

An Assessment of the Influence of Gas Turbine Lubricant Thermal Oxidation Test Method Parameters Towards the Development of a New Engine Representative Laboratory Test Method

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ABSTRACT

In the development of a more accurate laboratory scale method, the ability to replicate the thermal oxidative degradation mechanisms seen in gas turbine lubricants, is an essential requirement. This work describes an investigation into the influence of key reaction parameters and the equipment set up upon extent and mechanism of oil degradation.

The air flow rate through the equipment was found to be critical to both degradation rate and extent of volatilization loss from the system. As these volatile species can participate in further reactions, it is important that the extent to which they are allowed to leave the test system is matched, where possible, to the conditions in the gas turbine. The presence of metal specimens was shown to have a small influence on the rate of degradation of the lubricant. Loss of metal from the copper and silver specimens due to the mild corrosive effect of the lubricant was seen.

The Total Acid Number and viscosity of a series of oil samples from two service gas turbines are discussed. The ratio of these two physical properties was approximately constant between samples, indicating constant evaporation loss. Additionally, Gel Permeation Chromatography was used to compare the molecular weight distribution of a lubricant used in a gas turbine to laboratory samples. The replenishment of oil in service engines was highlighted as key difference between these samples. It is believed that laboratory methods can degrade oil similarly to service engines and therefore can be used to predict oil life and condition in service.

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INTRODUCTION

A gas turbine has a large number of metallic rotating components including those in bearing chamber and gearbox locations which require a lubricant in order to operate. Lubricants provide a number of functions critical to gas turbine operation; reduction of friction, heat management, debris removal and corrosion protection. In order to perform these functions, the lubricants used must be capable of withstanding a range of particularly harsh conditions without

significant reduction in performance. It is therefore important that gas turbine manufacturers, lubricant formulators and other interested parties have the capability to assess the rate and pathway by which lubricants degrade, in addition to the impact the degradation will have on their operating performance.

Oil system conditions

Perhaps the most severe conditions in gas turbines are found in mainline bearing chambers where oil is exposed to elevated temperature and pressure in an oxidative and catalytic environment [1]. Figure 1 shows a schematic of a bearing chamber including the major heat sources. Heat transmitted from the gas path in addition to that generated by shearing of the fluid itself, can lead to oil temperatures up to 250 °C upon exit from the bearing chamber via the scavenge pipe [2]. At the contact surface between rolling elements the lubricant is also subjected to high contact pressures which can exceed 2 GPa.[3] In addition to the harsh physical conditions, when air sealing is used the oil is heavily aerated as sealing air flows into the chamber. Since oxygen reacts with the lubricant, the presence of air promotes degradation [4]. Additionally, Zeeman *et al.* [5] observed that metals can act as catalysts in the degradation of lubricants; as gas turbine oil systems are comprised of a range of metals it is possible that oil degradation will be catalyzed in this way. Another factor that has an impact on the physical and chemical properties of service lubricants, are the losses from the system. Gas turbine lubricant systems must be vented in order to remove the air introduced through sealing, this air however also carries with it some components of the oil [1]. The preferential removal of the more volatile species present will result in compositional changes altering the physical and chemical properties of the bulk fluid.

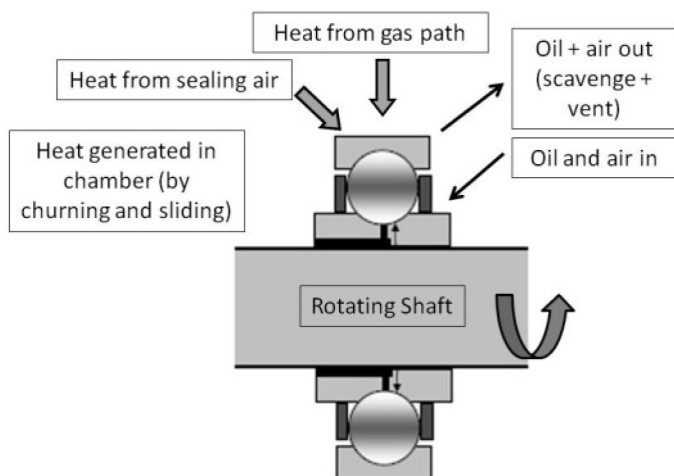


Figure 1. Schematic of a ball bearing chamber

Lubricant formulation

This paper focuses on polyol ester based lubricants with a kinematic viscosity of 5 mm²s⁻¹ (cSt) at 100°C, which are used in the vast majority of modern civil gas turbines. The majority (~95 %) of the formulation is a polyol or hindered ester base blend, manufactured from polyhydric alcohols and monoacids in a range of chain lengths (C₅ to C₁₀). Shown in Figure 2a is a pentaerythritol ester base stock [6]. The remainder of the formulation is comprised of additives which

are included to enhance a particular property, such as anti-wear, load-carrying, corrosion inhibition and anti-foaming additives. These additives are present in low concentrations and as such will have a limited influence on the degradation of the bulk fluid, however anti-oxidant additives are added specifically to slow the oxidative breakdown of the base ester. Hindered amines are used for this purpose, often the formulation will contain a mixture of amines such as phenyl- α -naphthylamine (Figure 2b) and dioctyldiphenylamine, in order to obtain the optimal anti-oxidant properties. Corrosion inhibition or metal passivation additives are known to bind to the surface of metals present in the oil system in order to prevent attack by oil species, they may also influence the catalytic effect metals have on oil degradation [7].

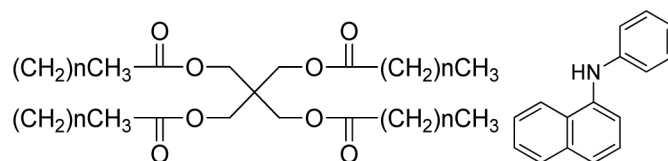


Figure 2. (a) pentaerythritol ester base stock. Where $n = 3-8$ units. (b) Phenyl- α -naphthylamine antioxidant additive.

Chemical degradation of the lubricant

Oxidation of pentaerythritol tetraester type oils can occur via a vast number of potential reaction pathways. These reactions are likely to be initiated by the abstraction of a proton to form a carbon radical on the alkyl chain component of the ester as shown in Figure 3 [8].

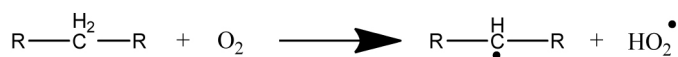


Figure 3. Radical reaction initiation by formation of a carbon radical on the alkyl chain.

Further radical reaction can then be either intrachain or interchain reactions resulting in the substitution of hydroxyl and carbonyl groups into the chain. Cleavage of the chain can occur readily where substitutions have occurred to leave ketone and carboxylic acid products. As the energy required for abstraction of a proton from carbon atoms next to the carbonyl group of the ester is much greater than those further away, the rate of reaction is greater for longer chain alkyl esters.[8]

The formation of acidic degradation products and intermediates, such as carboxylic acids will lead to an increase in the measured acidity of the lubricant. Unless the lubricant becomes strongly acidic this will have minimal influence on lubricant performance, however, it does provide a useful indicator to the level of degradation. As these short carbon chain length species tend to be more volatile than the majority of the lubricant, they can be preferentially

volatilized and therefore be vented from the system as discussed earlier [9].

Interchain free radical or condensation reactions lead to higher molecular weight oligomer products forming, these larger species can be significantly more viscous than the initial ester base stock. However, Karis *et al.* [8] found that the viscosity of the lubricant does not increase in line with molecular weight and the lubricant was in fact more viscous than the molecular weight distribution alone would suggest. It was found that increased hydrogen bonding from substituted hydroxyl groups increases the viscosity and therefore the energy required for flow.

As stated earlier gas turbine lubricant formulations contain aryl amine antioxidants which are included to reduce the rate of ester base stock degradation reactions which occur by the mechanisms discussed previously. These antioxidants will preferentially react with free radical species which would otherwise act to initiate the degradation reactions. Where the antioxidant acts to remove free radical initiators the rate of degradation of the ester base stock is reduced. Once reacted, antioxidant species can themselves oligomerise and subsequently polymerize. If antioxidant polymerization progresses they will become less able to perform their function, due to this, antioxidants are often thought of as being consumed in the oxidation process. These large antioxidant species can have poor solubility in the lubricant and therefore can form sludge or deposit [10][11].

Laboratory degradation methods

It is vital for both engine and oil manufacturers to understand a lubricant's ability to withstand thermal oxidative degradation and remain fit for purpose. The tools used to evaluate lubricants range in scale from small laboratory tests to rig scale to full size engine testing. Small scale laboratory tests are by design, relatively simple methods for assessing a lubricant's thermal and oxidative stability on an accelerated timescale, when compared to that seen in service. These techniques provide oil manufacturers with evaluation techniques when creating new formulations, engine manufacturers with relative performance data with which to compare products and quality control tools for use in lubricant manufacture. The quality of this data is therefore vital in order to ensure correct decisions, which ultimately affect engine safety, are made.

Currently the aviation lubricant industry evaluates lubricant bulk thermal stability at laboratory scale by four techniques; Federal Test Method Standard No 791C Method 3411 [12], Turbomeca Thermal Ageing Test [13], ASTM Method D4636 [14] and Defence Standard 05-50 (Part 61) Method 9 [15]. These methods are requirements for either (or both) MIL-PRF-23699 [16] and/or SAE AS5780 [17] lubricant specifications. These methods all differ in the equipment, test parameters and analysis used, some of which are summarized in Table 1. These differences give rise to advantages and disadvantages for each technique in order to find a compromise between a wide range of factors, however,

as the SAE AS5780 specification currently requires all of these methods, there is duplicated effort.

Table 1. Comparison of the thermal degradation test methods

Method	Ref	Oxidative method?	Air flow rate (mL min ⁻¹)	Includes condenser?	Includes test metals?	Includes rate relationship?
F.T.M. 3411	[12]	✗	-	✗	✓	✗
T.M. Ageing Test	[13]	✓	0	✓	✗	✗
ASTM D4636	[14]	✓	83	✓	✓	✗
Def. Method 9	[15]	✓	250	✗	✗	✓

Of these four methods, Federal Test Method Standard No 791C Method 3411 [12] is not an oxidative method as it evaluates thermal degradation in a sealed system in the absence of air, therefore as service oil can be heavily oxygenated, particularly in the regions of highest risk, it is of limited use in the prediction of service degradation. The Turbomeca Thermal Ageing Test [13] is considered an oxidation test method as it is not a sealed system like FTM Method 3411, however no positive air pressure is applied. ASTM Method D4636 [14] and Defence Standard 05-50 (Part 61) Method 9 [15] are both thermal oxidation methods, however, the equipment set up and air flow rate differ.

In all three oxidative methods the amount of oxygen available for oxidative processes will be different, and perhaps more importantly, as will the amount volatilized from the test vessel. These differences in both input and output will of course influence the chemical species available to participate in any degradation reaction.

Another difference is the inclusion of metal specimens to assess the catalytic and corrosive effects, only the ASTM Method D4636 [14] includes metal specimens in the test which are believed to influence the test. The standard test parameters of temperature and duration vary between test methods, therefore, some of the methods are more extreme than others in terms of the thermal stress the oil is exposed to.

There is scope to develop a revised method which can better meet the requirements of all interested parties, this would allow both a higher quality of data and the refinement of oil specifications to remove duplicate effort. It is important that this test method has the ability to reproduce the degradation mechanisms seen in service oils. This paper therefore is the first published effort to study the influence of test method parameters, in order to relate them to service oil condition. This information is key in the future development and refinement of test methodology.

In this paper, the influence of air flow rate through the test vessel, the chemistry of volatile species and the effect of metal test specimen inclusion was assessed, to provide the