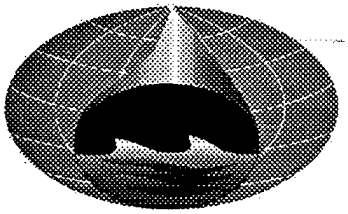
TARDEC



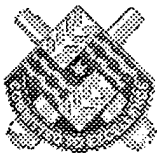
Technical Report

No. 13800

Investigation to Remove Lead and Antimony from Solid Film Lubricants

July 2001

By Steffen Schneider
German Exchange Engineer at
U.S. Army TACOM
Fuels & Lubricants Technology Team



U.S. Army Tank-Automotive and Armaments Command
Research, Development and Engineering Center
Warren, MI 48397-5000

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 074-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 2001	Final 28 Aug 2000 - 26 Jul 2001

4. TITLE AND SUBTITLE
Investigation to Remove Lead and Antimony from Solid Film Lubricants under the Engineer and Scientist Exchange Program between the Federal Republic of Germany and the United States of America

5. FUNDING NUMBERS

6. AUTHOR(S)
Steffen Schneider

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Tank-Automotive and Armament Command
ATTN: AMSTA-TR-D/210
Warren, MI 48397-5000
U.S.A.

Bundeswehr Research Institute for Materials, Explosives, Fuels & Lubricants
Institutsweg 1
85435 Erding
Germany

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution unlimited; approved for public release

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 Words)*

This report has been prepared under the Engineer and Scientist Exchange Program between the Federal Republic of Germany and the United States of America. The author is the POC for all technical matters regarding solid film lubricants within the German Bundeswehr. The report gives a summary about common solid film lubricant specifications and testing. This paper also covers the fundamentals of solid film lubricants. Topics discussed include the correlation between Falex endurance life and load carrying capacity to real field applications, galvanic corrosion caused by graphite in solid film lubricant formulations, and indications for successful application.
The report includes test procedure datasheets for single test procedures and a questionnaire regarding the requirements of a tribological system to solid film lubricants. The report mainly deals with solid film lubricants conforming MIL-PRF-46010, MIL-PRF-46147 and MIL-L-23398.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Bonded Solid Film Lubricant Specifications, Endurance Life and Load Carrying Capacity, Test Result Correlation, Test Procedure Data Sheets, Application Techniques	61
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

Final Report

About the Collaboration in the

Investigation to Remove Lead and Antimony from Solid Film Lubricants

under the

Engineer and Scientist Exchange Program between the Federal Republic of Germany and the United States of America

Author: Bauoberrat Steffen Schneider

German Place of Duty:
Bundeswehr Institute for Materials, Explosives, Fuels and Lubricants (WIWEB)
Division Tribology, Fuels and Lubricants
Institutsweg 1
85435 Erding
Germany

Phone: +49-8122-57403
Fax: +49-8122-57468
Email: SteffenSchneider@BWB.ORG

1 Introduction

From August 23, 2000 to August 10, 2001 the author took part in the Engineer and Scientist Exchange Program between the Federal Republic of Germany and the United States of America. During this time he worked as a team member in the Fuels and Lubricants Technology Team (FLTT) at U.S. Army TACOM, Warren MI.

This report is the result of the collaboration within the project "Investigation to Remove Lead and Antimony from Solid Film Lubricants". It gives a summary about all activities, testing and findings during the exchange program.

Solid film lubricants are widely used throughout DoD and private industry as well. Right now, the Army's solid film lubricants still have antimony in their formulation. The purpose of this project is to identify formulations of solid film lubricants without lead and antimony. Lead and antimony are heavy metals and considered hazardous waste. Suitable candidate products with reduced levels of toxins should be evaluated and analyzed. The technology should be applicable to products currently qualified under MIL-PRF-46010 and MIL-PRF-46147. The development of antimony free solid film lubricant will permit military and industrial users of these materials to reduce their waste disposal and worker safety costs. In addition, users will no longer be exposed to the antimony.

MIL-PRF-46010 covers corrosion inhibiting, heat cured, solid film lubricants, for the reduction of wear and prevention of galling, corrosion, and seizure of metals. MIL-PRF-46147 covers two types of an air-curing solid film lubricant. The lubricant provides both, lubrication and corrosion protection.

2 A Brief Survey about Solid Film Lubricants

The need for lubricants for use at extreme temperatures, radiation, vacuum and other extreme environmental conditions led to the development of bonded solid film lubricants at the end of the 1940s. Since then solid film lubricants have grown and are now applied to a wide variety of industrial, automotive, military and aerospace applications. Solid film coatings / lubricants are materials with inherent lubricating properties, which are firmly

bonded to the surface of a substrate by some method. Common methods of bonding are resin deposition, burnishing, mechanical impingement, sputtering, ion deposition, or physical vapor deposition. Of these, resin bonding has the most commercial significance. [Ref 1], [Ref 2], [Ref 3], [Ref 4]

Bonded solid film lubricants consist of three main elements: solid lubricant, resin binder and solvent. Furthermore, additives such as corrosion inhibitors, flow agents, etc. are added to the formulation.

Common solid lubricants are molybdenum disulfide, graphite, and polytetraflouroethylene. Strengths and weaknesses of the several solid lubricants are described in detail under [Ref 5], [Ref 6] and [Ref 7]. Molybdenum disulfide and graphite show a low friction coefficient and a high load carrying capacity. Polytetraflouroethylene shows the lowest friction coefficient, but also a lower load carrying capacity. Graphite is not allowed in most of the military specifications because it can cause galvanic corrosion [Ref 8]. In this context, it is also known that the use of molybdenum disulfide can also cause corrosion on application that can experience temperatures >350°C. At this temperature the MoS_2 oxydizes and creates sulphuric acid.

Finally, corrosion only occurs under certain environmental conditions [Ref 9]. Therefore, the exact knowledge of the requirements of the field applications to solid film lubricants is of high importance.

Binders are either organic or inorganic. Organic binders are typically acrylics, alkyds, epoxies, vinyls, and acetates. They are less expensive and more easily to apply. Inorganic binder systems are typically silicates, phosphates, aluminates, and some organometallic materials. They generally provide resistance to vacuum outgassing or resistance to liquid oxygen and are useful at high temperatures and in high radiation environments. [Ref 1], [Ref 2]

Most solid film lubricant formulations contain solvents such as methyl alcohol, methyl ethyl ketone, and toluene, which are volatile organic compounds (VOC) [Ref 10]. So in order to comply with environmental regulations newer solid film lubricant formulations

have a VOC content of 250 g/L or less. One way to accomplish this is with the use of water as a solvent. The latest evaluation of low VOC solid film lubricants within the U.S. Army shows that none of the examined low VOC, lead and antimony free solid film lubricants fulfilled the requirements of former MIL-L-46147B [Ref 10].

Additives also have a high influence on several properties of solid film lubricants. Antimony and lead compounds were added to improve the corrosion resistance of the molybdenum disulfide. Antimony trioxide also shows synergetic effects in interaction with solid lubricants in getting improved endurance life. Graphite also increases the load carrying capacity and endurance life of molybdenum disulfide based solid film lubricants. Removing additives from the formulation can drastically change properties like load carrying capacity or endurance life.

Finally, pretreatment of the parts and application of the solid film lubricant are also of high importance.

3 Common Specifications for Solid Film Lubricants

3.1 MIL-PRF-46147C, Type I: Lubricant, Solid Film, Air Cured, Corrosion Inhibiting [Ref 11]

Temperature Range: -67°C to +93°C

Intended use: The solid film lubricant, covered by this specification, is intended for use on aluminum, aluminum alloys, copper and copper alloys, steel, stainless steel, titanium, and chromium and nickel bearing surfaces. Solid film lubricants are often used on weapons, ground vehicles, and ground handling equipment. They are used for thin film lubricant for sliding motion application and under conditions where heavy-load capacity, solvent resistance, and long term corrosion protection are needed. They are useful under the following conditions:

- Where conventional lubricants are difficult to apply or retain.
- Where dust and dirt contamination on lubricated surfaces is deleterious.
- Where temperatures may range from -67°C to +93 °C.

Use limitations: The lubricant should not be used under the following conditions:

- In operations consisting of rotary motion above 100 revolution per minute (rpm) under heavy loads where the possibility of conventional fluid lubricant contamination exists. The cured lubricant film is highly resistant to conventional fluid lubricants, but the high fluid pressures developed in heavily loaded sleeve type bearings drastically reduces the wear life provided by the solid film lubricant film.
- On bearings containing rolling elements.

Major properties: see Appendix 1, page 29

Responsible: U.S. Army TACOM

3.2 MIL-PRF-46147C, Type II: Lubricant, Solid Film, Air Cured, Corrosion Inhibiting [Ref 11]

Temperature Range: -67°C to +93°C

Intended use: The solid film lubricant covered by this specification is intended for use on aluminum, aluminum alloys, copper and copper alloys, steel, stainless steel, titanium, and chromium and nickel bearing surfaces. Solid film lubricants are often used on weapons, ground vehicles, and ground handling equipment. They are used for thin film lubricant for sliding motion application and under conditions where heavy-load capacity, solvent resistance, and long term corrosion protection are needed. They are useful under the following conditions:

- Where conventional lubricants are difficult to apply or retain.
- Where dust and dirt contamination on lubricated surfaces is deleterious.
- Where temperatures may range from -67°C to +93°C.

Use limitations: The lubricant should not be used under the following conditions:

- In operations consisting of rotary motion above 100 revolution per minute (rpm) under heavy loads where the possibility of conventional fluid lubricant contamination exists. The cured lubricant film is highly resistant to conventional fluid lubricants, but the high fluid pressures developed in heavily loaded sleeve type bearings drastically reduces

the wear life provided by the solid film lubricant film.
- On bearings containing rolling elements.

Major properties: see Appendix 1, page 30

Responsible: U.S. Army TACOM

3.3 MIL-PRF-46010F: Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting [Ref 12]

Temperature Range: -68°C to +204°C

Intended use: The lubricant is intended for use on aluminum and aluminum alloys, copper and copper alloys, steel, stainless steel, titanium, and chromium and nickel bearing surfaces, and is useful under the following conditions:
- To touch up worn surfaces originally coated with lubricant conforming to MIL-L-8937, MIL-L-46010 or MIL-PRF-46010.
- For sliding motion applications such as plain and spherical bearing, flap tracks, hinges, threads, and cam surfaces.
- Where conventional lubricants are difficult to apply or retain, or where other lubricants may be easily contaminated with dirt and dust.
- Where temperature may range from -68 °C to +204 °C (although intermittent exposure to +260 °C is acceptable)
- If mechanisms are operated at infrequent intervals or are lubricated for life.

Use limitations: This lubricant should not be used under the following conditions:
- On materials which will be adversely affected by the curing temperatures of 204 ± 15°C.
- In operations consisting of rotary motion above 100 revolutions per minute (rpm) under heavy loads where the possibility of conventional fluid lubricant contamination exists. The cured lubricant film is highly resistant to conventional fluid lubricants, but the high fluid pressures developed in heavily loaded sleeve type bearings drastically reduces the wear life provided by the solid lubricant film.

- On bearings containing rolling elements.
- Where there is potential contact with liquid oxygen.

Major properties: see Appendix 1, page 31

Responsible: U.S. Army TACOM

3.4 MIL-L-23398D: Lubricant, Solid Film, Air Cured, Corrosion Inhibiting [Ref 13]

Temperature Range: -198 °C to + 300 °C

Intended use: This air cured solid film lubricant is intended for use on steel, titanium or aluminum bearing surfaces where moderate wear life and corrosion protection are desired. It is useful where conventional lubricants are difficult to apply or retain or where other lubricants may be contamined with dirt and dust. It is generally suitable for sliding motion applications such as in plain spherical bearings, flap tracks, hinges and cam surfaces, especially where it is not feasible to use the type of solid film lubricant which requires baking at an elevated temperature.

Use limitations: The use of this lubricant is not recommended on roller bearing elements or in conjunction with oils or greases unless field use indicates otherwise.

Major properties: see Appendix 1, page 32

Responsible: Naval Air Warfare Center Aircraft Division

3.5 MIL-L-81329D: Lubricant, Solid Film, Extreme Environment, Heat cured [Ref 14]

Temperature Range: -185 °C to +400 °C

Intended use: The lubricant covered by this specification is intended primarily for use in liquid oxygen systems, space vehicles, bearing assemblies, and other equipment where the environments of extreme temperature and nuclear radiation preclude the use of commercial lubricants and organic solid film lubricants. It is intended to reduce wear and

to prevent galling and seizing of metal surfaces.

Use limitations: Do not use the lubricant on material that may adversely affected by exposure to the specific cure temperature of 150 °C. The lubricant should not be used with oils or greases, unless field use indicates otherwise.

Major properties: see Appendix 1, page 33

Responsible: Naval Air Warfare Center Aircraft Division

3.6 SAE AS5272, Type I: Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting [Ref 15]

Temperature Range: -68°C to +204°C

Intended use: For aerospace fastener applications where temperatures may range from -68 to 204 °C

Use limitations: This lubricant shall not be used under the following conditions:
- On materials which are adversely affected by the curing temperature of 150 °C.
- Where there is a potential contact with liquid oxygen.

Major properties: see Appendix 1, page 34

Responsible: SAE International

3.7 SAE AS5272, Type II: Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting [Ref 15]

Temperature Range: -68°C to +204°C

Intended use: For aerospace fastener applications where temperatures may range from -68°C to 204°C

Use limitations: This lubricant shall not be used under the following conditions:
- On materials which are adversely affected by the curing temperature of 204 °C.
- Where there is a potential contact with liquid oxygen.

Major properties: see Appendix 1, page 35

Responsible: SAE International

3.8 SAE AS1701 C, Class I: Lubricant, Solid Film, Heat cured [Ref 16]

Temperature Range: -65°C to +450 °C

Intended use: The solid film lubricants covered by this specification are intended for aerospace applications exposed to extreme environments. Some may be suitable for use in vacuum at temperature ranging from -221°C to +760 °C.

Major properties: see Appendix 1, page 36

Responsible: SAE International

3.9 SAE AS1701 C, Class II: Lubricant, Solid Film, Air cured [Ref 16]

Temperature Range: -54°C to +232 °C

Intended use: The solid film lubricants covered by this specification are intended for aerospace applications exposed to extreme environments. Some may be suitable for use in vacuum at temperature ranging from -221°C to +760 °C.

Major properties: see Appendix 1, page 37

Responsible: SAE International

3.10 Summary

The above mentioned specifications are the known and most common military and commercial specifications about solid film lubricants. Datasheets for all specifications are provided in the appendix (Appendix 1). The datasheets are created to compare the different requirements especially concerning curing conditions, Falex testing and resistance against fluids.

In the past, solid film lubricant NATO-Code S-1738 was according to MIL-L-46010D, Type I. Introducing new solid film lubricants with a low VOC, a new Type III came into MIL-L-46010D [Ref 17]. Type III adopted the requirements concerning endurance life from Type II and concerning load carrying capacity from Type I. With the cancellation of Type I and II in MIL-PRF-46010F, Type III became solid film lubricant NATO-Code S-1738. Today S-1738 still has the same load carrying capacity but a considerably higher endurance life (450 min instead of 250 min).

The specification SAE AS5272 was published in 1997 as a result of the "Sunset Clause" of MIL-L-46010E. This specification contains the former Type I and II solid film lubricants of MIL-L-46010E [Ref 18]. Fastener industries stated that new lead free solid film lubricant formulations under MIL-L-46010E does not meet the requirements of real fastener applications. Therefore, SAE AS5272 still allows lead in solid film lubricant formulations [Ref 19]. Up to now new suitable test procedures correlating to real fastener applications are lacking.

The specification SAE AS1701C deals in total with six different classes of solid film lubricants. They distinguish in temperature limits, usage, primary lubricant, binder and curing.

Finally, commercial industry can afford to select solid film lubricants for each intended use. However, the US Military and German Bundeswehr are concerned with the number of products needed for vehicle / system maintenance. Therefore, military specifications are designed to address multiple intended uses. This is due to the tremendous logistical burden and the increase chances of errors / mistakes if multiple similar products exist in the military system. Therefore, the military system cannot afford multiple products and military solid film lubricant specifications must be designed around the most severe performance requirement.

4 Solid Film Lubricant Testing

4.1 Test Methods

4.1.1 General Testing

The different solid film lubricants require a wide range of testing. Datasheets concerning single test procedures according to standards or specifications are provided in the appendix (Appendix 2). Each datasheet contains information about:

- test method,
- based specification or standard,
- required equipment,
- required reagents and materials,
- the reference to MIL-specifications MIL-PRF-46147C, MIL-PRF-46010F and MIL-L-23396D (custodians are U.S. Navy and German Armed Forces)

The purpose of these datasheets is to provide a guideline for preparation and performance of the required tests.

All datasheets are prepared by the author. In case of any differences between single datasheets and the MIL- / ASTM-specification, MIL- / ASTM-specification has priority.

4.1.2 Remarks for Performing FALEX-Testing according to ASTM D2625

While the other test procedures are relatively easy to perform, Falex-testing is a very sensitive test. The test results are influenced by many factors. The most critical factors found by the author to effect the results are:

- Sandblasting / Phosphating of the specimen
- Cleaning of the specimen
- Application of the solid film lubricant
- Test setup

The following topics give some indications for successful application and testing which the author had experience with. Finally, it is not possible to predict all kind of failures

one can do during testing. At least there is a human factor. The operator has to work carefully and conscientious all the time.

4.1.2.1 Application

4.1.2.1.1 Stirring Solid Film Lubricant

Stir the solid film lubricant carefully in the can before filling into the spraying gun. Make sure that all solids are removed from the bottom of the can. Use a spatula for stirring. To get the solids into solution it is helpful to put the can into an ultrasonic bath while stirring by hand. Keep the can tightly closed the rest of the time.

4.1.2.1.2 Spraying

Spraying the specimen is a convenient technique when solid content of the solid film lubricant is around 20% by weight of solid material. Spraying is recommended by most of the manufacturers.

Fixing the pin in the clamping chuck of a hand drill was found to give more control and a more uniform film application. Let the pin rotate slowly while applying the coating.

After using the spraying gun, the gun needs to be dismantled and cleaned carefully. Cleaning is important to ensure a proper function of the gun and to avoid contamination while using the gun for another product.

4.1.2.1.3 Dipping

Dipping the specimen is a convenient technique when solid content of the solid film lubricant is around 30% by weight of solid material. Especially with the FALEX pins dipping leads to a more uniform coating.

4.1.2.1.4 Film Thickness Measurement

Solid film lubricants need to be applied within a defined narrow range of thickness. Therefore, a suitable thickness measurement device is necessary. ASTM specifications

[Ref 25, Ref 30] recommend a micrometer with a 1-ball anvil. However, it is shown that the use of an electromagnetic hand-held instrument provides better results [Ref 9]. Therefore, a Fischer Dualscope MP40 with an ED10 dual probe was purchased for further non-destructive film thickness measurement.

The Dualscope MP40 combines the magnetic induction and the eddy current methods in one hand-held instrument. This combination enables the user to measure in random order paint, plastic, and organic coatings on non-ferrous metals and on steel, and non-ferrous metal coatings on steel with the same instrument. With the smart ED10 dual probe the instrument even recognizes the material and selects the appropriate measurement method according to DIN specification.

Before any kind of testing according to [Ref 25] and [Ref 30], the thickness of the applied film has to be determined. With the ED10 dual probe, it is difficult to measure the film thickness inside the gap of the Falex Vee blocks. However, more important is the measurement of the film thickness at the Falex pins. For a good measurement, the pin has to be properly supported to avoid slipping and scratching of the pin. Although small imprints are unavoidable while performing the measurement, it will not effect the test results. Assembling the specimen in the Falex Pin&Vee Block Test Machine sometimes can cause bigger scratches before running a test than measuring the film thickness with the Dualscope MP40.

4.1.2.1.5 Storage of Coated Specimen

Store coated Falex pins always on hooks. Avoid scratches on the coating. Store the entire coated specimen in a desiccator at least 24 hours before testing.

4.1.2.2 Use of FALEX Pin & Vee Block Test Machine

Use FALEX Pin & Vee Block Test Machine according to the users manual and ASTM D2625. Check proper assembly of test equipment and specimen before starting the test. Take care that Vee blocks do not fall out off the jaw after assembling.

Switch off torque control before starting run in. Switch on torque control after run in for the remainder of the test.

Furthermore, it is also known that FALEX Pin & Vee Block Test Machine shows a poor repeatability and reproducibility in testing solid film lubricants [Ref 25] and oils [Ref 26]. This is also confirmed by several users of the FALEX Pin & Vee Block Test Machine. Therefore, PTI Inc. Hinckley, IL offers a new Epsilon Linear Precision Test Machine [Ref 27]. This machine is operating on the same principle but, according to the manufacturer, provides higher accuracy and more control capacity.

4.2 German Suppliers of Solid Film Lubricants

In addition to the known American manufacturers of solid film lubricants two German manufacturers were asked to provide suitable products for testing according to MIL-PRF-46010F and MIL-PRF-46147C. Both manufacturers are highly experienced and provide a variety of solid film lubricants e.g. for automobile industry. They both have offices and plants in U.S.A., too.

4.2.1 Fuchs Lubricants

German POC	U.S. POC
Fuchs Lubritech GmbH	Fuchs Lubricants Co.
Hans-Reiner-Str. 7-13	17191 Walter P. Chrysler Freeway
D-67685 Weilerbach	Detroit, MI 48203
Rainer Dörfler	Dick Cuff
Phone: +49 (0)89-3271 0621	Phone: (313) 891 3700
Email: Rainer.Doerfler@fuchs-lubritech.de	Fax: (313) 691 1450
Web page: http://www.fuchs-lubritech.de/	http://www.fuchs-lubritech.de/untern_e.htm

The German Fuchs Lubritech provided three products for testing: Gleitmo 920 (4.3.3), Gleitmo 940 (4.3.4), and Gleitmo SFL 9560 (4.3.5). Fuchs also provided data about tribological testing of all three products [Table 11]. The products were tested with the Al-

men Wieland Machine. The Almen Wieland Machine is similar to Falex Pin & Vee Block Test Machine.

4.2.2 Klüber Lubrication

German POC

Klüber Lubrication München KG
Geisenhausener Str. 7
D-81379 München
Rudolf Zechel
Phone: +49 (0)89-7876 611
Email: Rudolf.Zechel@klueber.com
Web page: http://www.klueber.com/

U.S. POC

Kluber Lubrication North America L.P.
54 Wentworth Avenue
Londonderry, NH 03053
Stephen Mazzola
Phone: (603) 434 7704 ext. 117
Email: steve.mazzola@us.kluber.com

Klüber Lubrication Germany is in the process of developing new environmentaly friendly solid film lubricants. To implement the needs of the U.S. Army Klüber Lubrication has knowledge about MIL-PRF-46010F and MIL-PRF-46147C regarding the desired performance of both products. As long as Klüber Lubrication has not finished its development the company will not introduce their new products. As soon as the products are available the company will offer them.

4.3 Test Results

4.3.1 Slickote M1, Sample ID: FL-11297-01

Slickote M1 is an air cured, low VOC solid film lubricant, using exempt solvents to achieve a low VOC of <135 g/l. It provides protection against wear and corrosion. The temperature range of the dry film is from -67°C to +93°C. Slickote M1 is free of lead and graphite, but contains antimony trioxide (<4%) to provide a better load carrying capacity. The manufacturer recommended this product as a solid film lubricant conforming MIL-PRF-46147°C, Type I and II. According to the manufacturer the product shows an endurance life >120 min (ASTM D-2625A) and a load carrying capacity >2500 lbs. (ASTM D-2625B).

To get the low VOC, both, the M1 and M2 contain high solids epoxy ester as a resign binder. Therefore, the curing time is very critical. Slickote recommends a curing time of at least 72 hours. The company also recommends allowing a longer curing time for a lead free formulation of solid film lubricants.

Falex pins 1 to 10 and all Vee blocks were coated by spraying in one or two steps. Falex pins M, N, O, P were coated by dipping in four steps. Average endurance life according to ASTM D2625 is 52 minutes in the first run [Table 1] and 61 minutes in the second run [Table 2]; average load carrying capacity according to ASTM D2625 is 3,050 lbs. [Table 3]. The results for endurance life provided by the manufacturer could not be confirmed. The product does not fulfill the requirements of MIL-PRF-46147C concerning endurance life but load carrying capacity.

4.3.2 Slickote M2, Sample ID: FL-11297-01

Slickote M2 is an air cured, low VOC solid film lubricant, using exempt solvents to achieve a low VOC of <135 g/l. It provides protection against wear and corrosion. The temperature range of the dry film is from -67°C to +93°C. Slickote M2 is free of lead, graphite and antimony trioxide. The manufacturer recommended this product as a solid film lubricant conforming MIL-L-23398D.

All Falex specimens were coated by dipping in three or four steps. Average endurance life according to ASTM D2625 is 65 minutes [Table 4]; average load carrying capacity according to ASTM D2625 is 2,417 lbs. [Table 5]. Pins E, F, H were tested after approximately 18 hours curing time. Pin D was tested after more than 72 hours curing time. The higher value in endurance life confirms the manufacturer's request for a longer curing time. The product fulfills the requirements of MIL-L-23398D concerning endurance life and load carrying capacity.

4.3.3 Gleitmo 920, Sample ID: FL-11336-01

Gleitmo 920 is an air drying MoS_2 solid film lubricant with an organic binder base. It can be hardened off at +150°C (minimum 30 minutes), will then be resistant to mineral oil. It

ensures low and constant friction and is very pressure compliant. The temperature range of the dry film is from -180°C to +250°C. Gleitmo 920 is free of lead and antimony trioxide, but contains graphite (<5%) to provide a better load carrying capacity.

Falex pins A, B, C, D, I, J, K, L were coated by dipping in two steps. Falex pins E, F, G, H and all Vee blocks were coated by spraying in one step. Average endurance life according to ASTM D2625 is 124 minutes [Table 6]; average load carrying capacity according to ASTM D2625 is 2,667 lbs. [Table 7]. The product fulfills the requirements of MIL-PRF-46147C concerning endurance life and load carrying capacity.

4.3.4 Gleitmo 940, Sample ID: FL-11337-01

Gleitmo 940 is a heat curing MoS_2 solid film lubricant with an organic binder base. It is oil and solvent resistant and provides high corrosion protection. Gleitmo 940 significantly improves the running-in properties of oil or grease lubricated parts. The temperature range of the dry film is from -180°C to +300°C. Gleitmo 940 is free of lead and antimony trioxide, but contains graphite (<5%) to provide a better load carrying capacity.

All Falex specimens were coated by dipping in two steps. Average endurance life according to ASTM D2625 is 147 minutes [Table 8]; average load carrying capacity according to ASTM D2625 is 2,562 lbs. [Table 9]. The product does not fulfill the requirements of MIL-PRF-46010F concerning endurance life but load carrying capacity.

4.3.5 Gleitmo SFL 9560, Sample ID: FL-11326-01

Gleitmo SFL 9560 is a white, heat curing solid film lubricant having PTFE as a constituent for lubrication efficiency. The product forms a dry lubricating film, which is distinguished by its excellent lubricating effect, high degree of abrasion resistance and very good corrosion protection. Gleitmo SFL 9560 is resistant to mineral oils and many chemicals. The temperature range of the dry film is from -70°C to +140°C.

All Falex specimens were coated by dipping in two steps. The product failed during run-in while testing endurance life according to ASTM D2625 [Table 10]. The cause why this product already failed during run-in is unknown. It does not fulfill the requirements of

MIL-PRF-46010F concerning endurance life and load carrying capacity. Also the temperature range is too low.

However, in the results provided by the manufacturer it is shown that this product has a similar load carrying capacity (scuff-limited load) like Gleitmo 920 and Gleitmo 940 (14 kN vs. 18 kN, see Table 11).

4.4 Future Candidate Products

After a research, the following candidate products were found for further evaluations.

- MIL-PRF-46010F: Tiodize 20/20
- MIL-PRF-46147C, Type I and Type II: Tiodize 75/75
- MIL-L-23398D, Amd.2: Tiodize 75/75

All products are available from Tiodize Inc., 5858 Engineer Drive, Huntington Beach, CA 92649.

5 Correlation between Test Results and real Applications in the Field

At this time, it seems that lower values in Falex endurance life or load carrying capacity are required for environmentally acceptable solid film lubricants. This investigation and [Ref 10] have shown that right now antimony trioxide or graphite are necessary additives to achieve the required values. On the other hand there is not much known about the use of solid film lubricants in the field. Only source of information about the use of solid film lubricants is Lube Order Database [Ref 28]. However, this source shows only the name of the ground system and its M number. It gives no answer what specific parts are lubricated with solid film lubricants.

To find out, where solid film lubricants are in use in general a questionnaire was sent to the U.S. Navy, U.S. Air Force, NASA and SAE (Appendix 4). Up to now the U.S. Air Force, U.S. Navy Sea and U.S. Navy Air answered the questionnaire. Accordingly, the U.S. Air Force and U.S. Navy Sea do not use solid film lubricant conforming MIL-PRF-46010 or MIL-PRF-46147.

Within the U.S. Navy Air solid film lubricant according to MIL-PRF-46010F is used extensively at Navy Depots where heat curing is available. Solid film lubricant according to MIL-PRF-46147 is used sparingly. Solid film lubricant according to MIL-L-23398D is used on many engines, including the F110, F404/414, T046 and T56. Up to now more detailed information about the components lubricated with solid film lubricants is not available.

The answers of NASA and SAE are still due.

Furthermore, there is no real correlation between laboratory performance and actual field performance. Although endurance life, load carrying capacity and corrosion protection can be measured in the laboratory, this information is not truly representative of the type of environment and stress conditions that would be encountered by moving mechanical assemblies in actual applications. The laboratory endurance life determination does not give an indication of the endurance life of a moving mechanical assembly coated with solid film lubricant. The same can be said for load carrying capacity and corrosion. It is also unknown which considerations and technical requirements led to set up special limit requirements for FALEX load carrying capacity and endurance life in several SFL specifications. In addition, the reason to increase the limits regarding FALEX endurance life during the time of developing solid film lubricant specifications is not completely clear. One reason might be the introduction of lead and antimony in solid film lubricant formulations. When lead and antimony were introduced, the time for FALEX endurance life was raised up to a limit, a supplier provided with his new products. However, there is nothing known about a need by special field applications regarding higher endurance life.

The FALEX Pin & Vee Block Test Machine was developed in the 1930's. Originally the test was intended for the evaluation of fluid lubricants under extreme pressure. At this time there was a need for a small and inexpensive test to screen different batches of the same oil or to get a ranking of different oils. There is no particular field application in context to this test method. Later the industries adopted this method for the evaluation of solid film lubricants. However, there is no guideline to correlate the test results with

results in the field. Lubricants, solid film lubricants as well as lubricating oils, tested with the FALEX Pin & Vee Block Test Machine can show a different behavior in the field according to the particular application.

To find out more about testing according to ASTM D2625 a questionnaire was sent out to Falex Corporation and SAE (Appendix 4). The answers are still due.

Therefore, for future evaluations regarding the requirements of a tribological system to solid film lubricants a questionnaire was prepared for sending to the Program Managers of U.S. Army TACOM (Appendix 5). The questionnaire contains a variety of questions. It is not expected to get this questionnaire completely answered. However, this questionnaire will help to determine the real requirements to solid film lubricant in field applications.

Another issue to be addressed, in that context, is galvanic corrosion. Galvanic corrosion occurs when a metal or alloy is electrically coupled to another metal or conducting non-metal in the same electrolyte. The three essential components are:

- Materials with different surface potential,
- A common electrolyte,
- A common electrical path.

It is recognizable by a buildup of corrosion at the less noble material at the joint between the dissimilar materials.

Because of concerns regarding galvanic corrosion [Ref 8, Ref 29], graphite is not allowed in solid film lubricants conforming MIL-PRF-46010F and MIL-PRF-46147C. It is unknown to the author whether the findings in [Ref 8] are based only on laboratory investigations or on real corrosion damages of field applications.

Of course, there is a risk of galvanic corrosion when graphite and aluminum (or steel) are in contact in the presence of an electrolyte and an electron conductive path. However, solid film lubricants contain only small amounts of small graphite particles. These particles mixed with molybdenum disulfide are wrapped in the binder. Therefore, it is unlikely that with less than 5% graphite in the solid film lubricant formulation galvanic

corrosion really occurs in field applications. Today's products containing graphite confirm this thesis. Gleitmo 920 (4.3.3) and Gleitmo 940 (4.3.4) are successfully used in the automotive sector.

In conclusion, it has to be distinguished between corrosion produced under laboratory conditions, and corrosion damages found in field applications. Therefore, in developing new, environmentally friendly solid film lubricants without lead and antimony trioxide the use of graphite as an additive should be reconsidered.

6 Conclusion and Preview

Development and use of solid film lubricants have a long history in the U.S. Army. It is difficult to get information on all the existing know-how regarding solid film lubricants since most of the information available is based on experience. There is hardly any public printed information available other than information of general nature.

Mainly, three different kinds of solid film lubricants are in use in the U.S. Military and German Bundeswehr:

- MIL-PRF-46147C
- MIL-PRF-46010F
- MIL-L-23398D, Amd. 2

Up to now, the only product evaluated under this investigation without lead and antimony trioxide that fulfills the requirements for endurance life and load carrying capacity according to MIL-L-23398D, Amd. 2, is Slickote M2. However, the requirement for endurance life under MIL-L-23398D, Amd. 2 is less than for the other before identified specifications.

All other products either contain antimony trioxide or graphite. In some cases, these products even fail the requirements concerning endurance life and load carrying capacity [Table 12].

Regarding the concerns of the fastener industries, it is recommended to include additional tribological test(s) into the current MIL-Specifications. It is possible to accomplish this with the DIN 65593 [Ref 20] and / or ASTM D2981 [Ref 21] test methods. These tests address oscillating motion stress not covered with currently required tests. Right now DIN 65593 is in the process of being converted into an ASTM specification [Ref 22]. The test apparatus needed for the DIN 65593 is the Translatory Oscillation Apparatus - SRV® [Ref 23]. Information on the test apparatus can also be obtained from the company web page listed as [Ref 24].

Finally, an investigation is necessary to validate the requirements of military solid film lubricant specifications to ensure the limits are appropriate to military field applications. At this time, the requirements of the military specifications are based on historical data / information, which may not properly reflect current modern equipment. Therefore, it is important to properly identify system requirements for solid film lubricants to ensure limits are appropriate for intended use. This will also help in maximizing the chances that solid film lubricants without lead and antimony can be used in the military without sacrificing performance.

Continued work in this area is needed to investigate new technologies that will be both environmentally compliant and meet military performance requirements.

By Order

Dipl.-Ing. Schneider

Bauoberrat

7 References

Ref 1 Gresham R.M., "Bonded Solid Film Lubricants," Handbook of Lubrication, Volume III, Booser, E.R., Ed., CRC Press, Boca Raton, FL, 1994, page 167

Ref 2 Gresham, R.M., "Bonded Solid Film Lubricants," Tribology Data Handbook, Booser, E.R., Ed., CRC Press, Boca Raton, FL, 1997, page 600

Ref 3 E/M Corporation, Solid Film Lubricants: Basics, http://www.emcoatings.com/services/solidfilm/basics.htm

Ref 4 Seide, T.S., "Information Compendium on Solid Film Lubricants", TARDEC Technical Report No. 13616, November 1994

Ref 5 E/M Corporation, Solid Film Lubricants: Technical Information, http://www.emcoatings.com/services/solidfilm/tech.htm

Ref 6 Lancaster, J.K., "Solid Lubricants," Handbook of Lubrication, Volume II, Booser, E.R., Ed., CRC Press, Boca Raton, FL, 1984, page 269

Ref 7 Booser, E.R., "Solid Lubricants," Tribology Data Handbook, Booser, E.R., Ed, CRC Press, Boca Raton, FL, 1997, page 156

Ref 8 Gabel, M.K., Peterson, M.B., "Study of Parameters which affect Corrosion between Solid Film Lubricants and Aircraft Alloys, Lubrication Engineering, 12/1977

Ref 9 Schneider, S. "Tribotechnische Bewertung Schmierstoffe - Gleitlacke", Bundeswehr Research Institute for Materials, Explosives, Fuels and Lubricants (WIWEB) Erding, Germany, 1998

Ref 10 Marbach, T., Wright, B.R., "Low Volatile and Ozone-Depleting Compound Free Solid Film Lubricant", U.S. Army TARDEC Fuels and Lubricants Research Facility, Southwest Research Institute San Antonio, TX, June 2000

Ref 11 MIL-PRF-46147C: Lubricant, Solid Film, Air Cured, Corrosion Inhibiting; 07 July 2000

Ref 12 MIL-PRF-46010F: Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting; 12 June 2000

Ref 13 MIL-L-23398D, Amd. 2: Lubricant, Solid Film, Air Cured, Corrosion Inhibiting, NATO-Code Number S-749; 18 January 1994

Ref 14 MIL-L-81329D: Lubricant, Solid Film, Extreme Environment, NATO-Code Number S-1737; 18 September 1998

Ref 15 SAE AS5272: Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting; March 1997

Ref 16 SAE AS1701C: Lubricant, Solid Film; March 2000

Ref 17 MIL-L-46010D: Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting; 2 December 1994

Ref 18 MIL-L-46010E: Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting; 11 April 1997

Ref 19 Fuels and Lubricants Mobility Technology Center Ft. Belvoir: MIL-L-46010 Meeting Minutes, 22 August 1996

Ref 20 DIN 65593: Tribologische Prüfung von gebundenen Trockenschmierstoffen auf dem translatorischen Oszillationsprüfgeraet (Tribological Test in Translatory Oscillation Apparatus of Bonded Solid Film Lubricants), November 2000

Ref 21 ASTM D2981-94: Standard Test Method for Wear Life of Solid Film Lubricants in Oscillating Motion

Ref 22 ASTM D02.L - Industrial Lubricants, Minutes of the Meeting, San Diego, 19 June 2001

Ref 23 SRV III Test System, Optimol Instruments Prüftechnik GmbH, Munich, Germany, Quotation, 11 September 2000

Ref 24 SRV III Test System, Optimol Instruments Prüftechnik GmbH, Munich, Germany, http://www.optimol-instruments.de/

Ref 25 ASTM D2625-94: Standard Test Method for Endurance (Wear) Life and Load-Carrying Capacity of Solid Film Lubricants (Falex Pin and Vee Method)

Ref 26 ASTM D2670-95: Standard Test Method for Measuring Wear Properties of Fluid Lubricants (Falex Pin and Vee Block Method)

Ref 27 PTI Inc., Hinckley, IL: New Epsilon Linear Precision Test Machine; Product Information, April 2001

Ref 28 Brocklin, C.v.: Lube Order Database; Letter Report 93-4; U.S. Army Belvoir Research, Development & Engineering Center, 1993

Ref 29 Campell, M.E.: Solid Lubricants - A Survey, National Aeronautics And Space Administration 1972

Ref 30 ASTM D2510: Standard Test Method for Adhesion of Solid Film Lubricants

Ref 31 ASTM D1400: Standard Test Method for Nondestructive Measurement of Dry Film Thickness of Nonconductive Coatings Applied to a Nonferrous Metal Base

Ref 32 ASTM D1186: Standard Test Method for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to a Ferrous Metal Base

Ref 33 ASTM D3960: Standard Practice for Determining Volatile Organic Compound (VOC) Content of Paints and Related Coatings

Ref 34 ASTM D2511: Standard Test Method for Thermal Shock Sensivity of Solid Film Lubricants

Ref 35 ASTM D 2649: Standard Test Method for Corrosion Characteristics of Solid Film Lubricants

Ref 36 ASTM B117: Corrosion Protection of Steel Against Salt Spray by Solid Film Lubricants

8 Appendix

Appendix 1: Datasheets about single Solid Film Lubricants

MIL-PRF-46147C, Type I **Lubricant, Solid Film, Air Cured, Corrosion Inhibiting** 07 July 2000

Curing	Air cured
Curing Conditions	1.) air dry for 18 hours
Temperature Range	-67°C to +93 °C
FALEX Endurance Life	120 minutes at 4450 N (1000 lbf) 4 tests, no test less than 100 minutes
FALEX Load Carrying Capacity	11,120 N (2500 lbf) 2 tests, no test less than 8950 N (2000 lbf)
Solid Content	24% by weight of solid material
Restricted Materials	no graphite or powdered metals
VOC	***Binder*** ***Solvent***
Responsible U.S. Army	U.S. Army TACOM Attn: AMSTA-TR-D/210 Warren, MI 48397-5000

Resistance against the following fluids required

Anti-icing fluid MIL-A-8243	☐		
Cleaning compound, solvent MIL-PRF-372	☑	***Trichloroethane, MIL-T-81533***	☐
Reagent water ASTM D1193, Type III	☑	***Substitute ocean water ASTM D1141***	☐
Hydraulic fluid, synthetic hydrocarbon base, MIL-H-46170	☑		
Hydraulic fluid, synthetic hydrocarbon base, MIL-PRF-83282	☐		
Turbine fuel, aviation, kerosene type, MIL-DTL-83133, JP8	☑		
Turbine fuel, aviation, kerosene type, MIL-DTL-5624, JP4/JP5	☐		
Lubricating oil, synthetic base, MIL-PRF-23699	☐		
Lubricating oil, synthetic base, MIL-PRF-7808	☑	***Lubricating oil, weapons, MIL-L-14107***	☑
Lubricating oil, aircraft, SAE J1966	☑	***Lubricant, all-weather, MIL-PRF-85336***	☐
Lubricating oil, general purpose, VV-L-800	☑	***Damping fluid, silicone base, VV-D-1078***	☑
Lubricating oil, internal comustion engine, MIL-L-2104	☐	***Lubricant, semi-fluid, MIL-L-46000***	☑
Lubricant, cleaner and preservative, MIL-PRF-63460	☑		

Intended use The solid film lubricant covered by this specification is intended for use on aluminum, aluminum alloys, copper and copper alloys, steel, stainless steel, titanium, and chromium and nickel bearing surfaces. Solid film lubricants are used for thin film lubricant for sliding motion application and under conditions where heavy-load capacity, solvent resistance, and long term corrosion protection are need. It is useful under the following conditions:
- Where conventional lubricants are difficult to apply or retain.
- Where dust and dirt contamination on lubricated surfaces is deleterious.
- In mechanisms operated at infrequent intervals.
- In mechanisms that are lubricated for the life of the mechanism.
- Where long-term corrosion protection is required.
- Where a dull, dark gray or black non-reflective surface is required.
- Where a sacrificial lubricant is necessary to carry extremely heavy loads developed in the initial start-up of heavily loaded mechanism designed for fluid lubrication.
- In operations consisting of reciprocating motion, loaded to 15 psi (103 kPa) or less, where contamination with conventional fluid lubricants are probable.
- To touch up worn surfaces originally coated with lubricant conforming to MIL-PRF-46010.
- For sliding motion applications such as plain & spherical bearings, flap tracks, hinges, threads, cam surfaces.

Use limitations The lubricant should not be used under the following conditions:
- In operations consisting of rotary motion above 100 revolution per minute (rpm) under heavy loads where the possibility of conventional fluid lubricant contamination exists. The cured lubricant film is highly resistant to conventional fluid lubricants, but the high fluid pressures developed in heavily loaded sleeve type bearings drastically reduces the wear life provided by the solid film lubricant film.
- On bearings containing rolling elements.

MIL-PRF-46147C, Type II Lubricant, Solid Film, Air Cured, Corrosion Inhibiting 07 July 2000

Curing	Air cured
Curing Conditions	1.) air dry for 24 hours
Temperature Range	-67°C to +93 °C
FALEX Endurance Life	90 minutes at 4450 N (1000 lbf) 4 tests, no test less than 75 minutes
FALEX Load Carrying Capacity	11,120 N (2500 lbf) 2 tests, no test less than 8950 N (2000 lbf)
Solid Content	24% by weight of solid material
Restricted Materials	no graphite or powdered metals
VOC 250 g/L	***Binder*** ***Solvent***
Responsible U.S. Army	U.S. Army TACOM Attn: AMSTA-TR-D/210 Warren, MI 48397-5000

Resistance against the following fluids required

Anti-icing fluid MIL-A-8243	☐		
Cleaning compound, solvent MIL-PRF-372	☑	***Trichloroethane, MIL-T-81533***	☐
Reagent water ASTM D1193, Type III	☑	***Substitute ocean water ASTM D1141***	☐
Hydraulic fluid, synthetic hydrocarbon base, MIL-H-46170	☑		
Hydraulic fluid, synthetic hydrocarbon base, MIL-PRF-83282	☐		
Turbine fuel, aviation, kerosene type, MIL-DTL-83133, JP8	☑		
Turbine fuel, aviation, kerosene type, MIL-DTL-5624, JP4/JP5	☐		
Lubricating oil, synthetic base, MIL-PRF-23699	☐		
Lubricating oil, synthetic base, MIL-PRF-7808	☑	***Lubricating oil, weapons, MIL-L-14107***	☑
Lubricating oil, aircraft, SAE J1966	☑	***Lubricant, all-weather, MIL-PRF-85336***	☐
Lubricating oil, general purpose, VV-L-800	☑	***Damping fluid, silicone base, VV-D-1078***	☑
Lubricating oil, internal comustion engine, MIL-L-2104	☐	***Lubricant, semi-fluid, MIL-L-46000***	☑
Lubricant, cleaner and preservative, MIL-PRF-63460	☑		

Intended use The solid film lubricant covered by this specification is intended for use on aluminum, aluminum alloys, copper and copper alloys, steel, stainless steel, titanium, and chromium and nickel bearing surfaces. Solid film lubricants are used for thin film lubricant for sliding motion application and under conditions where heavy-load capacity, solvent resistance, and long term corrosion protection are need. It is useful under the following conditions:
- Where conventional lubricants are difficult to apply or retain.
- Where dust and dirt contamination on lubricated surfaces is deleterious.
- In mechanisms operated at infrequent intervals.
- In mechanisms that are lubricated for the life of the mechanism.
- Where long-term corrosion protection is required.
- Where a dull, dark gray or black non-reflective surface is required.
- Where a sacrificial lubricant is necessary to carry extremely heavy loads developed in the initial start-up of heavily loaded mechanism designed for fluid lubrication.
- In operations consisting of reciprocating motion, loaded to 15 psi (103 kPa) or less, where contamination with conventional fluid lubricants are probable.
- To touch up worn surfaces originally coated with lubricant conforming to MIL-PRF-46010.
- For sliding motion applications such as plain & spherical bearings, flap tracks, hinges, threads, cam surfaces.

Use limitations The lubricant should not be used under the following conditions:
- In operations consisting of rotary motion above 100 revolution per minute (rpm) under heavy loads where the possibility of conventional fluid lubricant contamination exists. The cured lubricant film is highly resistant to conventional fluid lubricants, but the high fluid pressures developed in heavily loaded sleeve type bearings drastically reduces the wear life provided by the solid film lubricant film.
- On bearings containing rolling elements.

MIL-PRF-46010F **Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting** 12 June 2000

Curing	Heat cured
Curing Conditions	1.) air dry for 1 hour 2.a) Panels: air circulation oven at 150+/-15°C for 120+/-5 minutes 2.b) Panes, Falex specimen: air circulation oven at 204+/-15°C for 60+/-5 minutes 3.) Cool to room temperature
Temperature Range	-68°C to +204°C
FALEX Endurance Life	450 minutes at 4450 N (1000 lbf) 4 tests, no test less than 390 minutes
FALEX Load Carrying Capacity	11,120 N (2500 lbf) 2 tests, no test less than 10,000 N (2248 lbf)
Solid Content	40% by weight of solid material
Restricted Materials	lead, lead-containing compounds, graphite, powdered metal, ozone-depleting substances
VOC 250 g/L	***Binder*** ***Solvent***
Responsible U.S. Army	U.S. Army TACOM Attn: AMSTA-TR-D/210 Warren, MI 48397-5000

Resistance against the following fluids required

Anti-icing fluid MIL-A-8243	☑		
Cleaning compound, solvent MIL-PRF-372	☑	***Trichloroethane, MIL-T-81533***	☐
Reagent water ASTM D1193, Type III	☑	***Substitute ocean water ASTM D1141***	☑
Hydraulic fluid, synthetic hydrocarbon base, MIL-H-46170	☑		
Hydraulic fluid, synthetic hydrocarbon base, MIL-PRF-83282	☐		
Turbine fuel, aviation, kerosene type, MIL-DTL-83133, JP8	☑		
Turbine fuel, aviation, kerosene type, MIL-DTL-5624, JP4/JP5	☐		
Lubricating oil, synthetic base, MIL-PRF-23699	☑		
Lubricating oil, synthetic base, MIL-PRF-7808	☐	***Lubricating oil, weapons, MIL-L-14107***	☑
Lubricating oil, aircraft, SAE J1966	☐	***Lubricant, all-weather, MIL-PRF-85336***	☑
Lubricating oil, general purpose, VV-L-800	☐	***Damping fluid, silicone base, VV-D-1078***	☑
Lubricating oil, internal comustion engine, MIL-L-2104	☐	***Lubricant, semi-fluid, MIL-L-46000***	☑
Lubricant, cleaner and preservative, MIL-PRF-63460	☑		

Intended use The lubricant is intended for use on aluminum and aluminum alloys, copper and copper alloys, steel, stainless steel, titanium, and chromium and nickel bearing surfaces, and is useful under the following conditions:
- To touch up worn surfaces originally coated with lubricant conforming to MIL-L-8937 or MIL-PRF-46010.
- For sliding motion applications such as plain and spherical bearing, flap tracks, hinges, threads, and cam surfaces.
- Where conventional lubricants are difficult to apply or retain, or where other lubricants may be easily contaminated with dirt and dust.
- If mechanisms are operated at infrequent intervals or are lubricated for life.
- Where long-term corrosion protection is required under static conditions.
- Where a solvent-resistant coating is required.
- Where a lubricant requires extremely heavy load ability in the initial start-up of heavy loaded mechanisms designed for fluid lubrication.

Use limitations This lubricant should not be used under the following conditions:
- On materials which will be adversely affected by the curing temperatures of 204 ± 15°C.
- In operations consisting of rotary motion above 100 revolutions per minute (rpm) under heavy loads where the possibility of conventional fluid lubricant contamination exists. The cured lubricant film is highly resistant to conventional fluid lubricants, but the high fluid pressures developed in heavily loaded sleeve type bearings drastically reduces the wear life provided by the solid lubricant film.
- On bearings containing rolling elements.
- Where there is potential contact with liquid oxygen.

MIL-L-23398D, Amd. 2 **Lubricant, Solid Film, Air Cured, Corrosion Inhibiting, NATO-Code S-749** 18 January 1994

Curing	Air cured
Curing Conditions	air cured at 25+/-2 °C for 6 hours
Temperature Range	- 198 °C to + 300 °C
FALEX Endurance Life	60 minutes at 4450 N (1000 lbf) 4 tests, no test less than 50 minutes
FALEX Load Carrying Capacity	11,120 N (2500 lbf) 2 tests, no test less than 10,000 N (2248 lbf)
Solid Content	24% by weight of solid material
Restricted Materials	graphite, powdered metal, carbon black, charcoal or other forms of inorganic carbon
VOC ***Binder***	***Solvent***
Responsible U.S. Navy	Naval Air Warface Center Aircraft Division; Code 414100B120-3 Highway 547 Lakehurst, NJ 08733-5100

Resistance against the following fluids required

Anti-icing fluid MIL-A-8243	☑		
Cleaning compound, solvent MIL-PRF-372	☑	***Trichloroethane, MIL-T-81533***	☑
Reagent water ASTM D1193, Type III	☑	***Substitute ocean water ASTM D1141***	☐
Hydraulic fluid, synthetic hydrocarbon base, MIL-H-46170	☐		
Hydraulic fluid, synthetic hydrocarbon base, MIL-PRF-83282	☑		
Turbine fuel, aviation, kerosene type, MIL-DTL-83133, JP8	☐		
Turbine fuel, aviation, kerosene type, MIL-DTL-5624, JP4/JP5	☑		
Lubricating oil, synthetic base, MIL-PRF-23699	☑		
Lubricating oil, synthetic base, MIL-PRF-7808	☐	***Lubricating oil, weapons, MIL-L-14107***	☐
Lubricating oil, aircraft, SAE J1966	☐	***Lubricant, all-weather, MIL-PRF-85336***	☐
Lubricating oil, general purpose, VV-L-800	☐	***Damping fluid, silicone base, VV-D-1078***	☑
Lubricating oil, internal comustion engine, MIL-L-2104	☑	***Lubricant, semi-fluid, MIL-L-46000***	☐
Lubricant, cleaner and preservative, MIL-PRF-63460	☐		

Intended use This air cured solid film lubricant is intended for use on steel, titanium or aluminum bearing surfaces where moderate wear life and corrosion protection are desired. It is useful where conventional lubricants are difficult to apply or retain or where other lubricants may be contamined with dirt and dust. It is generally suitable for sliding motion applications such as in plain spherical bearings, flap tracks, hinges and cam surfaces, especially where it is not feasible to use the type of solid film lubricant which requires baking at an elevated temperature.

Use limitations The use of this lubricant is not recommended on roller bearing elements or in conjunction with oils or greases unless field use indicates otherwise.

MIL-L-81329D **Lubricant, Solid Film, Extreme Environment, NATO-Code S-1737** 18 September 1998

Curing	Heat cured
Curing Conditions	1.) Air dry for 30 minutes at room temperature (25+/-3 °C) 2.) Heat for two hours at 80+/-1 °C 3.) Heat for two hours at 150+/-3 °C
Temperature Range	-185 °C to +400 °C
FALEX Endurance Life	60 minutes at 4450 N (1000 lbf)
FALEX Load Carrying Capacity	no test
Solid Content	
Restricted Materials	
VOC	***Binder*** inorganic ***Solvent*** inorganic
Responsible	Naval Air Warface Center Aircraft Division; Code 414100B120-3 Highway 547 Lakehurst, NJ 08733-5100

Resistance against the following fluids required

- ***Anti-icing fluid MIL-A-8243*** ☐
- ***Cleaning compound, solvent MIL-PRF-372*** ☐
- ***Reagent water ASTM D1193, Type III*** ☐
- ***Trichloroethane, MIL-T-81533*** ☐
- ***Substitute ocean water ASTM D1141*** ☐
- ***Hydraulic fluid, synthetic hydrocarbon base, MIL-H-46170*** ☐
- ***Hydraulic fluid, synthetic hydrocarbon base, MIL-PRF-83282*** ☐
- ***Turbine fuel, aviation, kerosene type, MIL-DTL-83133, JP8*** ☐
- ***Turbine fuel, aviation, kerosene type, MIL-DTL-5624, JP4/JP5*** ☐
- ***Lubricating oil, synthetic base, MIL-PRF-23699*** ☐
- ***Lubricating oil, synthetic base, MIL-PRF-7808*** ☐
- ***Lubricating oil, aircraft, SAE J1966*** ☐
- ***Lubricating oil, general purpose, VV-L-800*** ☐
- ***Lubricating oil, internal comustion engine, MIL-L-2104*** ☐
- ***Lubricant, cleaner and preservative, MIL-PRF-63460*** ☐
- ***Lubricating oil, weapons, MIL-L-14107*** ☐
- ***Lubricant, all-weather, MIL-PRF-85336*** ☐
- ***Damping fluid, silicone base, VV-D-1078*** ☐
- ***Lubricant, semi-fluid, MIL-L-46000*** ☐

Intended use The lubricant covered by this specification is intended primarily for use in liquid oxigen systems, space vehicles, bearing assemblies, and other equipment where the environments of extreme temperature and nuclear radiation preclude the use of commercial lubricants and organic solid film lubricants. It is intended to reduce wear and to prevent galling and seizing of metal surfaces.

Use limitations Do not use the lubricant on material that may adversely affected by exposure to the specific cure temperature of 150 °C. The lubricant should not be used with oils or greases, unless field use indicates otherwise.

SAE AS5272, Type I **Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting** 1997-03

Curing	Heat cured
Curing Conditions	1.) air drying at 25+/-3°C for 10 minutes 2.) air circulation oven at 150+/-15°C for 60+/-5 minutes 3.) Cool to room temperature
Temperature Range	-68°C to +204 °C
FALEX Endurance Life	250 minutes at 4450 N (1000 lbf) 4 tests, no test less than 210 minutes
FALEX Load Carrying Capacity	11,120 N (2500 lbf) 2 tests, no test less than 10,000 N (2248 lbf)
Solid Content	40% by weight of solid material
Restricted Materials	graphite, powdered metal, ozone-depleting substances
VOC ***Binder***	***Solvent***
Responsible	SAE International 400 Commonwealth Drive Warrendale, PA 15096-0001

Resistance against the following fluids required

Anti-icing fluid MIL-A-8243	☑		
Cleaning compound, solvent MIL-PRF-372	☑	***Trichloroethane, MIL-T-81533***	☐
Reagent water ASTM D1193, Type III	☑	***Substitute ocean water ASTM D1141***	☑
Hydraulic fluid, synthetic hydrocarbon base, MIL-H-46170	☑		
Hydraulic fluid, synthetic hydrocarbon base, MIL-PRF-83282	☐		
Turbine fuel, aviation, kerosene type, MIL-DTL-83133, JP8	☑		
Turbine fuel, aviation, kerosene type, MIL-DTL-5624, JP4/JP5	☐		
Lubricating oil, synthetic base, MIL-PRF-23699	☑		
Lubricating oil, synthetic base, MIL-PRF-7808	☐	***Lubricating oil, weapons, MIL-L-14107***	☑
Lubricating oil, aircraft, SAE J1966	☐	***Lubricant, all-weather, MIL-PRF-85336***	☑
Lubricating oil, general purpose, VV-L-800	☐	***Damping fluid, silicone base, VV-D-1078***	☑
Lubricating oil, internal comustion engine, MIL-L-2104	☐	***Lubricant, semi-fluid, MIL-L-46000***	☑
Lubricant, cleaner and preservative, MIL-PRF-63460	☑		

Intended use For aerospace fastener applications where temperatures may range from -68°C to 204°°C

Use limitations This lubricant shall not be used under the following conditions
- On materials which are adversely affected by the curing temperature of 150 °C.
- Where there is a potential contact with liquid oxygen.

SAE AS5272, Type II **Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting** 1997-03

Curing	Heat cured
Curing Conditions	1.) air drying at 25+/-3°C for 10 minutes 2.) air circulation oven at 204+/-15°C for 60+/-5 minutes 3.) Cool to room temperature
Temperature Range	-68°C to +204 °C
FALEX Endurance Life	450 minutes at 4450 N (1000 lbf) 4 tests, no test less than 390 minutes
FALEX Load Carrying Capacity	8,900 N (2000 lbf) 2 tests, no test less than 7,780 N (1750 lbf)
Solid Content	40% by weight of solid material
Restricted Materials	graphite, powdered metal, ozone-depleting substances
VOC	***Binder*** ***Solvent***
Responsible	SAE International 400 Commonwealth Drive Warrendale, PA 15096-0001

Resistance against the following fluids required

Anti-icing fluid MIL-A-8243	☑		
Cleaning compound, solvent MIL-PRF-372	☑	***Trichloroethane, MIL-T-81533***	☐
Reagent water ASTM D1193, Type III	☑	***Substitute ocean water ASTM D1141***	☑
Hydraulic fluid, synthetic hydrocarbon base, MIL-H-46170	☑		
Hydraulic fluid, synthetic hydrocarbon base, MIL-PRF-83282	☐		
Turbine fuel, aviation, kerosene type, MIL-DTL-83133, JP8	☑		
Turbine fuel, aviation, kerosene type, MIL-DTL-5624, JP4/JP5	☐		
Lubricating oil, synthetic base, MIL-PRF-23699	☑		
Lubricating oil, synthetic base, MIL-PRF-7808	☐	***Lubricating oil, weapons, MIL-L-14107***	☑
Lubricating oil, aircraft, SAE J1966	☐	***Lubricant, all-weather, MIL-PRF-85336***	☑
Lubricating oil, general purpose, VV-L-800	☐	***Damping fluid, silicone base, VV-D-1078***	☑
Lubricating oil, internal comustion engine, MIL-L-2104	☐	***Lubricant, semi-fluid, MIL-L-46000***	☑
Lubricant, cleaner and preservative, MIL-PRF-63460	☑		

Intended use For aerospace fastener applications where temperatures may range from -68 to 204°°C

Use limitations This lubricant shall not be used under the following conditions
- On materials which are adversely affected by the curing temperature of 204 °C.
- Where there is a potential contact with liquid oxygen.

SAE AS1701 C, Class I **Lubricant, Solid Film** 2000-3

Curing	Heat cured
Curing Conditions	
Temperature Range	-65°C to +450 °C
FALEX Endurance Life	450 minutes at 4450 N (1000 lbf) 4 tests, no test less than 390 minutes
FALEX Load Carrying Capacity	11,120 N (2500 lbf) 2 tests, no test less than 10,000 N (2248 lbf)
Solid Content	
Restricted Materials	silver or its compounds, lead, halogenated sovents
VOC ***Binder***	Organic ***Solvent***
Responsible	SAE International 400 Commonwealth Drive Warrendale, PA 15096-0001

Resistance against the following fluids required

Anti-icing fluid MIL-A-8243	☑		
Cleaning compound, solvent MIL-PRF-372	☐	***Trichloroethane, MIL-T-81533***	☐
Reagent water ASTM D1193, Type III	☐	***Substitute ocean water ASTM D1141***	☑
Hydraulic fluid, synthetic hydrocarbon base, MIL-H-46170	☐		
Hydraulic fluid, synthetic hydrocarbon base, MIL-PRF-83282	☑		
Turbine fuel, aviation, kerosene type, MIL-DTL-83133, JP8	☐		
Turbine fuel, aviation, kerosene type, MIL-DTL-5624, JP4/JP5	☑		
Lubricating oil, synthetic base, MIL-PRF-23699	☑		
Lubricating oil, synthetic base, MIL-PRF-7808	☑	***Lubricating oil, weapons, MIL-L-14107***	☐
Lubricating oil, aircraft, SAE J1966	☐	***Lubricant, all-weather, MIL-PRF-85336***	☐
Lubricating oil, general purpose, VV-L-800	☐	***Damping fluid, silicone base, VV-D-1078***	☑
Lubricating oil, internal comustion engine, MIL-L-2104	☐	***Lubricant, semi-fluid, MIL-L-46000***	☐
Lubricant, cleaner and preservative, MIL-PRF-63460	☐		

Intended use The solid film lubricants covered by this specification are intended for aerospace applications exposed to extreme environments. Some may be suitable for use in vacuum at temperature ranging from -221°C to +760 °C.

Use limitations

SAE AS1701 C, Class II **Lubricant, Solid Film** 2000-3

Curing	Air cured
Curing Conditions	
Temperature Range	-54°C to +232 °C
FALEX Endurance Life	90 minutes at 4450 N (1000 lbf) 4 tests, no test less than 75 minutes
FALEX Load Carrying Capacity	11,120 N (2500 lbf) 2 tests, no test less than 8896 N (2000 lbf)
Solid Content	
Restricted Materials	silver or its compounds, lead, halogenated sovents
VOC ***Binder***	Organic ***Solvent***
Responsible	SAE International 400 Commonwealth Drive Warrendale, PA 15096-0001

Resistance against the following fluids required

Anti-icing fluid MIL-A-8243	☑		
Cleaning compound, solvent MIL-PRF-372	☐	***Trichloroethane, MIL-T-81533***	☐
Reagent water ASTM D1193, Type III	☐	***Substitute ocean water ASTM D1141***	☑
Hydraulic fluid, synthetic hydrocarbon base, MIL-H-46170	☐		
Hydraulic fluid, synthetic hydrocarbon base, MIL-PRF-83282	☑		
Turbine fuel, aviation, kerosene type, MIL-DTL-83133, JP8	☐		
Turbine fuel, aviation, kerosene type, MIL-DTL-5624, JP4/JP5	☑		
Lubricating oil, synthetic base, MIL-PRF-23699	☑		
Lubricating oil, synthetic base, MIL-PRF-7808	☑	***Lubricating oil, weapons, MIL-L-14107***	☐
Lubricating oil, aircraft, SAE J1966	☐	***Lubricant, all-weather, MIL-PRF-85336***	☐
Lubricating oil, general purpose, VV-L-800	☐	***Damping fluid, silicone base, VV-D-1078***	☑
Lubricating oil, internal comustion engine, MIL-L-2104	☐	***Lubricant, semi-fluid, MIL-L-46000***	☐
Lubricant, cleaner and preservative, MIL-PRF-63460	☐		

Intended use The solid film lubricants covered by this specification are intended for aerospace applications exposed to extreme environments. Some may be suitable for use in vacuum at temperature ranging from -221°C to +760 °C.

Use limitations

Appendix 2: Solid Film Lubricant Testing - Datasheets about single Test Procedures

Title of Method:

Standard Test Method for Endurance (Wear) Life of Solid Film Lubricants (Falex Pin and Vee Block Method)

Specification:

ASTM D 2625, Procedure A

Equipment:

- FALEX Pin and Vee Block Test Machine with Load Gage, 4500-lbf range, or 3000-lbf direct-reading gage
- Desiccator
- Oven, forced-circulation, capable of maintaining a temperature 149±5°C (300±10°F)
- Thickness measurement devise:
  Fischer Dualscope MP40 or
  Micrometer with a 1-ball anvil, reading 0 to 25.4±0.0025 mm
- Vapor degreasing bath

Reagents and Materials:

- Standard Vee blocks
- Standard Test Pins
- Shear Pins
- Aluminum Oxide, white angular abrasive, 180 grit to 220 grit
- Solvent, safe, nonfilming, nonchlorinated (Toluol)
- Beaker
- Ultrasonic Cleaner

Calibration:

Needs to be specified

Monitoring of Result Quality:

Needs to be specified

Reference:

MIL-Specification	MIL-PRF-46147C	MIL-PRF-46010F	MIL-L-23396D
Requirement	3.3.1	3.3.1	3.4.4
Verification	4.3.3.1	4.3.3.1	Table II

Title of Method:

Standard Test Method for Load-Carrying Capacity of Solid Film Lubricants (Falex Pin and Vee Block Method)

Specification:

ASTM D 2625, Procedure B

Equipment:

- FALEX Pin and Vee Block Test Machine with Load Gage, 4500-lbf range, or 3000-lbf direct-reading gage
- Desiccator
- Oven, forced-circulation, capable of maintaining a temperature 149±5°C (300±10°F)
- Thickness measurement devise:
  Fischer Dualscope MP40 or
  Micrometer with a 1-ball anvil, reading 0 to 25.4±0.0025 mm
- Vapor degreasing bath

Reagents and Materials:

- Standard Vee blocks
- Standard Test Pins
- Shear Pins
- Aluminum Oxide, white angular abrasive, 180 grit to 220 grit
- Solvent, safe, nonfilming, nonchlorinated (Toluol)
- Beaker
- Ultrasonic Cleaner

Calibration:

Needs to be specified

Monitoring of Result Quality:

Needs to be specified

Reference:

MIL-Specification	MIL-PRF-46147C	MIL-PRF-46010F	MIL-L-23396D
Requirement	3.3.2	3.3.2	3.4.5
Verification	4.3.3.2	4.3.3.2	Table II

Title of Method:

Standard Test Method for Adhesion of Solid Film Lubricants

Specification:

ASTM D 2510, Procedure A

Equipment:

- Rubber Covered Steel Roller
- Stylus
- Thickness measurement devise:
  Fischer Dualscope MP40 or
  Micrometer with a 1-ball anvil, reading 0 to 25.4±0.0025 mm
- Oven, forced-circulation, capable of maintaining a temperature at 149±5.5°C (300±10F°)

Reagents and Materials:

- Test Panels, of aluminum alloy 2024, 75x150x0.5 mm (3x6x0.020 in.), anodized
- Tape, masking, 25 mm wide
- Water, conforming to Specification D 1193
- Solvent, safe, nonfilming, nonchlorinated

Calibration:

Needs to be specified

Monitoring of Result Quality:

Needs to be specified

Reference:

MIL-Specification	MIL-PRF-46147C	MIL-PRF-46010F	MIL-L-23396D
Requirement	3.4.1	3.4.1	3.4.1
Verification	4.3.4.1	4.3.4.1	Table II

Title of Method:

Standard Test Method for Nondestructive Measurement of Dry Film Thickness of Nonconductive Coatings Applied to a Nonferrous Metal Base

Specification:

ASTM D 1400

Equipment:

- Thickness measurement devise:
  Fischer Dualscope MP40 or
  Eddy Current Thickness Gage
- Nonconductive Thickness Shims for Calibration

Reagents and Materials:

- Test Panels, of aluminum alloy, conforming to SAE AMS-QQ-A-250/5, 75x150x0.5 mm (3x6x0.020 in.), anodized

Calibration:

Needs to be specified

Monitoring of Result Quality:

Needs to be specified

Reference:

MIL-Specification	MIL-PRF-46147C	MIL-PRF-46010F	MIL-L-23396D
Requirement	3.4.2	3.4.2	3.3 (according FED-STD-791 3816)
Verification	4.3.4.2	4.3.4.2	Table II

Title of Method:

Standard Test Method for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to a Ferrous Metal Base

Specification:

ASTM D 1186

Equipment:

- Thickness measurement devise:
  Fischer Dualscope MP40 or
  Permanent Magnet
- Nonmagnetic Thickness Shims or Polished Metal Certification Calibration Standards

Reagents and Materials:

- Test Panels, of corrosion resistant steel, conforming to ASTM A 167, 75x150x1.0 mm (3x6x0.35 in.)

Calibration:

Needs to be specified

Monitoring of Result Quality:

Needs to be specified

Reference:

MIL-Specification	MIL-PRF-46147C	MIL-PRF-46010F	MIL-L-23396D
Requirement	3.4.2	3.4.2	3.3 (according FED-STD-791 3816)
Verification	4.3.4.2	4.3.4.2	Table II

Title of Method:

Determination of the Solids Content

Specification:

N/A

Equipment:

- Scale
- Weighing dish
- Oven, forced-circulation, capable of maintaining 204±3°C
- Desiccator with calcium sulfate

Reagents and Materials:

Calibration:

Needs to be specified

Monitoring of Result Quality:

Needs to be specified

Reference:

MIL-Specification	MIL-PRF-46147C	MIL-PRF-46010F	MIL-L-23396D
Requirement	3.4.5	3.4.3	3.5.1 & 3.5.2
Verification	4.3.4.5	4.3.4.3	4.6.5.1 & 4.6.5.2

Title of Method:

Standard Practice for Determining Volatile Organic Compound (VOC) Content of Paints and Related Coatings

Specification:

ASTM D 3960 (ASTM D 4017 / ASTM D 4457)

Equipment:

- Karl Fischer Apparatus
- Syringe, 100-µL capacity, with needle
- Syringes, 1-mL and 10-mL capacity, without needle, but equipped with caps
- Chromatograph, gas-liquid chromatographic
- Recording potentiometer with a full-scale deflection of 10 mV
- Pre-Column, 40 in. by 1/8 in. outside diameter, packed with glass wool
- Column, 4 ft. by 1/8 in. outside diameter, packed with porous polymer packing material
- Liquid charging devices, such as microsyrings of 5-µL or 10-µL capacity
- Vials, 25-mL, capable of being sealed

Reagents and Materials:

- Classical Karl Fischer Reagent
- Nonpyridine based Karl Fischer Reagent
- Pyridine
- 1-Ethylpiperidine
- Hydrochlorid acid (HCl), concentrated
- Water, conforming Spec. 1193, Type II
- Carrier gas, Helium
- Dimethylformamide (DMF)
- 1-Propanol
- 1,1,1-Trichloroethane
- Dichlormethane
- Halogenated hydrocarbon stabilizers

Calibration:

Needs to be specified

Monitoring of Result Quality:

Needs to be specified

Reference:

MIL-Specification	MIL-PRF-46147C	MIL-PRF-46010F	MIL-L-23396D
Requirement	3.4.6	3.4.4	Not required
Verification	4.3.4.6	4.3.4.4	

Title of Method:

Standard Test Method for Adhesion of Solid Film Lubricants / Resistance to Fluids Other Than Water

Specification:

ASTM D 2510, Procedure C

Equipment:

- Rubber Covered Steel Roller
- Stylus
- Thickness measurement devise:
  Fischer Dualscope MP40 or
  Micrometer with a 1-ball anvil, reading 0 to 25.4±0.0025 mm
- Oven, forced-circulation, capable of maintaining 149±5.5°C (300±10F°)

Reagents and Materials:

- Test Panels, of aluminum alloy 2024, 75x150x0.5 mm (3x6x0.020 in.), anodized
- Tape, masking, 25 mm wide
- Water, conforming to Specification D 1193
- Solvent, safe, nonfilming, nonchlorinated
- (Aliphatic Naphtha / Acetone)
- Anti-icing fluid — MIL-A-8243
- Cleaning compound, solvent — MIL-PRF-372
- Reagent water — ASTM D 1193, Type III
- Substitute ocean water — ASTM D 1141
- Hydraulic fluid, rust inhibited, fire resistant, synthetic hydrocarbon base — MIL-H-46170
- Turbine fuel, aviation, kerosene type — MIL-DTL-83133, JP-8
- Lubricating oil, aircraft turbine engine, synthetic base — MIL-PRF-23699
- Damping fluid, silicone base — VV-D-1078
- Lubricating oil, weapons, low temperature — MIL-L-14107
- Lubricant, semi-fluid — MIL-L-46000
- Lubricant, cleaner and preservative for weapons and weapons systems — MIL-PRF-63460
- Lubricant, all-weather — MIL-PRF-85336

Calibration:

Needs to be specified

Monitoring of Result Quality:

Needs to be specified

References:

MIL-Specification	MIL-PRF-46147C	MIL-PRF-46010F	MIL-L-23396D
Requirement	3.6.1	3.6.1	3.4.2
Verification / Test	4.3.6.1	4.3.6.1	Table II

Title of Method:

Standard Test Method for Thermal Shock Sensivity of Solid Film Lubricants

Specification:

ASTM D 2511

Equipment:

- Sub-Zero Cabinet, capable of maintaining a constant temperature of -54±0.5°C (-65±1F°)
- Thickness measurement devise:
  Fischer Dualscope MP40 or
  Micrometer with a 1-ball anvil, reading 0 to 25±0.0025 mm
- Oven, forced-circulation, capable of maintaining a temperature at 260±5.5°C (500±10F°)

Reagents and Materials:

- Test Panels, of corrosion resistant steel, 75x150x0.9 mm (3x6x0.036 in.), conforming to Spec. A 167, No. 2D
- Dry cleaning solvent, conforming U.S. FedSpec P-D-680

Calibration:

Needs to be specified

Monitoring of Result Quality:

Needs to be specified

Reference:

MIL-Specification	MIL-PRF-46147C	MIL-PRF-46010F	MIL-L-23396D
Requirement	3.6.2	3.6.2	3.4.3
Verification / Test	4.3.6.2	4.3.6.2	Table II

Title of Method:

Standard Test Method for Corrosion Characteristics of Solid Film Lubricants

Specification:

ASTM D 2649

Equipment:

- Bolt, No. 3/8-24UNF-3A, made of aluminum alloy 2024, conforming to Spec. B 211
- Nut, No. 3/8-24UNF-3B, having threads conforming MIL-Spec. MIL-S-7742
- Channel, made of aluminum alloy 2024, conforming to Spec. B 308, 179 mm long, 76 mm wide, 35 mm high
- Humidity Environmental Test Chamber, capable of producing 95±3% relative humidity, 49±1°C
- Torque Wrench, with capacity of 2.8 Nm
- Thickness measurement devise:
  Fischer Dualscope MP40 or
  Micrometer with a 1-ball anvil, reading 0 to 25.4±0.0025 mm
- Oven, forced-circulation, capable of maintaining a temperature at 149±5.5°C (300±10°F)

Reagents and Materials:

- Test Panels, of aluminum alloy 2024, 75x150x0.5 mm (3x6x0.020 in.), anodized
- Trichlorethylene, conforming MIL-T-27602
- Resin Coating, permanent, conforming MIL-R-3043

Calibration:

Needs to be specified

Monitoring of Result Quality:

Needs to be specified

Reference:

MIL-Specification	MIL-PRF-46147C	MIL-PRF-46010F	MIL-L-23396D
Requirement	Not required	3.6.3	3.4.6
Verification		4.3.6.3	Table II

Title of Method:

Corrosion Protection of Steel against Sulferous Acid-salt Spray by Solid Film Lubricants

Specification:

FED-STD-791, Method 5331

Equipment:

- Air supply, filtered, 69 gage kPa to 103 gage kPa
- Air flow regulator, capable of regulating air flow at 472 mL/s
- Spray nozzle, corrosion resistant with a 13 cm diameter acrylic baffle
- Turntable assembly (turntable – 26.7 cm diameter & driving mechanism – 1/3 RPM)
- Specimen holder (holder cap & ice jacket)
- Jar, 30.5 cm I.D. and 30.5 cm high
- Support rods
- Flexible Tygon Tubing, 0.96 cm I.D.

Reagents and Materials:

- Steel specimen, disk with 5.4 cm diameter & thickness of 0.16 cm, made of carbon steel
- Synthetic sea water-sulfurous acid test solution
- Aluminum oxide cloth, 240 grit
- 1,1,1 Trichlorethane
- Distilled water
- Sulfurous acid

Calibration:

Needs to be specified

Monitoring of Result Quality:

Needs to be specified

Reference:

MIL-Specification	MIL-PRF-46147C	MIL-PRF-46010F	MIL-L-23396D
Requirement	Not required	3.6.4	3.4.7
Verification		4.3.6.4	Table II

Title of Method:

Corrosion Protection of Steel against Salt Spray by Solid Film Lubricants

Specification:

ASTM B 117

Equipment:

- Salt spray cabinet according ASTM B 117, Appendix X1

Reagents and Materials:

- Test panels, 76x127x0.8 mm (3.0x5.0x0.0315 in.), steel SAE 1008
- Salt solution according ASTM B117
- Reagent grade water, ASTM D1193, Type IV

Calibration:

Needs to be specified

Monitoring of Result Quality:

Needs to be specified

Reference:

MIL-Specification	MIL-PRF-46147C	MIL-PRF-46010F	MIL-L-23396D
Requirement	3.6.3	3.6.5	Not required
Verification	4.3.6.3	4.3.6.5	

Appendix 3: Test Results

Pin #	Application technique	Film Thickness				Endurance Life
		mean	S	min	max	
1	Spraying, one time	3.5	2.0	1.50	7.50	60 min
2	Spraying, two times	5.3	1.7	3.50	7.90	51 min
4	Spraying, one time	N/A	N/A	N/A	N/A	60 min
5	Spraying, two times	8.0	3.5	4.20	14.80	37 min
	Average					52 min

Table 1: Slickote M1 - Endurance Life, 1st run

Pin #	Application technique	Film Thickness				Endurance Life
		mean	S	min	max	
M	Dipping, four times	6.0	1.3	3.4	7.6	65 min
N	Dipping, four times	5.7	2.3	3.1	8.7	74 min
O	Dipping, four times	6.3	2.1	3.7	9.2	49 min
P	Dipping, four times	5.2	1.6	4.0	8.3	55 min
	Average					61 min

Table 2: Slickote M1 - Endurance Life, 2nd run

Pin #	Application technique	Film Thickness				Load Carrying Capacity
		mean	S	min	max	
6	Spraying, two times	9.0	4.2	4.30	16.80	2750 lbs
7	Spraying, one time	11.0	6.2	1.40	22.80	3000 lbs
8	Spraying, one time	4.1	1.3	2.00	7.00	3250 lbs
9	Spraying, one time	3.6	2.7	1.10	7.30	3250 lbs
10	Spraying, one time	4.4	2.7	0.72	9.30	3000 lbs
	Average					3050 lbs

Table 3: Slickote M1 - Load Carrying Capacity

Pin #	Application technique	Film Thickness				Endurance Life
		mean	S	min	max	
D	Dipping, three times	16.2	2.2	11.9	18.9	78 min
E	Dipping, four times	14.4	2.9	11.2	19.1	57 min
F	Dipping, three times	13.8	2.1	11.2	17.9	62 min
H	Dipping, three times	14.7	1.5	12.6	17.2	63 min
	Average					65 min

Table 4: Slickote M2 - Endurance Life

Pin #	Application technique	Film Thickness				Load Carrying Capacity
		mean	S	min	max	
A	Dipping, three times	15.4	4.4	10.5	22.3	2500 lbs
B	Dipping, three times	18.3	5.1	12.1	28.2	2250 lbs
G	Dipping, four times	10.9	4.9	6.5	21.7	2500 lbs
	Average					2417 lbs

Table 5: Slickote M2 - Load Carrying Capacity

Pin #	Application technique	Film Thickness				Endurance Life
		mean	S	min	max	
A	Dipping, two times	10.9	2.2	6.9	14.4	122 min
B	Dipping, two times	9.2	2.8	5.9	14.2	128 min
C	Dipping, two times	10.6	2.5	7.3	13.6	121 min
D	Dipping, two times	9.7	2.2	7.0	12.6	120 min
E	Spraying, one time	27.3	2.8	23.8	31.6	139 min
F	Spraying, one time	26.4	10.3	14.3	50.1	112 min
	Average					124 min

Table 6: Gleitmo 920 - Endurance Life

Pin #	Application technique	Film Thickness				Load Carrying Capacity
		mean	S	min	max	
G	Spraying, one time	29.3	9.5	12.6	41.0	2000 lbs
H	Spraying, one time	16.4	4.5	8.2	22.4	2250 lbs
I	Dipping, two times	12.3	2.4	7.6	15.2	3000 lbs
J	Dipping, two times	11.6	3.1	7.1	17.0	3000 lbs
K	Dipping, two times	9.6	1.8	7.2	12.2	3000 lbs
L	Dipping, two times	11.8	2.3	8.1	15.9	2750 lbs
	Average					2667 lbs

Table 7: Gleitmo 920 - Load Carrying Capacity

Pin #	Application technique	Film Thickness				Endurance Life
		mean	S	min	max	
Q	Dipping, three times	11.8	2.4	8.1	16.1	147 min
R	Dipping, three times	9.2	2.7	6.4	14.3	158 min
S	Dipping, three times	9.6	3.3	4.3	15.3	128 min
T	Dipping, three times	8.5	2.8	3.0	12.7	125 min
U	Dipping, three times	10.5	2.4	8.7	14.3	183 min
V	Dipping, three times	9.9	2.8	6.7	15.5	143 min
	Average					147 min

Table 8: Gleitmo 940 - Endurance Life

Pin #	Application technique	Film Thickness				Load Carrying Capacity
		mean	S	min	Max	
W	Dipping, three times	9.9	3.1	6.1	16.2	2750 lbs
X	Dipping, three times	9.6	2.1	6.8	13.3	2500 lbs
Y	Dipping, three times	9.7	3.0	4.7	15.0	2500 lbs
Z	Dipping, three times	8.5	2.9	4.5	14.7	2500 lbs
	Average					2562 lbs

Table 9: Gleitmo 940 - Load Carrying Capacity

Pin #	Application technique	Film Thickness				Endurance Life
		mean	S	min	Max	
A	Dipping, three times	41.7	13.3	24.7	64.5	0 min
B	Dipping, three times	23.1	6.8	17.1	34.4	0 min
C	Dipping, three times	20.9	6.2	14.1	32.6	0 min
D	Dipping, three times	18.4	5.3	12.2	29.2	3 min
E	Dipping, three times	19.9	6.7	11.4	31.8	0 min
F	Dipping, three times	22.8	7.2	12.7	33.5	0 min
K	Dipping, one time	4.7	1.9	2.1	7.9	2 min
L	Dipping, two times	10.1	1.5	7.9	12.8	4 min

Table 10: Gleitmo SFL 9560 - Endurance Life

Value	Specimen pretreatment	Gleitmo 920	Gleitmo 940	Gleitmo SFL 9560
Friction coefficient	Steel	0.07	0.06	0.17
Friction coefficient	Surface phosphated	0.08	0.06	0.07
Scuff-limited load	Steel	> 18 kN	> 18 kN	> 6.5 kN
Scuff-limited load	Surface phosphated	> 18 kN	> 18 kN	> 14 kN

Table 11: Gleitmo products tested on Almen Wieland Machine

Product	Sample ID	Contains			MIL-Specification	Endurance	Load Car-
	FL-	Antimony	Lead	Graphite		Life	rying Cap.
Slickote M1	11297-01	Yes	No	No	MIL-PRF-46147C	Failed	Passed
Slickote M2	11297-01	No	No	No	MIL-L-23398D	Passed	Passed
Gleitmo 920	11336-01	No	No	Yes	MIL-PRF-46147C	Passed	Passed
Gleitmo 940	11337-01	No	No	Yes	MIL-PRF-46010F	Failed	Passed
Gleitmo SFL 9560	11326-01	No	No	No	MIL-PRF-46010F	Failed	Failed

Table 12: Results survey

Appendix 4: Questionnaires - Use of Solid Film Lubricants and Falex Pin & Vee Block Machine

Questionnaire to Military / NASA about the Use of Solid Film Lubricants

1. Does the U.S. Navy / U.S. Air Force / NASA use solid film lubricants according to MIL-PRF-46010 or MIL-PRF-46147?

2. In which systems are these solid film lubricants in use? What are the components in the systems these are used in? If available, what are the load conditions of these components?

3. Which application / conditions led you to set up the special Falex[1] limit requirements in the specifications you are responsible for? (Navy only)

4. Do you know of any environmentally acceptable solid film lubricants (i.e., without graphite, lead and antimony) with high (heat cured >400 min., air cured >60 min.) Falex endurance life (Please product name / brand and manufacturer)?

5. At this time it seems that lower values in Falex Endurance Life or Load Carrying Capacity are required for environmentally acceptable solid film lubricants. Do you know of any application / component that requires / justifies the existing Falex values in solid film lubricant specifications, which will prevent lowering of the limits to accommodate environmentally friendlier products?

Questionnaire to SAE about the Use of Solid Film Lubricants

1. Do you know companies using solid film lubricants according to MIL-PRF-46010 or MIL-PRF-46147? If yes, please provide company name.

2. If yes to 1 above, Do you know the application or components the lubricants are being used in? If yes, provide name of component / application.

3. Which application / conditions led you to set up the special Falex limit requirements in the specifications you are responsible for?

4. Do you know of any environmentally acceptable solid film lubricants (i.e., without graphite, lead and / or antimony) with high (heat cured >400 min., air cured >60 min.) Falex endurance life (Please provide product name/brand and manufacturer)?

5. At this time it seems that lower values in Falex Endurance Life or Load Carrying Capacity are required for environmentally acceptable solid film lubricants. Do you know of any application / component that requires / jus-

tifies the existing Falex values in solid film lubricant specifications, which will prevent lowering of the limits to accommodate environmentally friendlier products?

Questionnaire to ASTM & FALEX Corp.

About the Use of FALEX Pin & Vee Block concerning Solid Film Lubricant Testing

1. What was the reason to develop the FALEX Pin & Vee Block? What was the test originally intended for?

2. What are the guidelines to correlate the test results with the applications in the field (solid film lubricant testing)?

3. Are research reports available, which deal with the correlation of test results and applications in the field?

4. Which application / conditions led to set up the special Falex limit requirements for load carrying capacity and endurance life in several SFL specifications[2]?

[1] Falex: Endurance Life and Load Carrying Capacity according ASTM D2625
[2] SAE AS1701C, Class I & II / SAE AS5272, Type I & II

Appendix 5: Questionnaire - Requirements of a Tribological System to Solid Film Lubricants

QUESTIONNAIRE
TO EVALUATE THE REQUIREMENTS OF A TRIBOLOGICAL SYSTEM TO SOLID FILM LUBRICANTS

1
- Organization .....
- POC (name / phone) .....

2
- Weapon system / equipment .....
- NSN number, manufacturer .....

3 Technical description of the tribological system
- Purpose .....
- Functional characteristics .....
  - What is the component / part? .....
  - What is the objective or problem? .....
  - Material and hardness of the mating parts? .....
- Technical drawing or geometry of mating parts .....
  .....

4 Lubricant
- Used solid film lubricant .....
- NSN number .....
- Specification .....

5 Operating conditions

5.1 Load and motion
- What is the surface load? .....
  - Constant or alternating? .....
- What type of motion is occurring? .....
  - Sliding .....
  - Rolling .....
  - Vibration .....
  - Other .....
- Speed .....
  - RPM or Sliding speed .....
  - Constant or alternating? .....

5.2 Temperature
- Operating temperature – component surface .....
- Ambient lowest temperature .....
- Highest surface/component temperature .....
- Are there material curing restrictions? .....

5.3 Environmental conditions
- Humidity .....
- Contamination by chemicals? Which? .....
- Are there dielectric concerns? .....
- Is corrosion protection required? .....
- Radiation .....
- Vacuum .....

6 Application
- Pretreatment before applying the coating .....
- Way of applying the coating .....
  - Spraying .....
  - Dipping .....
  - Brushing .....

7 Maintenance
- Maintenance rate .....

13800

OPSEC REVIEW CERTIFICATION

(AR 530-1, Operations Security)

I am aware that there is foreign intelligence interest in open source publications. I have sufficient technical expertise in the subject matter of this paper to make a determination that the net benefit of this public release outweighs any potential damage.

Reviewer: Luis A. Villahermosa GS-14 Team Leader FLTT
Name Grade Title

Luis A. Villahermosa 7/18/01
Signature Date

Description of Information Reviewed: #13800

Title: Tech Report - Investigation to Remove Lead & Antimony from Solid Film Lubricants

Author/Originator(s): Steffen Schneider

Publication/Presentation/Release Date: July 2001

Purpose of Release: Completion of Investigation

An abstract, summary, or copy of the information reviewed is available for review.

Reviewer's Determination (circle one):

(1.) Unclassified Unlimited.

2. Unclassified Limited, Dissemination Restrictions IAW _____.

3. Classified. Cannot be released, and requires classification and control at the level of _____.

Security Office (AMSTA-CS-S):

(Concur)/Nonconcur Signature 25 Jul 01
Date

Public Affairs Office (AMSTA-CS-CT):

(Concur)/Nonconcur Margaret Compton July 25, 2001
Signature Date