



Cedarville University  
**DigitalCommons@Cedarville**

Science and Mathematics Faculty Publications

Department of Science and Mathematics

1999

# The Effect of Stress and TiC Coated Balls on Lubricant Lifetimes Using a Vacuum Ball-on-Pleate Rolling Contact Tribometer

William R. Jones

Mark J. Jansen

Larry S. Helmick  
*Cedarville University*, [helmickl@cedarville.edu](mailto:helmickl@cedarville.edu)

QuynGiao Nguyen

Donald R. Wheeler

*See next page for additional authors*

Follow this and additional works at: [http://digitalcommons.cedarville.edu/science\\_and\\_mathematics\\_publications](http://digitalcommons.cedarville.edu/science_and_mathematics_publications)

 Part of the [Mechanical Engineering Commons](#)

## Recommended Citation

Helmick, L. S. (1999). The Effect of Stress and TiC Coated Balls on Lubricant Lifetimes Using a Vacuum Ball-on-Pleate Rolling Contact Tribometer. *NASA Technical Memorandum* (209055).

This Technical Memorandum is brought to you for free and open access by DigitalCommons@Cedarville, a service of the Centennial Library. It has been accepted for inclusion in Science and Mathematics Faculty Publications by an authorized administrator of DigitalCommons@Cedarville. For more information, please contact [digitalcommons@cedarville.edu](mailto:digitalcommons@cedarville.edu).



---

**Authors**

William R. Jones, Mark J. Jansen, Larry S. Helmick, QuynGiao Nguyen, Donald R. Wheeler, and Han J. Boving



# The Effect of Stress and TiC Coated Balls on Lubricant Lifetimes Using a Vacuum Ball-on-Plate Rolling Contact Tribometer

William R. Jones, Jr.  
Glenn Research Center, Cleveland, Ohio

Mark J. Jansen  
AYT Corporation, Brook Park, Ohio

Larry H. Helmick  
Cedarville College, Cedarville, Ohio

QuynhGiao Nguyen  
AYT Corporation, Brook Park, Ohio

Donald R. Wheeler  
Glenn Research Center, Cleveland, Ohio

Hans J. Boving  
CSEM Centre Suisse d'Electronique et de Microtechnique SA, Neuchatel, Switzerland

Prepared for the  
33rd Aerospace Mechanisms Symposium  
sponsored by the National Aeronautics and Space Administration and Lockheed Martin  
Pasadena, California, May 19–21, 1999

National Aeronautics and  
Space Administration

Glenn Research Center

## Acknowledgments

The authors would like to acknowledge the contribution of Stephen Pepper of the GRC Tribology and Surface Science Branch for providing the contact severity calculations.

This report is a preprint of a paper intended for presentation at a conference. Because of changes that may be made before formal publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

Available from

NASA Center for Aerospace Information  
7121 Standard Drive  
Hanover, MD 21076  
Price Code: A03

National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22100  
Price Code: A03

# **The Effect of Stress and TiC Coated Balls on Lubricant Lifetimes Using a Vacuum Ball-on-Plate Rolling Contact Tribometer**

William R. Jones, Jr.  
National Aeronautics and Space Administration  
Glenn Research Center  
Cleveland, Ohio

Mark J. Jansen  
AYT Corporation  
Brook Park, Ohio

Larry H. Helmick  
Cedarville College  
Cedarville, Ohio

QuynhGiao Nguyen  
AYT Corporation  
Brook Park, Ohio

Donald R. Wheeler  
National Aeronautics and Space Administration  
Glenn Research Center  
Cleveland, Ohio

Hans J. Boving  
CSEM Centre Suisse d'Electronique et de Microtechnique SA  
Neuchatel, Switzerland

## **ABSTRACT**

A vacuum ball-on-plate rolling contact tribometer was used to determine the relative lifetimes of a perfluoropolyether (Krytox 143 AC) on 440C stainless steel. The effect of mean Hertzian stresses (0.75, 1.0, 1.5 and 2.0 GPa) and the use of TiC coated balls on lubricant lifetime was studied. Other conditions included: ~100 rpm, ~50  $\mu\text{g}$  of lubricant, an initial vacuum level of  $< 1.0 \times 10^{-8}$  Torr, and room temperature (~23°C). Increasing the mean Hertzian stress from 0.75 to 2.0 GPa results in an exponential decrease in lubricant lifetime for both material combinations. However, substituting a TiC ball for the 440C ball quadrupled lifetime at low stress levels (0.75 and 1.0 GPa) and doubled life at higher stresses (1.5 and 2.0 GPa). The reduced reactivity of the TiC surface with the PFPE lubricant is considered to be the reason for this enhancement. Decreasing lifetime with increasing stress levels correlated well with energy dissipation calculations.

## INTRODUCTION

The materials revolution from improved steels to new-generation, advanced materials, such as technical ceramics or wear resistant, low friction coatings, made its introduction into ball bearing technology several years ago. Today, much has been published on the properties and advantages of hybrid bearings (steel races and ceramic - essentially  $\text{Si}_3\text{N}_4$  - balls), used on a regular basis in machine tool applications. Pseudo-hybrid bearings (steel races and ceramic coated - essentially TiC-steel - balls) are state-of-the-art today in many aerospace applications; e.g. inertial navigation instruments and space mechanisms. The properties of TiC balls (Ref. 1 to 3) and their performance in rolling contacts have been reported (Ref. 4, 5).

TiC balls have important features, which make them a favorable compromise to conventional and hybrid bearings. TiC balls have the same bulk properties as steel balls (i.e. elasticity, thermal expansion, and density) and therefore do not influence the bearing load capacity and stiffness. In addition, solid preloaded pseudo-hybrid bearings allow more thermal excursions than hybrid bearings. TiC balls have similar surface properties as ceramic balls (i.e. chemical inertness, hardness, low friction, wear resistance, and smoothness) and therefore do influence the surface-lubricant reactions during asperity collisions (Ref. 6).

Because of the improved surface roughness of TiC balls, less asperity interactions occur. When interactions do occur, there is a strongly decreased tendency for micro-welding, accompanied by negligible material transfer and surface roughening. The raceway surface deterioration in a pseudo-hybrid bearing was found to be much smaller than for conventional, all-steel bearings (Ref. 7).

Initially, TiC balls were developed to operate in bearings for space mechanisms without lubrication. Although some of these dry bearings are still used in space, the great majority of applications utilize conventional liquid lubricants and greases. For example, the GOES weather satellite program uses TiC balls for all of their Krytox lubricated bearings.

Krytox represents a series of polymeric perfluoropolyethers (PFPEs) manufactured by DuPont (Ref. 8). All unformulated PFPEs function in a corrosive wear mode during mixed or boundary lubrication (Ref. 9). This wear mode, which results in the formation of surface fluorides, allows lubricated contacts to survive without catastrophic failure. However, these surface fluorides accelerate the destruction of the PFPE, eventually resulting in contact failure as the lubricant is totally consumed. It has been shown by Carré (Ref. 10) that the substitution of solid ceramic balls (silicon nitride) or TiN coatings can extend the performance of PFPEs by a factor of 5 to 10 times. This same study showed a decrease in bearing lifetime with increasing Hertzian stress.

The objective of this work was twofold. First, the effect of a wide range of mean Hertzian stress (0.75, 1.0, 1.5, and 2.0 GPa) on lubricant lifetime of a perfluoropolyether (Krytox 143 AC) on 440C steel was studied using a vacuum ball-on-plate rolling contact tribometer. Secondly, the effect of substituting a TiC ball under the same conditions was determined. Other conditions included: ~100 rpm, ~50  $\mu\text{g}$  of lubricant, room temperature (~23 °C), and an initial vacuum of  $< 1.0 \times 10^{-8}$  Torr.

## EXPERIMENTAL

The NASA Ball on Plate rolling contact tribometer (BoP) was used for all tests. This device (Figure 1) is essentially a thrust bearing using a single bearing ball and two flat races having contact stresses and ball motions similar to those in an angular contact ball bearing. This tribometer is fully described in Reference 11. Other details appear in References 12 and 13. Balls and plates are cleaned with a series of solvents and a final cleaning using UV-ozone. The ball is then lubricated with approximately 50 micrograms of Krytox 143 AC. This is accomplished by placing droplets of a Freon 113 solution of Krytox on a rotating ball. As the solvent evaporates, a Krytox film is deposited. The final lubricant charge is determined by weighing the ball before and after deposition using a sensitive microgram balance. The plates are unlubricated. The ball is placed between the plates and loaded to the desired stress. When the pressure level reaches  $1 \times 10^{-8}$  Torr, the test is automatically started. As the upper plate rotates (100 rpm), the ball is driven in a spiral orbit. At this speed, the system operates in the boundary lubrication regime. A force transducer in the mounting arm of the guide plate (Figure 1) measures the force required to force the ball back to the starting point of the original orbit. As the lubricant is consumed during the rolling process, this force increases until at some predetermined friction coefficient (0.75 for these tests), the test is automatically terminated. A typical coefficient of friction as a function of test time appears in Figure 2. In addition, other parameters (contact resistance and system pressure) are monitored during the test. An example of system pressure as a function of test duration for the test from Figure 2 appears in Figure 3.

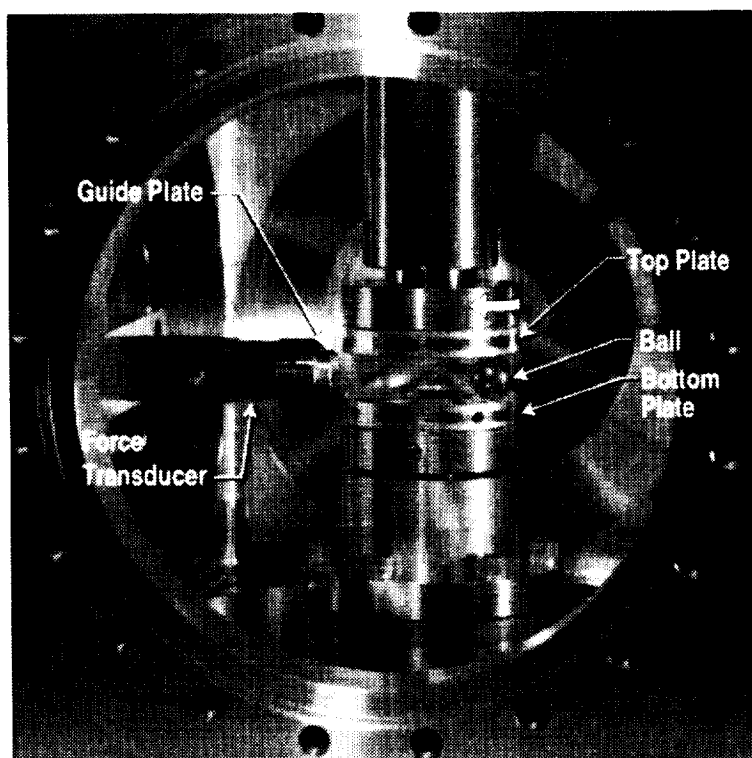
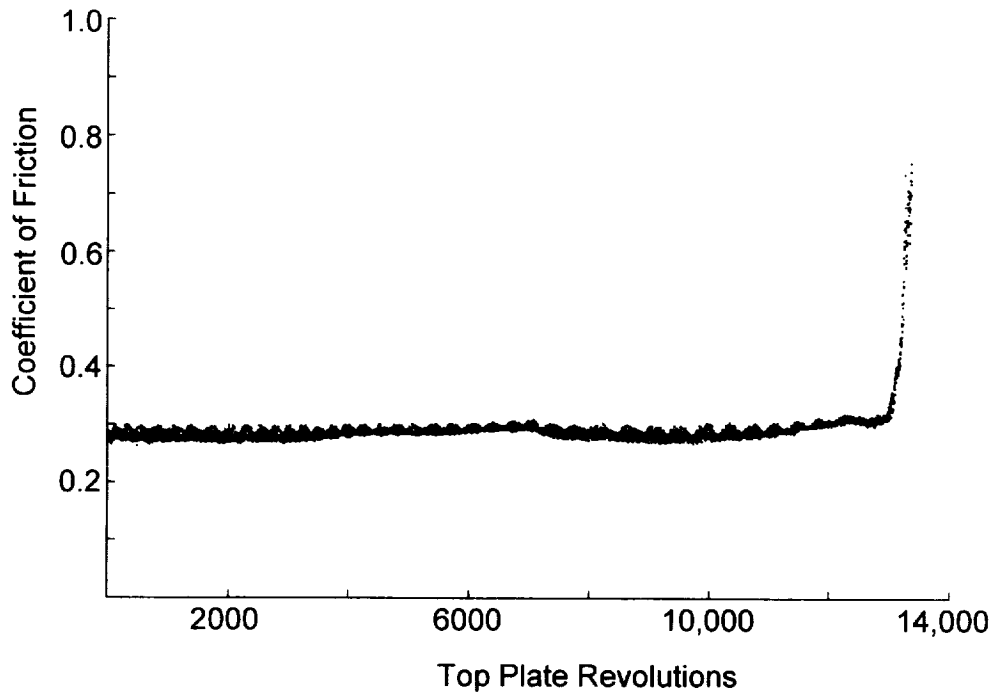
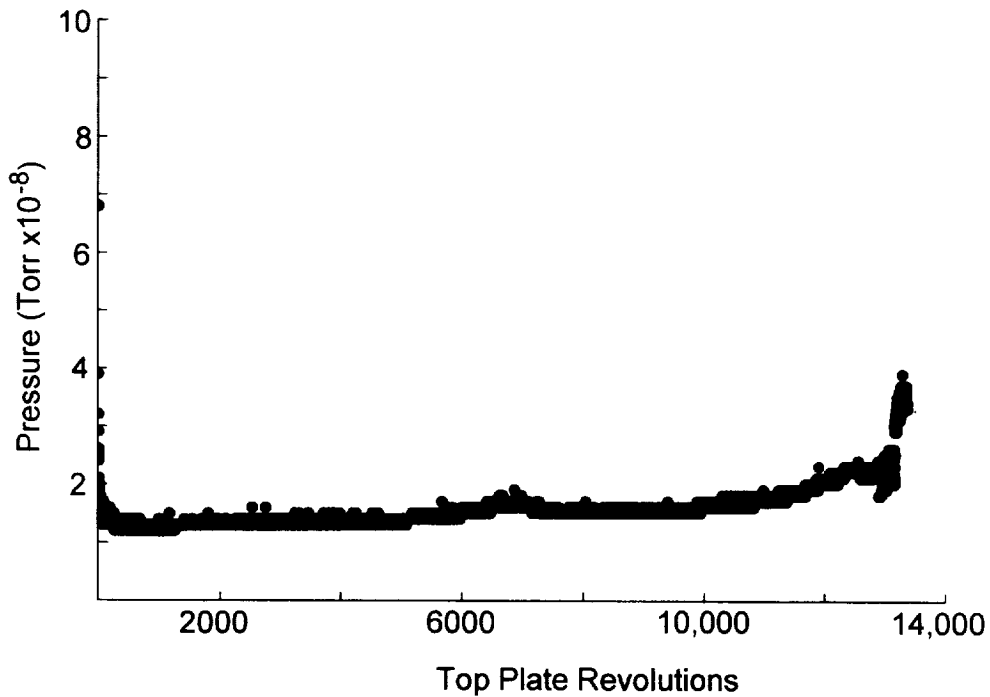


Figure 1. Ball on Plate (BOP) Tribometer



**Figure 2. Typical friction trace as a function of top plate revolutions for a BoP test (1.5 GPa, TiC Ball)**



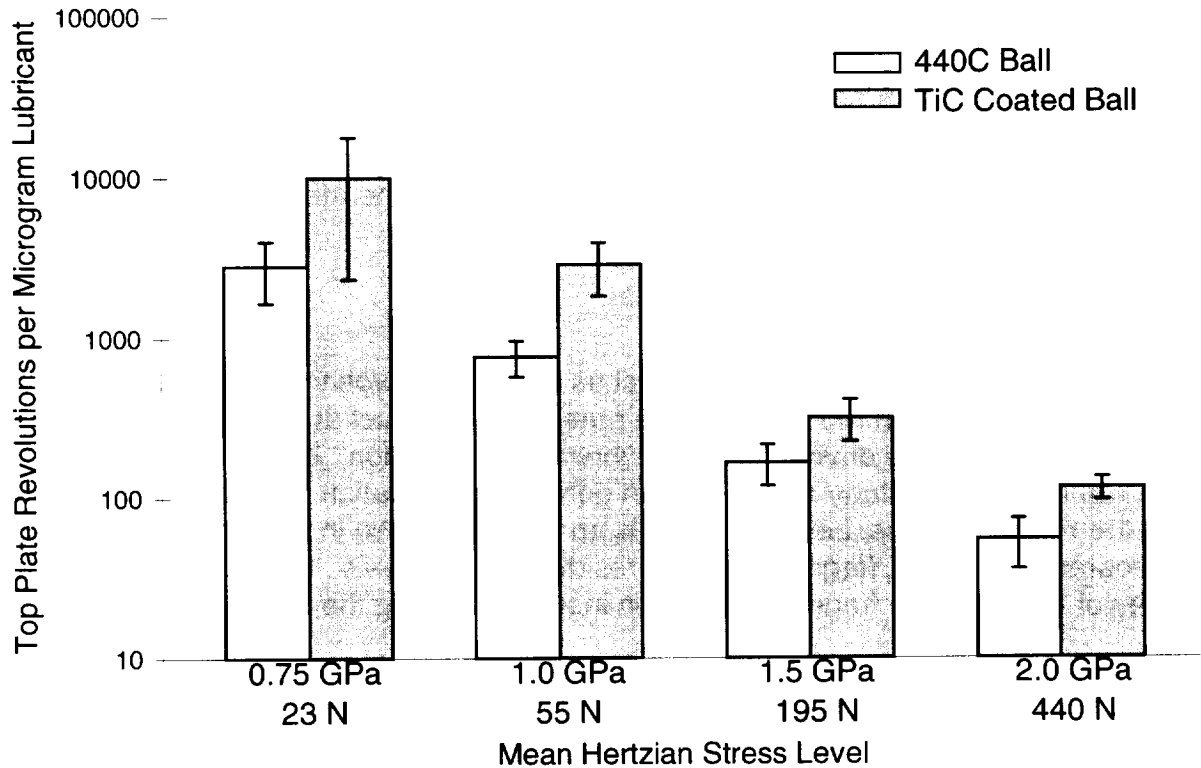
**Figure 3. Typical pressure data as a function of top plate revolutions for a BoP test (1.5 GPa, TiC Ball)**



## RESULTS

### Lubricant Lifetimes

The effect of mean Hertzian contact stress on lubricant lifetime is shown in Figure 4. Each condition represents from four to eight tests, except for the 2.0 GPa TiC condition that was only run twice. Normalized lubricant lifetime as the number of top plate revolutions per microgram of lubricant is plotted for four different mean stress levels (0.75, 1.0, 1.5, and 2.0 GPa). In addition, data for TiC balls under the same conditions is shown. A decrease in lubricant lifetime that is apparently exponential as a function of contact stress is evident for both material combinations. However, it is also clear that the substitution of a TiC ball enhances lubricant lifetime at all conditions. Life is quadrupled at 0.75 and 1.0 GPa and doubled at 1.5 and 2.0 GPa.



**Figure 4. Effect of Hertzian stress on lubricant lifetimes using 440C and TiC coated bearing balls**

## Surface Chemical Analysis

Several balls from selected tests were analyzed at test conclusion with X-ray photoelectron spectroscopy (XPS) and  $\mu$ -Fourier Transform Infrared Spectroscopy ( $\mu$ -FTIR). In addition, a 440C ball run to 4,400 cycles at 1.5 GPa (~half-life) was also analyzed. Minimal amount of metallic fluoride is seen on the half-life test. In contrast, a large amount of metallic fluoride is evident on the specimen run to test conclusion. Surface fluoride was evident on all balls run to test conclusion. However, the amount of fluoride was quite variable. There was no correlation with stress level.

## **DISCUSSION**

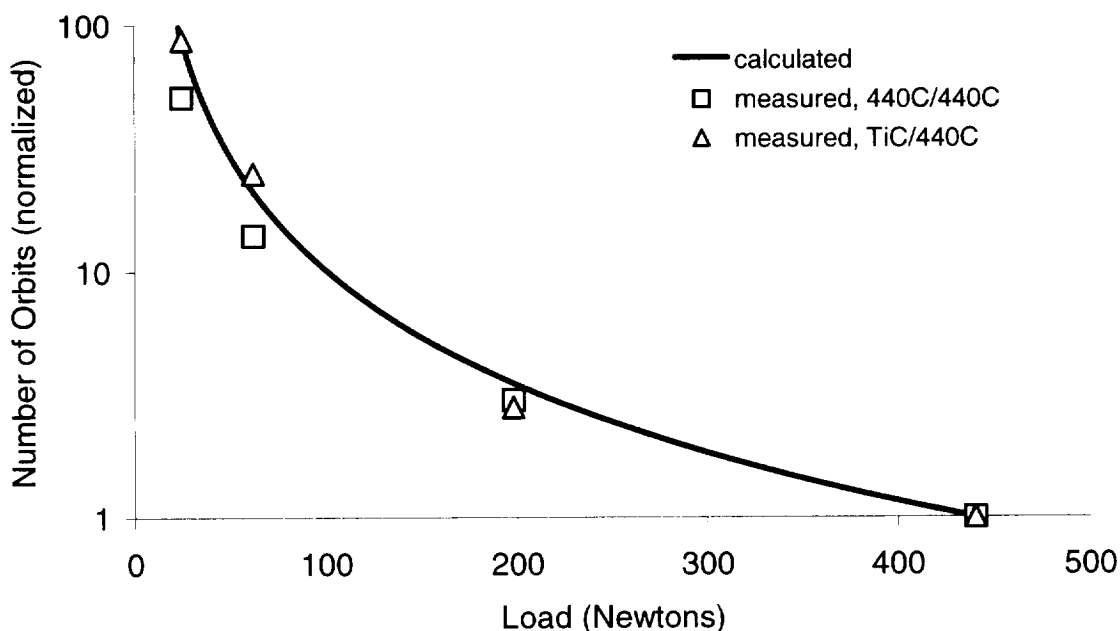
The Hertzian contact region in a rolling element bearing is essentially a microchemical reactor. In this high pressure region, the lubricant can undergo chemical reactions due to the asperity interactions and catalytic effects of the surfaces. For PFPE lubricants, these reactions include: chain scission, cross linking, unzipping, defluorination, and eventual conversion into a graphitic amorphous carbon (Ref. 14).

In the ball-on-plate tribometer, most of the orbit represents the normal rolling with pivot (Ref. 15) that is seen in instrument bearings. When the spiraling ball contacts the guide plate, it is forced back into the original (smaller radius) orbit. During this process, termed the scrub, pure sliding takes place between the ball and upper plate. The distance of the scrub is typically about 4 mm. The force generated during the scrub allows the coefficient of friction to be determined.

### Energy Dissipation

Energy is dissipated in the Hertzian contact as a result of pivoting during the rolling portion of the orbit and in the scrub, at the pure sliding contact at the upper plate. This energy dissipation is the driving force for lubricant degradation. It is obvious that for the Krytox lubricant of this study and PFPEs in general, degradation is initiated immediately during the rolling process, because there is an immediate rise in system pressure and an appearance of PFPE fragments in the residual gas analysis. In addition, the intensity of fluorocarbon fragment emission increases during the scrub.

A detailed analysis of energy loss during rolling/sliding in a 3 ball system appears in Reference 11. The same analysis can be applied to the present one ball operation. The total energy dissipation per unit time is termed "severity". The severity can be integrated over the time of a complete orbit. Since the lubricant is only on the ball (at least initially), the fraction of the ball's surface rolled upon per orbit must also be considered. Then, assuming that lubricant lifetime is inversely proportional to the energy dissipated during an orbit, one can calculate a relative lifetime at different stresses. This data, plotted as a function of load, appears in Figure 5. All lifetime data is normalized to the highest load. Experimental data for relative lifetimes for both 440C and TiC appear, as well. There is good agreement between the calculated and experimental results. Thus, the load dependence on lubricant lifetime may be understood on the basis of lubricant degradation by frictional energy dissipation at the ball/plate contacts.



**Figure 5. Relative lifetime of Krytox 143AC as a function of load in the BoP Tribometer**

### Rate of Lubricant Degradation

As stated earlier, lubricant degradation commences immediately as the ball starts to roll and increases by an order of magnitude during the scrub. By studying the friction force and pressure curves during a test, it appears that this degradation is relatively constant until late into the test. For Krytox, there is a rise in system pressure at about 80 to 90% of life followed by an abrupt increase in friction, which results in test termination.  $\mu$ -FTIR analysis of the balls indicates very little lubricant remaining and what is left is severely degraded. XPS analysis indicates the formation of metallic surface fluoride.

Zehe and Faut (Ref. 16) have shown that reactions of a linear PFPE fluid and iron oxide powder involves a two stage process. The first stage is the slow catalytic decomposition of the PFPE, which generates highly reactive fluorocarbon species, which attack and eventually convert the oxide to fluoride. The second stage involves the rapid degradation of the PFPE by the much more catalytic iron fluoride. This appears to be the process involved here.

## TiC versus 440C

Shogrin et al (Ref. 17) performed ball on disc pure sliding experiments with 440C specimens implanted with various species (disc only) and lubricated with Krytox 143 AC. Lubricated lifetimes were enhanced by implantation with either Ti or a combination of Ti + C. It was postulated that these implanted species produced a passivating layer that reduced the catalytic degradation of the Krytox lubricant, thus increasing lifetime. The life enhancement using TiC balls in the current study is considered to be a similar phenomenon.

### CONCLUSIONS

1. For space bearing applications where perfluoropolyether lubricants (such as Krytox) are chosen, the use of TiC balls is beneficial.
2. The lifetimes of perfluoropolyether lubricants used for long term space applications will be adversely affected at high Hertzian contact stresses.
3. The life enhancement gained by using TiC instead of 440C steel balls decreases with increasing stress level.
4. Relative lubricant lifetime can be correlated with the severity of energy dissipation in the rolling/sliding contacts.

### REFERENCES

1. Boving, H. J. and Hintermann, H. E., "Properties and Performance of CVD TiC-coated Ball Bearing Components", *Thin Solid Films*, **153**, pp 253-266 (1987).
2. Hanson, R. H., "The Adhesion and Deformation Properties of CVD TiC Coated Bearing Balls under Heavy Load", *MRS Symp. Proc.*, **140**, pp 477-482 (1989).
3. Wong, S. and Cababe, H., "Analysis of TiC Coated Balls ", *Proc. Inter. Rolling Element Bearing Symp.*, DoD, REBG, Orlando, FL, April 28-30 (1997).
4. McKee, F. B., "Silicon Nitride and TiC coated Balls in Heavily Loaded Oscillating Bearings", *Proc. Bearing Symp.*, DoD, RBWG, Orlando, FL, April 8-12 (1991).
5. Walker, R. W., Boving, H. J., Price, R. and Kingsbury, E. P., "Ceramic Coatings as Wear Inhibitors in Slow-Rolling Contact", *Proc. ICMCTF*, San Diego, CA, April 19-23 (1993).
6. Gill, S., Price, W. B., Rowntree, R. A., Boving, H. J. and Hintermann, H. E., "In-Vacuum Performance of Fomblin Z25-Lubricated 52100 Steel Bearings with TiC-Coated Balls", *Proc. Fifth European Space Mech. And Tribology Symp.*, ESA SP-334, April (1993).
7. Boving, H. J., Fluehmann, F., Schaible, F. and Kleinbard, M., "TiC and Steel Ball Wear Evaluations and Comparisons", *Proc. Inter. Rolling Element Bearing Symp.*, REBG, Orlando, FL, April 28-30 (1997).
8. Gumprecht, W. H., "PR-143-A New Class of High-Temperature Fluids", *ASLE Trans.*, **9**, pp 24-30 (1966).
9. Jones, W. R., Jr., "Properties of Perfluoropolyethers for Space Applications", *STLE Trans.*, **38**, pp 557-564 (1995).

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

<b>1. AGENCY USE ONLY</b> (Leave blank)		<b>2. REPORT DATE</b> March 1999	<b>3. REPORT TYPE AND DATES COVERED</b> Technical Memorandum	
<b>4. TITLE AND SUBTITLE</b> The Effect of Stress and TiC Coated Balls on Lubricant Lifetimes Using a Vacuum Ball-on-Plate Rolling Contact Tribometer			<b>5. FUNDING NUMBERS</b>  WU-615-63-00-00	
<b>6. AUTHOR(S)</b> William R. Jones, Jr., Mark J. Jansen, Larry H. Helmick, QuynhGiao Nguyen, Donald R. Wheeler and Hans J. Boving				
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  E-11591	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> National Aeronautics and Space Administration Washington, DC 20546-0001			<b>10. SPONSORING/MONITORING AGENCY REPORT NUMBER</b>  NASA TM-1999-209055	
<b>11. SUPPLEMENTARY NOTES</b> Prepared for the 33rd Aerospace Mechanisms Symposium sponsored by the National Aeronautics and Space Administration and Lockheed Martin, Pasadena, California, May 19-21, 1999. William R. Jones, Jr. and Donald R. Wheeler, Glenn Research Center; Mark J. Jansen and QuynhGiao Nguyen, AYT Corporation, Brook Park, Ohio; Larry J. Helmick, Cedarville College, Cedarville, Ohio; Hans J. Boving, Centre Suisse d'Electronique et de Microtechnique SA, Neuchatel, Switzerland. Responsible person, William R. Jones, Jr., organization code 5140, (216) 433-6051.				
<b>12a. DISTRIBUTION/AVAILABILITY STATEMENT</b>  Unclassified - Unlimited Subject Category: 27  This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.			<b>12b. DISTRIBUTION CODE</b>	
<b>13. ABSTRACT (Maximum 200 words)</b> A vacuum ball-on-plate rolling contact tribometer was used to determine the relative lifetimes of a perfluoropolyether (Krytox 143 AC) on 440C stainless steel. The effect of mean Hertzian stresses (0.75, 1.0, 1.5 and 2.0 GPa) and the use of TiC coated balls on lubricant lifetime was studied. Other conditions included: ~100 rpm, ~50 µg of lubricant, an initial vacuum level of < 1.0 x 10 <sup>-8</sup> Torr, and room temperature (~23°C). Increasing the mean Hertzian stress from 0.75 to 2.0 GPa results in an exponential decrease in lubricant lifetime for both material combinations. However, substituting a TiC ball for the 440C ball quadrupled lifetime at low stress levels (0.75 and 1.0 GPa) and doubled life at higher stresses (1.5 and 2.0 GPa). The reduced reactivity of the TiC surface with the PFPE lubricant is considered to be the reason for this enhancement. Decreasing lifetime with increasing stress levels correlated well with energy dissipation calculations.				
<b>14. SUBJECT TERMS</b>  Tribology; Space lubricants			<b>15. NUMBER OF PAGES</b> 15	
			<b>16. PRICE CODE</b> A03	
<b>17. SECURITY CLASSIFICATION OF REPORT</b> Unclassified	<b>18. SECURITY CLASSIFICATION OF THIS PAGE</b> Unclassified	<b>19. SECURITY CLASSIFICATION OF ABSTRACT</b> Unclassified	<b>20. LIMITATION OF ABSTRACT</b>	

10. Carré, D. J., "The Use of Solid Ceramic and Ceramic Hard-Coated Components to Prolong the Performance of Perfluoropolyalkylether Lubricants", *Surface and Coating Tech.*, **43/44**, pp 609-617 (1990).
11. Pepper, S. V., Kingsbury, E. and Ebihara, B. T., "A Rolling Element Tribometer for the Study of Liquid Lubricants in Vacuum", NASA TP 3629, October 1996.
12. Kingsbury, E., "Evaluation of the NASA Ball on Plate Tribometer as an Angular Contact Ball Bearing", *Proc. Inter. Rolling Element Bearing Symp.*, REBG, Orlando, FL, April 28-30 (1997).
13. Pepper, S. V. and Kingsbury, E., "Destruction of Fomblin Z-25 by Different Bearing Metals", *Proc. Inter. Rolling Element Bearing Symp.*, REBG, Orlando, FL, April 28-30 (1997).
14. Herrera-Fierro, P., Shogrin, B. and Jones, W. R., Jr., "Spectroscopic Analysis of Perfluoropolyether Lubricant During Boundary Lubrication", NASA TM 107299, Sept. 1996.
15. Kingsbury, E., "Pivoting and Slip in an Angular Contact Bearing", *ASLE Trans.*, **27**, pp 259-262 (1984).
16. Zehe, M. J. and Faut, O. D., "Acidic Attack of Perfluorinated Alkyl Ether Lubricant Molecules by Metal Oxide Surfaces", *STLE Trans.*, **33**, p 634-640 (1990).
17. Shogrin, B., Jones, W. R., Jr., Wilbur, P. J., Herrera-Fierro, P. and Williamson, D. L., "The Effects of Ion Implantation on the Tribology of Perfluoropolyether Lubricated 440C Stainless Steel Couples", *Trib. Trans.* **39**, 3, pp 507-516 (1996).