NASA/TM—2007-215035

Feasibility Study of Vapor-Mist Phase Reaction Lubrication Using A Thioether Liquid

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December 2007

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Prepared for the
62nd Annual Meeting and Exhibition
sponsored by the Society of Tribologists and Lubrication Engineers
Philadelphia, Pennsylvania, May 6–10, 2007

National Aeronautics and
Space Administration

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Cleveland, Ohio 44135

December 2007

This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

Level of Review: This material has been technically reviewed by technical management.

Available from

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Abstract

A primary technology barrier preventing the operation of gas turbine engines and aircraft gearboxes at higher temperatures is the inability of currently used liquid lubricants to survive at the desired operating conditions over an extended time period. Current state-of-the-art organic liquid lubricants rapidly degrade at temperatures above 300 °C; hence, another form of lubrication is necessary. Vapor or mist phase reaction lubrication is a unique, alternative technology for high temperature lubrication. The majority of past studies have employed a liquid phosphate ester that was vaporized or misted, and delivered to bearings or gears where the phosphate ester reacted with the metal surfaces generating a solid lubricious film. This method resulted in acceptable operating temperatures suggesting some good lubrication properties, but the continuous reaction between the phosphate ester and the iron surfaces led to wear rates unacceptable for gas turbine engine or aircraft gearbox applications. In this study, an alternative non-phosphate liquid was used to mist phase lubricate a spur gearbox rig operating at 10,000 rpm under highly loaded conditions. After 21 million shaft revolutions of operation the gears exhibited only minor wear.

Introduction

Advances in the development of future jet and rotorcraft engines will depend on the successful high temperature lubrication of the engine bearings and gears. Current state of the art liquid lubricants provide excellent protection over a moderate temperature range, but unfortunately at temperatures above 300 °C these advanced liquid lubricants will degrade rapidly via thermal and oxidation decomposition. Due to the thermal limitations exhibited by conventional liquid lubricants, vapor or mist phase reaction lubrication (VMPL) has received a great deal of attention as an alternative method for high temperature lubrication.

Before proceeding, clarification of the term VMPL will be addressed as some confusion exists regarding how it relates to other vapor or mist lubrication techniques. In a regular oil-mist lubrication system, mineral or synthetic hydrocarbon oil is delivered, in an air stream, as a fine oil mist to mechanical components where the oil- mist coagulates on the wearing surfaces providing lubrication. No intended reaction between the oil and the metal surfaces occurs and the oil functions as a normal liquid lubricant within its operating temperature range. In gaseous lubrication a light hydrocarbon gas, such as acetylene, is delivered to mechanical components operating at sufficiently high temperatures that the gas decomposes on the wearing surfaces generating a lubricious graphitic material which provides lubrication. In the VMPL method, an organic liquid is either vaporized or misted and delivered in an air stream to mechanical components operating at high enough temperatures that the organic molecules react in the wearing surfaces generating a lubricious deposit which provides effective lubrication.

A number of VPML studies have utilized a liquid phosphate ester that was transported as a vapor or mist to bearings or gears where the phosphate ester reacted on the metal surfaces generating a lubricious iron-phosphate type film or deposit (refs. 1 and 2). VMPL studies on a variety of metallic and ceramic substrates have shown the need for a transition metal, such as iron, to be present in order for a film to be produced successfully (refs. 3 and 4). The chemical reaction between the phosphate ester and iron containing surfaces produces an iron-phosphorus type film also containing oxygen and carbon (refs. 5 to 7). This film has been shown to lubricate iron based surfaces at temperatures greater than 300 °C but at a price. Prolonged, continuous lubrication of bearings and gears led to excessive wear due to a constant rapid reaction between the phosphate ester and the iron. This rapid reaction between a phosphate ester vapor and a pure iron foil was studied using a modified thermal gravimetric analysis (TGA) unit (ref. 7). It was found that the reaction generated a phosphate type film on the iron surface which grew with time via a diffusion-reaction mechanism.

If the VPML method is to be successfully used in future applications then the excessive wear problem must be minimized. One possible solution is the use of an alternative, non-phosphorus reactive organic liquid. In references 8 and 9, Morales investigated some of the properties of a polyphenyl thioether liquid. Polyphenyl thioethers are derivatives of polyphenyl ethers where one or more of the oxygen atoms in the polyphenyl ethers are replaced by sulfur atoms. Although the thioethers are thermally stable to 390 °C, simple pin-on-disk tests conducted at 25 °C revealed that they easily break down under boundary lubrication conditions leading to the formation of a polymeric type material. Morales subsequently demonstrated the polymer forming abilities of the thioethers under dynamic boundary lubricating conditions and under static conditions using an electrochemical cell. This polymeric material may well be lubricious and thus the use of the thioether as an alternate VMPL liquid was considered.

An initial investigation into the use of a thioether as a VMPL lubricant was conducted using a high temperature reciprocating pin-on-plate tribometer (ref. 10). The tests revealed that the thioether was able to lubricate a ceramic pin and plate pair, at temperatures greater than 450 °C, with a coefficient of friction less than 0.05 with minimal wear of the substrates. Based on these outstanding results, a thioether liquid was tested as a VMPL lubricant using an enclosed spur gearbox rig operating under high loads and speeds. This paper reports the results of this test with particular attention to the wear of the spur gears.

Test Specimens, Test Rig, and Procedure

The thioether lubricant used in this study is actually a blend of four chemical components (fig. 1) consisting of one 3-ring phenyl component and three 4-ring phenyl components. These four components were blended by a commercial company in order to produce a thioether liquid lubricant with a pour point of –29 °C (ref. 9) for potential aerospace applications.

The test gears used for this study were case-carburized and ground AISI 9310 spur gears. The spur gear geometry is provided in table 1. The gears provided a lead crown having a radius of 323 mm (12.7 in.). This crown provides an approximate 0.014 mm (0.00055 in.) rise across the nominal facewidth of 6.35 mm (0.250 in.). The gear geometry accuracies were inspected using a coordinate measuring machine. The gear profile and tooth spacing geometry quality was found to be ANSI-AGMA 2000-A88 class 11 which is aerospace quality. The lead crown geometry was also verified using the coordinate measuring machine inspection data. The nominal chemical composition and heat treatment procedure for the test gears are provided in tables 2 and 3. The specified surface hardness of the test gears, as provided by the commercial supplier, was Rockwell C 58–62.

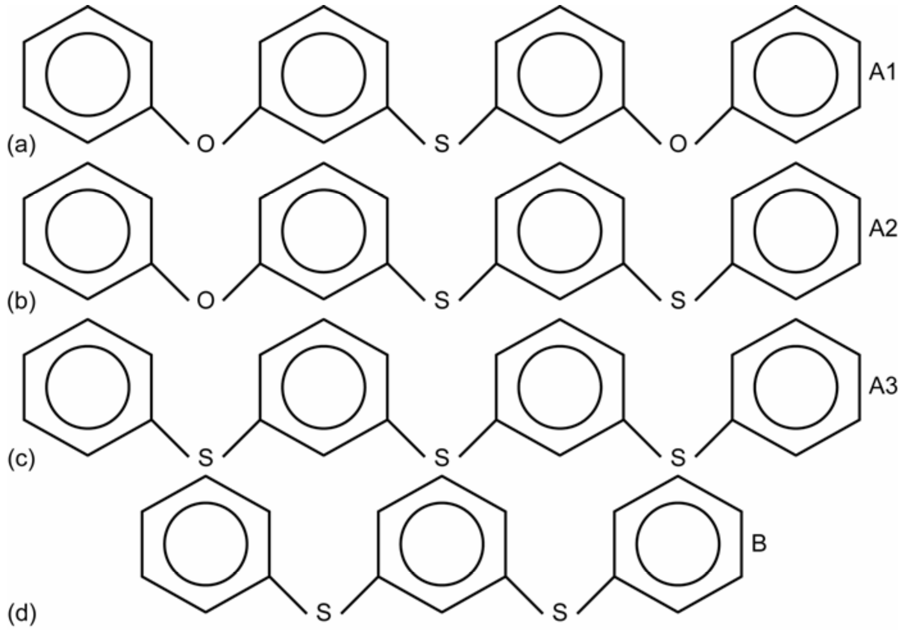

Figure 1.—Chemical components of thio-ether. (a) 1, 1-thiobis [3-phenoxybenzene]; molecular weight, 370. (b) 1-phenoxy-3-[[3-(phenylthio) phenyl] thio] benzene; molecular weight, 386. (c) 1, 1-thiobis [3-(phenylthio) benzene]; molecular weight, 402. (d) 1, 3-bis (phenylthio) benzene; molecular weight, 294.

TABLE 1.—SPUR TEST GEAR DESIGN PARAMETERS
[GEAR TOLERANCES ARE PER ANSI-AGMA CLASS 11.]

Number of teeth	28
Module, mm (in.)	3.18 (0.125)
Diametral pitch, in.$^{-1}$	8
Circular pitch, mm (in.)	9.975 (0.3927)
Whole depth, mm (in.)	7.62 (0.300)
Addendum, mm (in.)	3.18 (0.125)
Chordal tooth thickness ref., mm (in.)	4.85 (0.191)
Pressure angle, deg.	20
Pitch diameter, mm (in.)	88.90 (3.500)
Outside diameter, mm (in.)	95.25 (3.750)
Root fillet, mm (in.)	1.02 to 1.52 (0.04 to 0.06)
Measurement over pins, mm (in.)	96.03 to 96.30 (3.781 to 3.791)
Pin diameter, mm (in.)	5.49 (0.216)
Backlash reference, mm (in.)	0.254 (0.010)
Lead crown radius, mm (in.)	323 (12.7)

TABLE 2.—NOMINAL CHEMICAL COMPOSITION
OF AISI 9310 GEAR MATERIAL

Element	Weight, percent
Carbon	0.10
Nickel	3.22
Chromium	1.21
Molybdenum	0.12
Copper	0.13
Manganese	0.63
Silicon	0.27
Sulfur	0.005
Phosphorous	0.005
Iron	Balance

TABLE 3.—HEAT TREATMENT FOR AISI 9310 GEARS

Step	Process	Temperature		Time, hr
		K	°F	
1	Preheat in air	-----	-----	-----
2	Carburize	1,172	1,650	8
3	Air cool to room temperature	-----	-----	-----
4	Copper plate all over	-----	-----	-----
5	Reheat	922	1,200	2.5
6	Air cool to room temperature	-----	-----	-----
7	Austentize	1,116	1,550	2.5
8	Oil quench	-----	-----	-----
9	Subzero cool	189	-120	3.5
10	Double temper	450	350	2 each
11	Finish grind	-----	-----	-----
12	Stress relieve	450	350	2

The spur gearbox test facility used in this study is shown in figure 2. A detailed description and explanation on the operation of this facility is given in reference 1. In this study the spur gearbox was modified to accommodate a misting unit (fig. 3). The mister was filled with the thioether and both were kept at room temperature. Dried and filtered compressed shop air was then used to deliver the thioether to the spur gearbox as an extremely fine mist. This delivery method was chosen because previous studies showed that the VMPL lubricant could be delivered successfully as either a vapor or a mist (refs. 1 and 2). The mister was adjusted to deliver about 15 ml/hr of thioether in a flowing air stream of about 400 l/hr. The outlet of the gearbox was connected to a condensing unit where most of the thioether was collected. The flowing air was vented from the condensing unit. A thermocouple was installed inside the

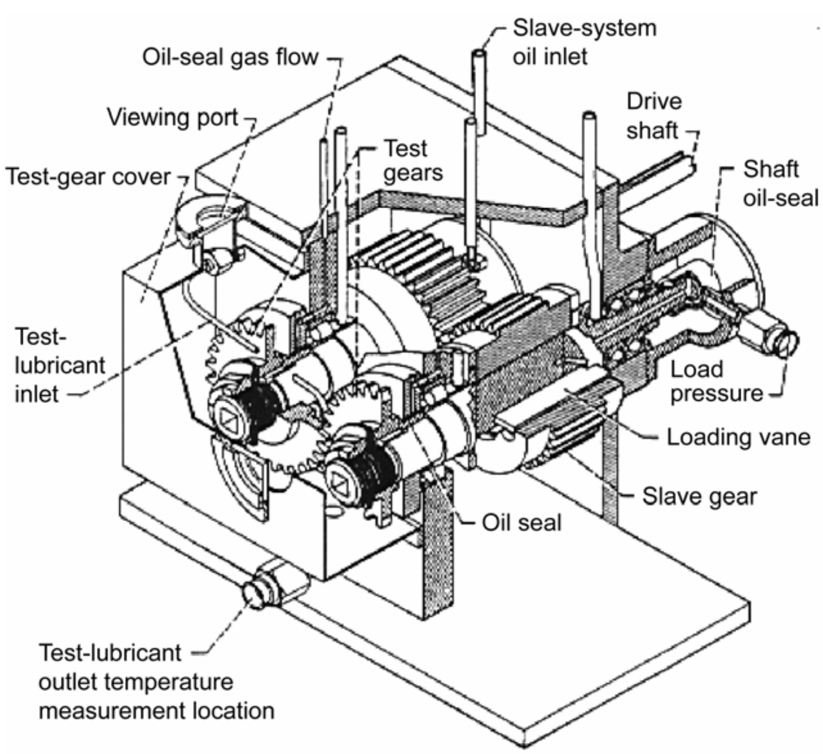

Figure 2.—Spur gear fatigue rig used for conducting tests.

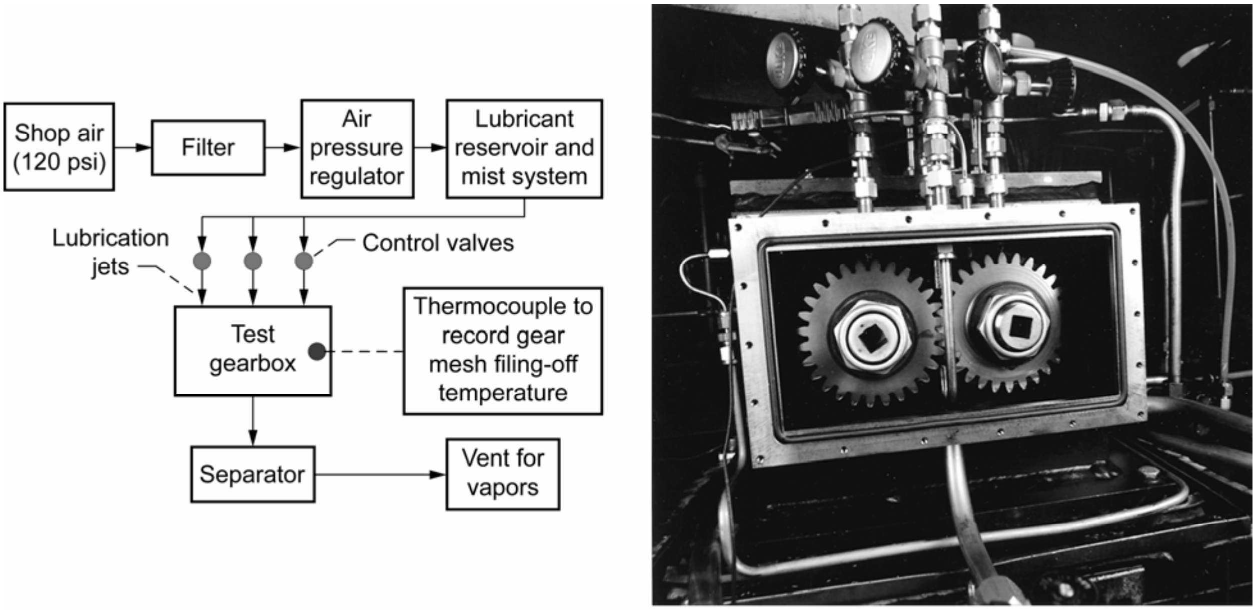

Figure 3.—(a) Vapor/mist phase lubrication system. (b) Photograph of experimental test arrngement.

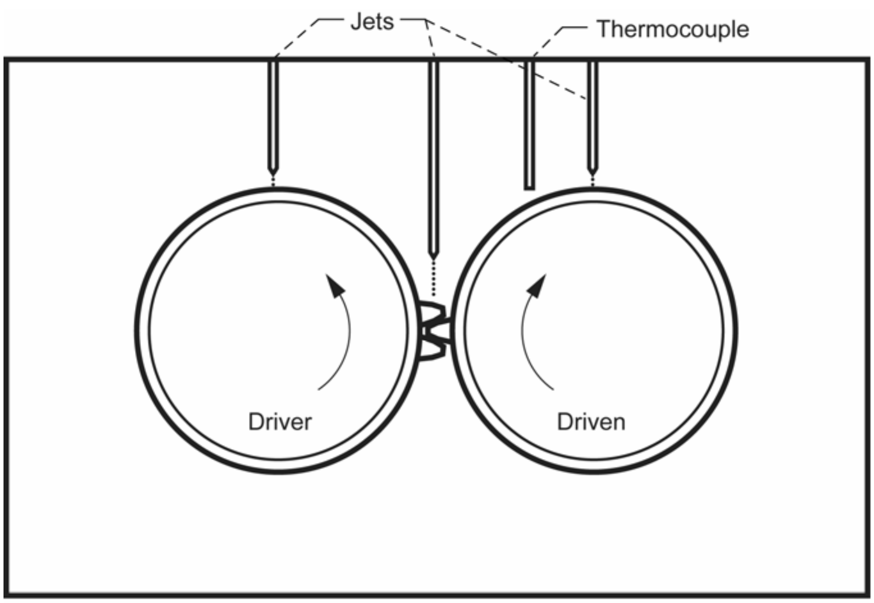

Figure 4.—Spur gearbox showing jet and thermocouple placement. Each gear has twenty eight teeth, only a select few shown here.

gearbox to record the temperature of the turbulent air near the rotating gears. The thermocouple was located close to the position where the meshing gear teeth disengage, the so-called “fling-off” position (fig. 4). Accelerometers monitored the gearbox housing vibration.

Two AISI 9310 spur gears, cleaned and weighed, were installed with faces aligned. Note that figure 2 depicts test gears installed with faces offset as has been used for gear surface fatigue tests using test gears with zero lead crowning. For the present work, gears with lead crowning were employed and so gears were operated with faces aligned having zero face offset. After the gears were installed, a transparent plexiglass cover was bolted to the front of the gearbox (fig. 3(b)) sealing it. The plexiglass cover allowed one to view the gears in operation and measure their speed using a tachometer. The test started by first slowly rotating the gears under a light load and then turning on the mister. As soon as the thioether mist was observed inside the gearbox, both speed and load were increased to test conditions of 10,000 rpm speed and gear tooth force of 516 N (116 lb force). The speed and load were adjusted gradually over a 2 min period allowing for a short break-in period. The tooth force stated is the force normal to the tooth surface (tangent to the base circle) for static equilibrium. Hertzian analysis was done for operation at the pitch-point and by assuming static equilibrium. At test conditions the nominal contact ellipse size was 2.42 by 0.337 mm (0.0954 by 0.0133 in.) and peak contact pressure was 1.2 GPa (175,000 psi).

The testing was completed over six test sessions (table 4). In total the gears were operated at the test load and speed for 21 million cycles. At the end of the test, the spur gears were removed, cleaned and weighed. Surface profile measurements of several gear teeth were taken before and after testing.

TABLE 4.—TESTING TIME SUMMARY

Test session	Operating time, min	Shaft rotations accumulative, millions of cycles
1	330	3.3
2	429	7.6
3	419	11.8
4	393	15.7
5	234	18.0
6	316	21.2

Results and Discussion

The thermocouple temperature and vibration readouts for the first and final test sessions are shown in figures 5 and 6. At the start of the first test session, as the gear speed was increased to 10,000 rpm and the load applied, the thermocouple temperature increased to near 121 °C, then decreased to about 107 °C and held steady at this temperature for 320 min. During this time the vibration readout quickly increased to 15 g (rms) and remained steady at this reading until the spur gearbox rig was shut down. At the end of test session one, visual inspection of the gears revealed no gross wear. When testing resumed the next day, the

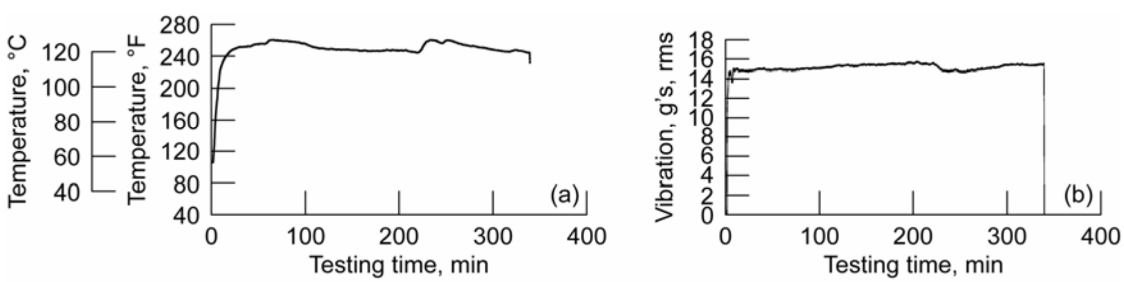

Figure 5.—(a) Trends of the (a) oil mist temperature and (b) housing vibration during testing session number 1.

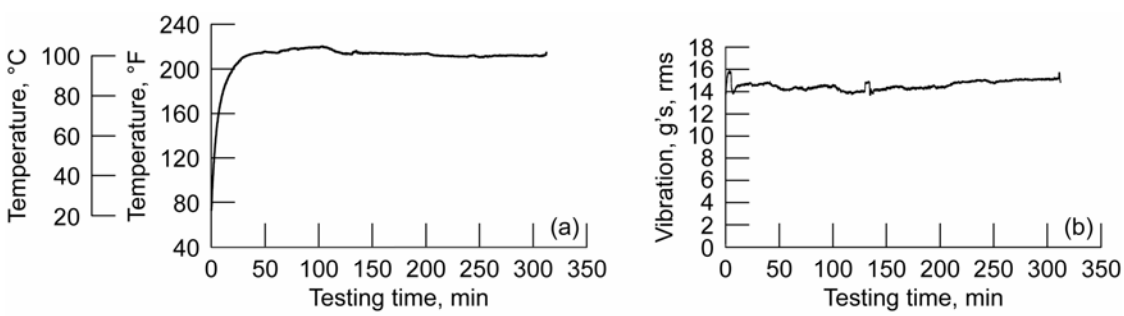

Figure 6.—(a) Trends of the (a) oil-mist temperature and (b) housing vibration during final testing session number 6.

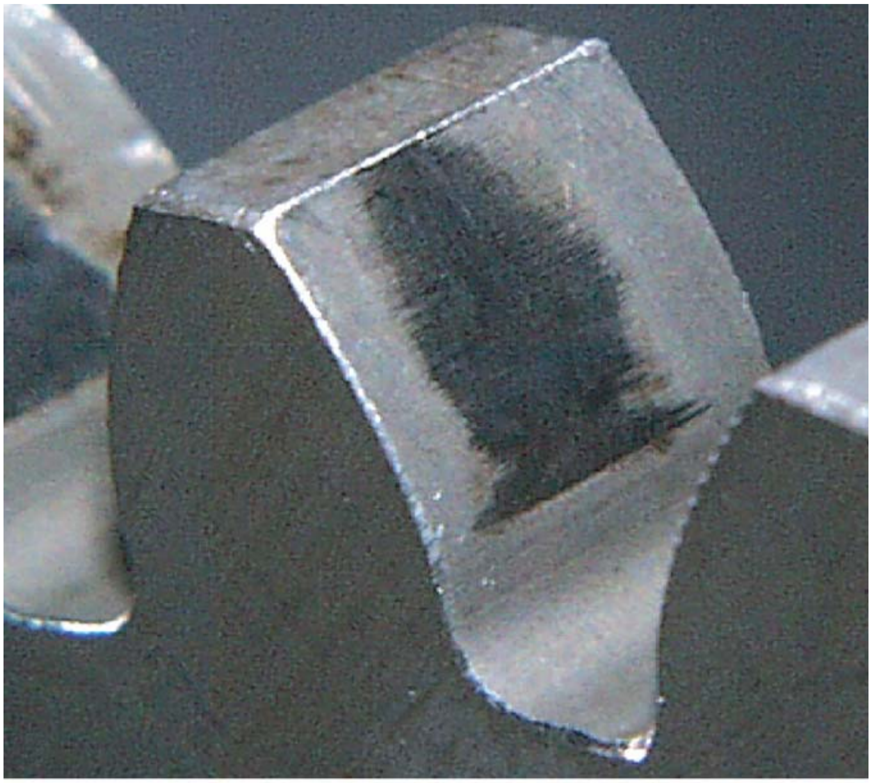

Figure 7.—Typical condition of gear tooth surface after 7.6 million shaft revolutions at test speed and load.

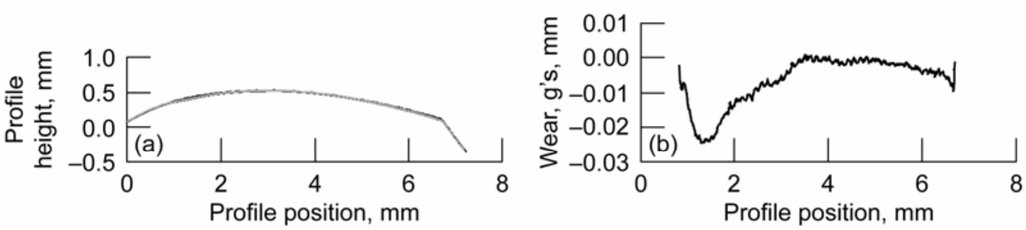

Figure 8.—(a) Typical suface profile measurements of a spur gear tooth before and after a test. (b) Wear difference profile of the spur gear tooth.

thermocouple temperature again increased to and remained steady near 107 °C while the vibration reading leveled out at 15 g (rms). This behavior repeated itself over the next four test sessions. At the end of test session 2 visible inspection of the gears revealed that the contacting portions of the tooth surfaces showed a running-in type polishing wear of asperities (fig. 7). The final 4 test sessions showed similar trends and results. The total accumulative testing time was 2120 min or 35.3 hr (21.2 million shaft revolutions). It should be mentioned that no traces of coking on the gears was noticed as occurred when gears were vapor-mist lubricated using synthetic paraffinic oil (ref. 11).

Table 5 lists the masses of the two spur gears before and after the tests. Spur gear #1 (the driving pinion) lost 8 mg of material and spur gear #2 (the driven gear) lost 6 mg. In terms of percentages this represents losses less than 0.002 percent. Figure 8(a) shows typical surface profile measurements of a spur gear tooth before and after a test. As can be seen the surface profiles overlap to a near identical match. Figure 8(b) shows the wear difference profiles of the spur gear tooth. This figure is generated by subtracting the “after test” profile from the “before test” profile. Very little wear is observed.

TABLE 5.—GEAR MASSES

	Before test, g	After test, g
Gear #1	402.3146	402.3065
Gear #2	402.1564	402.1503

The results from this study clearly showed a dramatic improvement over the results from previous studies (ref. 11), using a synthetic paraffinic oil and a phosphate ester oil, in several respects. For instance, the primary evidence that good lubrication was provided, using the thioether, was the observed minimal gross wear on the gear teeth even after 35 hr of operation. Gear tooth wear, however, was observed using the paraffinic oil and phosphate ester after only 10 min of operation. The fling-off thermocouple temperature readings for the thioether test was constant at 107 °C with no fluctuation, whereas for the previous tests the temperatures were much higher, in some cases approaching 205 °C, and the temperatures fluctuated up and down. No coking was observed on the gears in this study using the thioether lubricant whereas substantial coking was present in the VPLM tests using the paraffinic oil.

Conclusions

A thioether was used as a VMPL lubricant to successfully lubricate a spur gearbox rig operating at 10,000 rpm and a torque load level corresponding to a 1.2 GPa maximum Hertz pressure at the pitch-line for over 21 million shaft revolutions. The use of the thioether resulted in minimal wear of the spur gears in contrast to previous studies using phosphate esters. This study has demonstrated that the thioether is clearly superior to the traditional phosphate esters as a VMPL lubricant and has clear potential for practical applications.

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REPORT DOCUMENTATION PAGE						*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01-12-2007

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Feasibility Study of Vapor-Mist Phase Reaction Lubrication Using a Thioether Liquid

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Morales, Wilfredo; Handschuh, Robert, F.; Krantz, Timothy, L.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 877868.02.07.03.01.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-16223

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORS ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2007-215035

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Categories: 01 and 23
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301-621-0390

13. SUPPLEMENTARY NOTES

14. ABSTRACT
A primary technology barrier preventing the operation of gas turbine engines and aircraft gearboxes at higher temperatures is the inability of currently used liquid lubricants to survive at the desired operating conditions over an extended time period. Current state-of-the-art organic liquid lubricants rapidly degrade at temperatures above 300 °C; hence, another form of lubrication is necessary. Vapor or mist phase reaction lubrication is a unique, alternative technology for high temperature lubrication. The majority of past studies have employed a liquid phosphate ester that was vaporized or misted, and delivered to bearings or gears where the phosphate ester reacted with the metal surfaces generating a solid lubricious film. This method resulted in acceptable operating temperatures suggesting some good lubrication properties, but the continuous reaction between the phosphate ester and the iron surfaces led to wear rates unacceptable for gas turbine engine or aircraft gearbox applications. In this study, an alternative non-phosphate liquid was used to mist phase lubricate a spur gearbox rig operating at 10,000 rpm under highly loaded conditions. After 21 million shaft revolutions of operation the gears exhibited only minor wear.

15. SUBJECT TERMS
Chemistry; Vapor phase lubrication; Gears; Tribology

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email:help@sti.nasa.gov)
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