and oxidatively stable additive system. The additive package also exhibits low volatility, is ashless, soluble and present at treat rates that provide robust optimal multifunctional performance.

Design Verification - Laboratory Testing

An extensive array of laboratory testing was performed to determine if Prototype EP/AW turbine oil, RDF-9908, met the approval requirements of the GEK 101941A specification. Typical

characteristics of RDF-9908 are shown in Table 4. Properties to note are the excellent foaming resistance and air release, the high load carrying ability (FZG result), and excellent oxidative stability (RPVOT and TOST values), which greatly exceed the requirements of GEK 101941A. It is also important to mention that the flash point required by GEK 101941A could not be achieved without the use of Group II base oils since they normally have higher flash points and lower volatility than Group I oils [14]. The properties afforded by this turbine oil also surpass the requirements of other OEM specifications for geared turbine lubricants such as; Siemens TLV 9013-04, Solar ES 9-224V, Alstom HTGD 90 117, etc.

Table 4: Typical Properties of Prototype EP/AW Turbine Oil – RDF-9908

ASTM Test Method No.	Test	GEK 101941A Recommended Value	RDF-9908 Typical
D-287	Gravity (°API)	29-33.5	31.3
D-1500	Color	2.0 (max.)	0.5
D-445	Viscosity - 40°C (cSt)	28.8-35.2	34.15
D-2270	Viscosity Index	95 (min.)	97
D-97	Pour Point (°F/°C)	+10 /-12 (max.)	-27.4/-33
D-92	Flash Point COC (°F/°C)	420/215 (min.)	433/223
D-665	Rust Prevention - B (24 hrs)	Pass	Pass
D-130	Copper Corrosion	1B (max.)	1A
D-892	Foam - Seq. I (mL)	50/0 (max.)	5/0
	Foam - Seq. II (mL)	50/0 (max.)	15/0
	Foam - Seq. III (mL)	50/0 (max.)	5/0
D-3427	Air Release (minutes)	5 (max.)	2
D-524	Carbon Residue Ramsbottom (%)	0.10 (max.)	0.03
D-974	Neutralization No. or TAN (mg KOH/g)	0.20 (max.)	0.18
D-943	Turbine Oil Oxidation Test (TOST) (hrs.)	3000 (min.)	10,000+
D-2272	Rotary Pressure Vessel Oxidation Test (RPVOT) (minutes)	500 (min.)	2,000+
D-2272	Modified RPVOT (%)	85% (min.) of time in unmodified test	100
D-5182 (or DIN 51354)	FZG Gear Rig Test Failure Load Stage	8 (min.)	11
D-4951	Atomic Emission Spectroscopy	Zinc Content < 5ppm	0

Design Validation - Field Testing

Field testing and in-service oil monitoring preceding the establishment of a new formulation or design philosophy is good practice. It has long been recognized by the power-generation industry as being required to ensure long, trouble-free operation of turbines [12]. Following the extensive bench testing of this prototype formulation a field trial site was arranged in order to confirm the performance of the product. This was deemed necessary given the high value of modern turbine systems and the fact that a complete correlation between bench testing and actual field performance still does not exist [2].

Laboratory test results are based on new oil properties, which can drastically change in service. Incidents of turbine failures have occurred due to oil deterioration which sparked the advent of the condemning limits proposed in ASTM D4378-97 “In-service Monitoring of Mineral Turbine Oils for Steam and Gas Turbines”. These limits are used to prompt action prior to the development of operational problems. Condemning limits include a 5% change in viscosity, an increase in acidity or TAN of 0.3-0.4 mg KOH/g over new oil, less than 25% of the original

RPVOT value as well as limits and recommended actions for other parameters such as oil cleanliness, rust, colour, flash point, and foam [12].

Field Trial Test Equipment

The equipment used for the field trial was a General Electric PG6561B Frame 6B (MS6001B) Heavy Duty Gas Turbine. The MS6001B consists of a gas turbine driving a generator through a gearbox. The turbine runs at 5100 RPM and drives the 60 Hz generator at 3600 RPM. Lubrication of the turbine bearings and gearbox is provided through a common 7,500L lubricant reservoir. The turbine itself is a single shaft, 2 bearing design, with 39.1 MW output, 1104°C (2020°F) firing temperature, and 539°C (1003°F) exhaust temperature.

The Terra Nova FPSO (Floating Production Storage and Offloading) vessel employs two such GE Frame 6B turbines for its power generation needs. Terra Nova's topsides facilities are installed approximately 4.5m above the main deck. They include the necessary equipment to produce 150,000b/d of oil, and inject 250,000bbl of seawater/day and 125 MMcf/d of gas. The location of the PG6561B turbine generators is towards the aft of the vessel. Running Terra Nova's compressors for gas re-injection into the oil reservoir requires essentially the full output of one turbine. The other turbine supplies power for such things as the bow and stern thrusters (5 thrusters - 5 MW each), seawater injection pumps, crude pumps, and deck hydraulics.

Terra Nova FPSO: A Challenging Environment

The Terra Nova FPSO vessel operates in the Terra Nova oil field, 350 kilometers off the east coast of Canada in the Jeanne d'Arc oil basin in the Grand Banks region of the Atlantic Ocean.

For the Terra Nova field trial, the turbine lubricant requirements specified for the GE Frame 6B (MS6001B) heavy-duty gas turbines was an oil meeting GEK 101941A. RDF-9908 certainly met this criteria; however, it was understood that shipboard environments such as the Terra Nova FPSO, can place uniquely high demands on the lubricants used for the various machinery. Turbines running in the Terra Nova field trial are under mission critical operation; reliable power generation is a necessity. Any downtime or repair of damages can lead to significant financial consequences of up to millions of dollars for every day of lost production. Moreover, power generated from the turbines is used to maintain vessel position during operation. Several factors can directly influence the turbine oil's performance and service life; 1) formulation, 2) turbine design and construction, and 3) operating conditions. Since formulation details were previously discussed, this section will focus on the later two factors.

In terms of design, the turbines themselves are packaged in a small footprint to minimize space requirements onboard. Minimizing weight on the vessel is equally important. As a result, undersized oil reservoir volumes may be necessary. The turbines on the Terra Nova FPSO use a 7500L oil reservoir which is fairly small for a 39.1 MW turbine. In most cases, as with this design, smaller reservoirs with less oil can lead to shorter residence times, meaning each volume of oil is circulated more often. Dwell time for the lubricant in these turbines is estimated to be approximately 4.3 minutes and is not ideal. An adequate dwell time of approximately 5 minutes is required to ensure good de-aeration and dirt settling [10]. In other cases, designers may

compensate for small reservoir volumes by decreasing oil flow rates to achieve a particular oil dwell time. Both instances will essentially lead to an increase in oil operating temperatures.

These turbines are also subject to unique and demanding environmental operating conditions. Production must be maintained in windy, heavy seas with significant wave action. The vessel experiences dynamic movement such as pitching, rolling, heaving, and yawing [1]. This vibrational motion, bending and twisting can put substantial strain on the turbine. In addition, the movement or ‘sloshing’ of the lubricant in the oil reservoir can lead to significant air entrainment. Special baffling and drain cavities are incorporated in the reservoir design to reduce this phenomenon [1].

Monitoring and preventative maintenance are extremely important for ensuring reliable gas turbine operation; however, this is very difficult to accomplish on a FPSO vessel. To reduce production downtime on the Terra Nova FPSO, maintenance is minimized and has, to date, been restricted to one planned outage per turbine per year. There is little opportunity for frequent preventative maintenance or problem troubleshooting. In many cases, minor problems must be alleviated for the short term until the maintenance or repair can be properly managed. Weather conditions also play a role in scheduling downtime. Major inspections that require crane operations to lift larger parts must be executed during the spring and summer when sea conditions are suitable. The fact that the vessel is in a remote location also presents logistical challenges for maintenance and repair since spare parts, machinery required, and personnel are not always available. For Terra Nova, this complexity increases because there are on-shore personnel directing remote off-shore maintenance workers. Also, limitations on the number of people permitted on the vessel at any one time further complicates the scheduling of maintenance work. The accommodations and number of lifeboats are designed for 80 people. Once the personnel required for production operations, vessel operations, catering and all the other support services are subtracted there is a limited number left to deal with breakdowns or to troubleshoot unexpected problems. This illustrates the difficulty involved with maintenance activities and the need to have robust turbine oil which gives plenty of advance warning with regards to the need for oil change out.

Gas turbine oils, by comparison to steam turbine oils have a shorter service life since they are subjected to significantly higher localized “hot spot” temperatures [12]. Over its course of lubrication and path through the system, the turbine oil picks up significant amounts of heat that must be dissipated. According to GEK 101941A [2], normal bearing inlet oil temperatures should be between 54.4°C (130°F) and 71.1°C (160°F). Normal lubricant temperature rise when a reduction gear is involved may be as high as 33.3°C (60°F); hence, bearing outlet temperatures can reach as high as 104.4°C (220°F). This specification also notes that during normal operation, the bulk oil temperature will be between 68.3°C (155°F) and 93.3°C (200°F). Lube oil coolers, of the shell and tube heat exchanger type, are used to control operating temperatures for Terra Nova’s turbines and seawater is employed as the coolant.

Oil coolers should be sized with some margin for fouling and must account for the warmest climate in which the system must operate, as well as the warmest temperature of available cooling water. The oil coolers for these turbines were designed for cooling water at 12°C (53.6°F), but in reality the cooling water inlet temperature can be as high as 18°C (64.4°F) due to

the Gulf Stream effect. Although the local seawater temperature may be cooler than this, the water is heated significantly as it is pumped through the Terra Nova super structure. These higher than expected cooling water temperatures caused the oil to run even hotter than anticipated. The coolers were never able to achieve bearing inlet temperatures below 60°C (140°F), which was significantly higher than the 54.4°C (130°F) recommended in GEK 101941A. These hot temperatures suggest that the oil coolers were undersized not accounting for the possibility of fouling on the oil side as well as marine fouling growth that could occur on the water side of the cooler. In fact, a problem was encountered with cooler fouling and header temperatures of about 74°C (165.2°F) were achieved by turbine #2 at the peak of this fouling problem. The coolers may have been undersized for two reasons 1) to save on space, due to limitations on board the ship, and 2) poor assumptions for the average sea water temperature, which can be substantially warmer in the summer.

Aside from issues with the oil coolers, the turbines themselves were running hotter than expected. The power output of the units had been de-rated in order to control the oil and bearing temperatures within acceptable limits. Trending reports showed that with only 3,000-5000 fired hours the turbines were running at 33-34 MW output with an oil header temperature of 60°C (140°F), and bearing drain temperatures of 90°C (194°F). This 30°C temperature delta in the early stages of operation, was already at the upper end of the operating conditions quoted in GEK 101941A. This may have been attributed to the undersized oil reservoir. To maximize oil service life it is desirable to minimize operating temperatures by increasing oil reservoir capacity.

With the oil header temperatures surpassing the 71.1°C (160°F) limit, and the bulk of the oil remaining at a constant temperature of 90°C (194°F) in the oil reservoir, this field trial can certainly be considered severe service. Higher temperatures serve to further accelerate fluid oxidation and can lead to oil breakdown causing varnish, sludge and deposit formation. The rate of oxidation doubles for every 10°C (18°F) above 60°C (140°F) [10]. In addition to accelerating oxidation, high temperatures can also lead to additive breakdown and evaporation. In short, ‘thermal stresses’ can lead to premature turbine oil failure.

Not only is the rate of oxidation directly related to temperature, but it is also affected by the presence of catalysts, fluid make-up rate and oil stability. Catalysts for oxidation include iron, copper, cadmium, zinc, lead, products of oxidation and water. Turbine oils operating in an offshore environment are susceptible to water contamination via leakage as well as exposure to humidity which can be drawn in with the air at the bearing and shaft labyrinth seals [10]. Oil make-up can delay oil oxidation because it replenishes the inhibitors and has a dilution effect on the catalysts, contaminants and products of oxidation. In turbines where oil make-up is very low (below 5%), a truer picture of oil degradation is obtained [12]. An oil make-up rate below 5% was certainly the case for the Terra Nova field trial, which was another factor affecting the severity imposed on the oil.

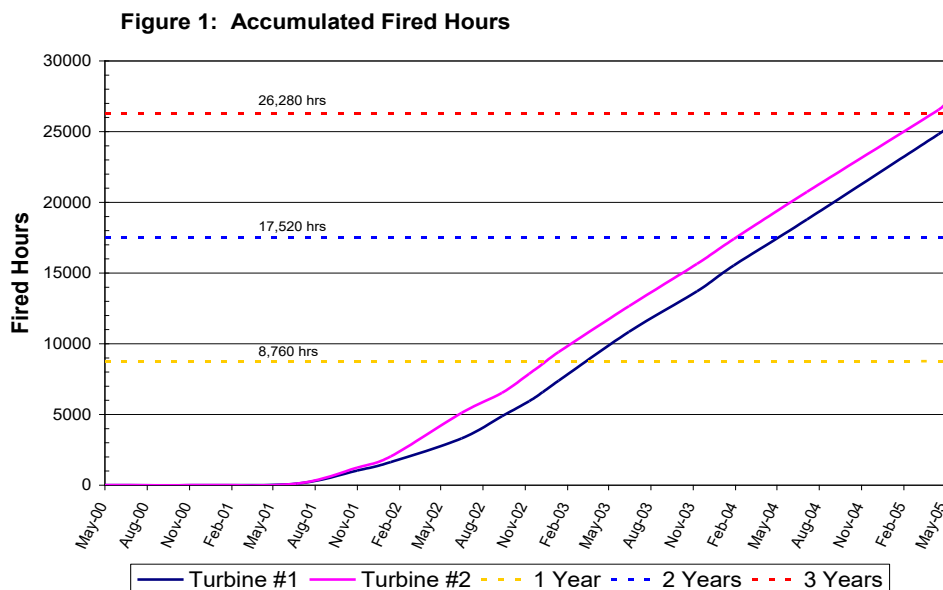
The challenges presented on the Terra Nova FPSO can certainly have a significant impact on the turbine oil longevity. There have been several cases of identical turbines used in offshore oil field projects, using EP/AW type turbine oils, which have encountered major difficulties during operation. Details on the actual problems encountered are vague; however, they have been

related to sticking hydraulic valves, deposit formation, varnishing problems, excessive fouling on cooler surfaces and issues related to the additives not being dispersed evenly throughout the oil. The Terra Nova field trial is currently at 25,000+ fired hrs for turbine 1 and 27,000+ for turbine 2, without encountering any such oil related issues.

Accumulation of Fired Hours

The initial fill of Terra Nova's turbines was performed in April 2000. However, the accumulation of running hours was a slow process due to the extensive commissioning work required for the FPSO vessel. As a result, there was a delay of approximately 1 year while waiting for the commissioning to be completed before the vessel was ready for sea trials, during which the turbines would provide power.

Accumulated fired hours for both turbines are shown in Figure 1. From this graph it can be seen that turbine #2 accumulated about 2000 more hours than turbine #1. This resulted from the fact that Terra Nova only needed one turbine for power supply during the pre-startup phase since gas



gas compression was not in operation. The graph illustrates the relationship between in-service years and years corresponding to the accumulation of fired hours (i.e. 1 year of running time = 8760 fired hrs). Currently, both turbines have been in service for about 4 years and have accumulated over 25,000 fired hours of operation, which corresponds to approximately 3 years of running time.

Issues Encountered During Field Trial

Two issues arose during the course of the field trial at Terra Nova, bearing failures and oil cooler fouling, but neither were attributed to the oil itself.

Failure was noted for the pinion shaft bearing where the high-speed shaft from the turbine enters the gearbox. The turbine shaft speed of 5100 RPM is stepped down to 3600 RPM in the gearbox for the generator. Testing performed on the oil, including foaming characteristics, found no issues. Review of the gearbox design revealed that the gearbox had been modified to accommodate for the motion of the ship in heavy seas, but still encompasses the basic General Electric design. Terra Nova later reported that the turbine contractor had determined that bearing failure was due to rapid load cycling of the gearbox leading to unstable shaft position in the bearing. Subsequently, the same failure mode was reported for the second turbine, shortly after. All instances of bearing failures were diagnosed and reported to be mechanical in nature, related to the gearbox design and not to the lubricant itself. No further instances of bearing failure have been reported to date.

Degradation in turbine performance/power output due to oil cooler fouling was the second issue encountered during the later stages of the field trial. Power output was decreased in order to control high bearing and oil temperatures. Inspection of the outer tube surfaces revealed a very thin soft film which was easily wiped off. There were no signs of the hard, tightly adhering, varnish like material normally associated with oil oxidation. Analysis revealed that the soft oily film was not oxidized oil. The oil was in excellent condition; it contained all of the antioxidants at fresh oil levels. However, the oil contained a foreign polar material or corrosion inhibitor. This suggests that contamination had occurred with residual preservative oil (vapour space corrosion inhibiting additive), initially placed in the turbine. After the coolers were thoroughly chemically cleaned their performance was restored. Both units were operating within 1-2°C of each other, and the oil temperatures exiting the oil coolers were recorded as 61°C (141.8°F) and 60°C (140°F), as opposed to the 74°C (165.2°F) header temperature achieved by turbine #2 at the peak of the fouling problem. To date, temperatures have not risen and these units have not shown signs of re-fouling or decline in performance. Once again, this implies that the fouling was a one time issue and was related to contamination as opposed to ongoing oil degradation. This view is supported by oil analysis which shows a stable and low TAN as well as high residual antioxidant content, and RPVOT values. This highlights the importance of adequate cleaning of all surfaces and thorough flushing of a system prior to commissioning a new turbine.

Results & Discussion

Lubricants can undergo significant change as a result of deterioration, volatilization and contamination which can eventually lead to turbine operational problems. Thermal and oxidative stresses can change the lubricant's physical and chemical properties making it less efficient at, or preventing it altogether from performing its role and function. This includes changes in viscosity, sludge, varnish and acid build-up, foam, air entrainment as well as the increase in volatile combustible products that can lead to fires [10]. Oil in-service monitoring is recommended to detect, predict and avoid these types of problems. It is for this reason that samples were taken throughout the course of the field trial and several properties were tested for both turbine #1 (Starboard Main Power Generator) and turbine #2 (Port Main Power Generator).

Properties which were monitored (some regularly, others not) included: 1) viscosity, 2) additive levels and depletion, 3) oxidative stability, 4) oil cleanliness, 5) foaming tendency and air separation, 6) rust / corrosion protection and several other parameters. A summary of the physical and chemical properties of the EP/AW turbine fluid (RDF-9908) over the course of the field trial, in both turbines, is discussed in detail below.

Viscosity

Viscosity is the most important characteristic of turbine oil, as oil film thickness under hydrodynamic lubrication is critically dependent on the oil's viscosity [12]. Viscosity increase can lead to excessive friction in the bearings and an accompanying generation of heat, as well as detrimental effects to the performance of pumps and gears. The kinematic viscosity at 40°C (104°F) and 100°C (212°F) was measured for the oil in both turbines according to ASTM D445.

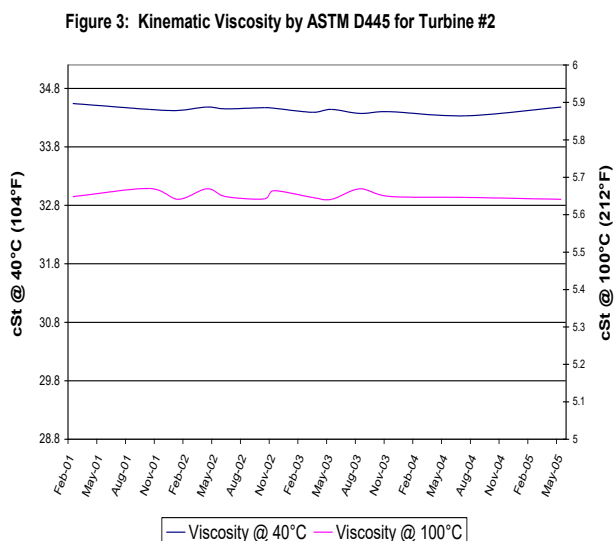
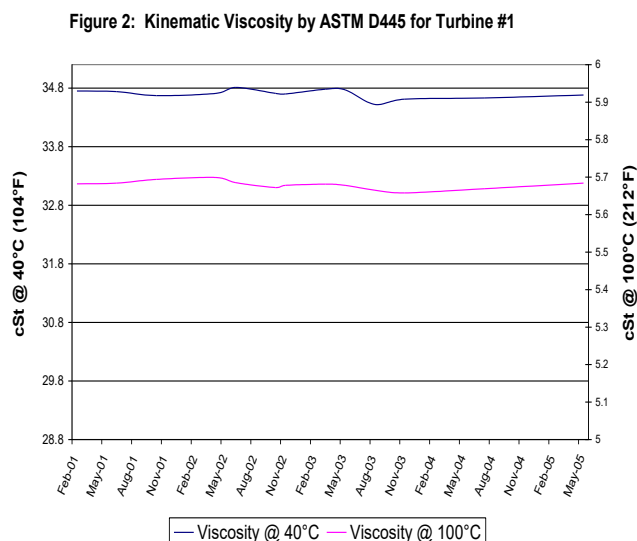


Figure 2 and 3 show that the viscosity of RDF-9908 has essentially remained constant, with no indication of thickening due to degradation, water emulsions, or dilution from other contaminants. The changes observed are within the 5% limit set by ASTM D4378 [12].

Additive Levels & Depletion

It is important to monitor changes in additive concentrations that are imparting the key desirable properties such as: antioxidants, corrosion/rust inhibitors, as well as the EP/AW additives. HPLC (High Pressure Liquid Chromatography) was the method used to detect the additive concentrations remaining in the turbine oil samples. Antioxidants are consumed while preventing oxidation. Figure 4 and 5 indicate that with about 4 years of in-service operation and 25,000+ fired hours, over 65% and 63% antioxidant remain in turbine #1 and #2, respectively. This is not a significant change, and concentrations remain above the condemning limit of 25% as stated in ASTM D4378 [12]. The concentration of the copper corrosion inhibitor in the oil declined rapidly, as expected. This additive functions by forming a coating on the surfaces it protects. The level of the EP/AW additive was also monitored and has essentially remained constant.

Figure 4: Additive Depletion by HPLC for Turbine #1

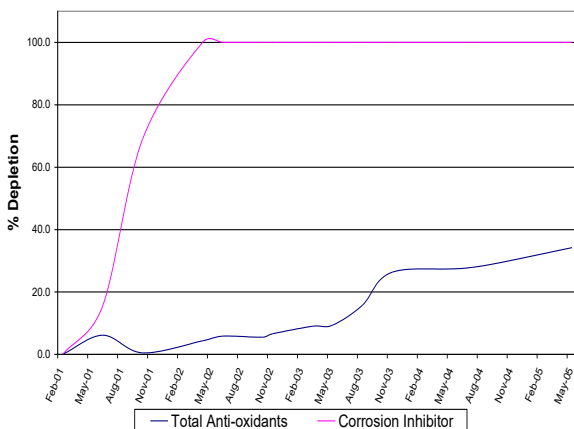
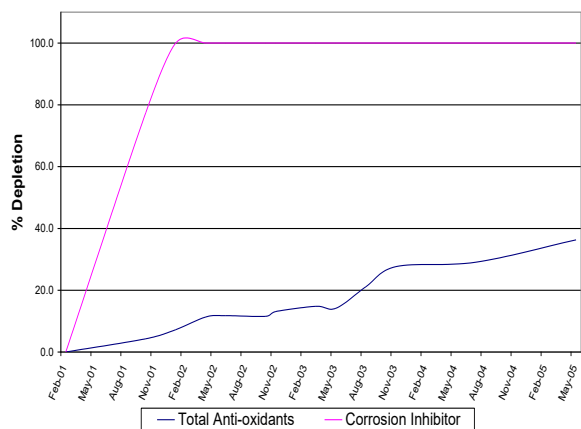


Figure 5: Additive Depletion by HPLC for Turbine #2

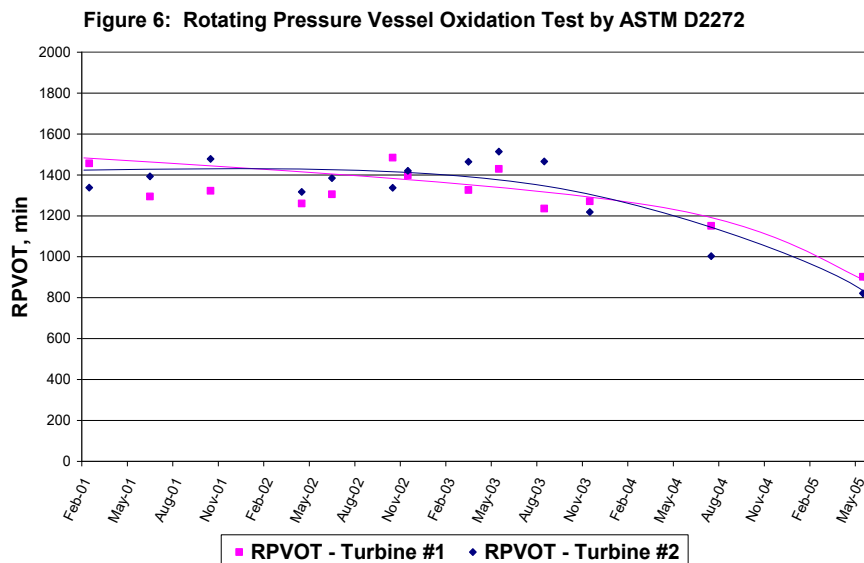


Oxidative Stability

Oxidation stability or antioxidant reserve will gradually decrease in service as a result of degradation and depletion of the antioxidant. Typically the test method used to detect oxidative degradation is the neutralization number or total acid number, TAN, measured by ASTM D974. After 25,000+ fired hours, the TAN levels for turbine #1 and turbine #2 were recorded as 0.18 mg KOH/g and 0.20 mg KOH/g, respectively. Considering that the fresh oil TAN for RDF-9908 is 0.18 mg KOH/g, these low values suggest that there is no significant presence of acidic oxidation by-products in these turbine oils. This has been confirmed via FTIR (Fourier Transport Infrared) analysis which showed no sign of oxidation between the wavelength bands of the spectra in which oxidation would normally appear (i.e. 1710 – 1725 cm^{-1}).

Oxidation stability reserve in turbine oils is measured by test method ASTM D2272. RPVOT results remained consistently high over the duration of the field trial, and are only recently trending lower, as shown in Figure 6. However, the reduction in RPVOT has not reached the condemning limits stated by ASTM D4378 [12] of 25% of the initial value. It should be noted that lubricant (RDF-9908) taken from both turbines, after the initial fill, was tested and the RPVOT results were in the 1400 minute range. This is significantly lower than the 2000+ minute RPVOT results typically achieved with fresh RDF-9908 laboratory samples. It is unclear why the initial RPVOT values were lower than typical as the initial antioxidant levels were within specification. It is possible that contamination or reaction with the new surfaces in the turbines may have been the cause of this issue. Also, there appears to be excess variation in the test results, which can be attributed to the test repeatability itself. Precision and bias reported in ASTM D2272-02 [13] states that successive test results can differ by 12% of the mean value for results in the range of 30 to 1000 minutes. According to the method, results greater than 1000 minutes exhibited such poor repeatability and reproducibility in a 1995 study that a precision statement was not included.

Despite this variation, the RPVOT results coupled with consistently low TAN values and a gradual drop in antioxidant level confirms that the fluid continues to resist oxidation and has ample service life remaining. This is significant performance considering the challenging operating conditions previously described.



Oil Cleanliness

During operation, the turbines can accumulate significant amounts of particulates, sludge, or other contaminants resulting from degradation and corrosion by-products. These materials promote scoring and damage to the journal bearings as well as cause malfunctioning or sluggish response and sticking of hydraulic controls and servo valves in the governor system. The desired cleanliness level that was required for the GE Frame 6B turbines was NAS 6, which is equivalent to approximately ISO 4406 – 17/15/11 (ISO cleanliness code). This is a typical recommendation for hydraulic control systems encompassing servo-systems. As of May 2005, analysis via test method ISO 11500/ ISO 4406 yielded levels of 15/13/10 for turbine #1 and 15/12/9 for turbine #2, which are within the recommended guidelines. Visual inspection of turbine reservoirs, bearing housings, seals and gears during maintenance shutdowns has also confirmed no operational problems associated with oil cleanliness.

Other Properties

Foaming and air entrainment can be problematic, resulting in overflowing reservoirs and leading to possible pump cavitation, premature oxidation and excessive wear. After 4 years in service, the oil in both turbines, when tested for Air Release via test method ASTM D3427, resulted in values of 3.8 and 3.7 minutes. These results meet the GEK 101941A specification for fresh oil, which specifies a maximum of 5 minutes. According to ASTM D4378 [12], turbine oils in service should not exceed values of 450/10 for the ASTM D892 Foam Test – Sequence 1. These

same samples were recorded to have foam test results of 190/0 for turbine #1 and 70/0 for turbine #2, respectively, which are much lower than the condemning limit.

Test method ASTM D665 B, Seawater Rust Test, is recommended to determine if a satisfactory level of anti-rust inhibitor remains in the formulation. Although condemning limits allow for a 'light fail' in this test, samples from each turbine were tested and the results were recorded as 'very light rusting' which was hardly noticeable. Similarly ASTM D130, Copper Strip Corrosion Test, is used to measure the ability of the oil to guard itself against corrosion brought about by active sulfur or strong acids. The latest oil sample from turbine #1 gave a result of 1a in this test and 1b for the sample taken from turbine #2, which meets the GEK 101941A specification for fresh oil.

Water content measured throughout the field trial by ASTM D1744 was always less than 0.1%, which is acceptable according to ASTM D4378 [12]. Colour was frequently tested according to ASTM D1500 and the appearance of the oil showed no signs of haziness or the rapid darkening that is indicative of excessive degradation.

ASTM D4378 [12] recommends change out if the flash point drops by 30°F. Flash Point testing by ASTM D92, for recent field samples indicated that the lubricant continues to exceed GE's recommendation for new fluids of 215°C (419°F). This ensures that there is no significant level of low boilers in the oil; hence, the turbines can still operate safely with no risk of fire.

Summary & Conclusions

Turbine oil formulation, turbine design and construction as well as operating conditions can influence the oil's service life and performance.

An anti-wear turbine oil was designed for use in geared turbines in which the main bearings and gearbox are lubricated by the same fluid. The formulation was developed using high quality, severely hydrocracked/hydrotreated GII basestocks coupled with a robust, non-corrosive additive system that exhibits low volatility, and thermal and oxidative stability. Synergistic effects were obtained through the use of optimized additive ratios and multifunctional additives, which allowed for reduced treat rates and better overall formulation solubility.

This product was designed to meet the fluid properties as detailed in General Electric's GEK 101941A EP/AW (Extreme Pressure/Anti-Wear) turbine lubricant specification. The final prototype fluid, RDF-9908, was laboratory bench tested to verify that all design inputs were met. RDF-9908 surpassed these requirements along with other OEM turbine oil specifications.

A field trial was deemed necessary to ensure that the product was 'fit for use' or would perform adequately in a real world setting. The validation activity or field test was executed in two General Electric Frame 6B turbines installed on the Terra Nova FPSO (Floating Production Storage and Offloading) vessel.

Despite the unique and challenging demands that are placed on turbo machinery installed on offshore environments like the Terra Nova FPSO vessel, this EP/AW formulation met these challenges well. During this field trial the system was continuously running at or near its thermal limits, with the bulk of the oil remaining at a constant temperature of 90°C (194°F) in the oil reservoir. Furthermore, vessel design, environmental conditions and subsequent movements, difficulty with maintenance and monitoring as well low oil top up rates all added to the severity of this field trial. Knowledge gained from this trial includes the importance of thorough cleaning and flushing prior to the initial fill of new turbines, in order to remove all possible contaminants including traces of preservative oil. This is critical in avoiding unnecessary operational issues on a FPSO vessel.

The key to superior oil is property retention and this turbine oil has shown no significant oxidative or thermal degradation, additive depletion, or change in other physical and chemical properties. The RPVOT performance, Total Acid Number (TAN), and additive levels indicate that the fluid is still in good condition. After 4 years in-service and 25,000+ fired hours of operation, this turbine lubricant continues to provide reliable service without signs of varnishing, servo valve sticking problems, and issues with the gear set.

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