

# Effect of Test Atmosphere on Moving Mechanical Assembly Test Performance

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## Abstract

Satellites and many of the moving mechanical assemblies (MMAs) on board operate under the low-pressure conditions of the orbital environment. In order to assess the lifetime performance of these devices, it is desirable to test them under the same conditions they will experience during mission operation. However, many times contractors test MMAs in a nitrogen gas environment at ~1 atm pressure, assuming the test results will be comparable to those obtained in a vacuum test due to the inertness of the nitrogen gas. We were concerned that impurities in nitrogen gas, such as oxygen even at  $\leq 1$ -ppm levels, would lead to different chemistry and rates of reaction compared to vacuum conditions, where the oxygen levels are lower by at least a factor of 1000. In order to test this hypothesis, we performed a set of experiments using our in-house, thrust-bearing wear-test facility with hydrocarbon oils containing an aryl phosphate ester additive mixture. We used a load that resulted in a Hertzian stress of 1.52 GPa, at the high end of typical ball-bearing stresses. We used test time to failure to assess performance differences. The wear tests lasted at least a factor of 5 times longer in nitrogen gas than in vacuum. Since the temperatures of the vacuum and nitrogen tests were matched, this implies that there are chemistry differences occurring at the metal surfaces. We conclude from our test results that nitrogen gas at ~1 atm pressure is not a realistic substitute for vacuum conditions for life testing of MMAs that will operate under orbital low-pressure conditions.

## Introduction

The external pressure in which interplanetary spacecraft and Earth satellites operate is typically  $< 1 \times 10^{-4}$  Pa. Many of the moving mechanical assemblies (MMAs) are vented to the external environment so that the external and internal MMA pressures are equilibrated. It is desirable to perform life tests of these MMAs under the low-pressure conditions in which they will operate [1]. However, due to budget constraints, contractors often test the MMAs in a near-ambient pressure, nitrogen gas environment. The assumption is that the relatively inert nitrogen gas will give results that are comparable to those obtained in a low-pressure (vacuum) environment. We have held the belief that there are differences in chemistry between the two environments, as well as obvious thermal differences due to the presence or absence of convection. For example, in nitrogen gas with an oxygen content of ~1 ppm, a low impurity level, there is approximately a thousand times more oxygen than there is in a low-pressure test at a pressure of  $1.3 \times 10^{-4}$  Pa. This could lead to significant differences in the rates of surface reactions, which could adversely affect performance and invalidate the results of the nitrogen gas testing. In addition, the source of the nitrogen gas could play a pronounced role. Blow-off gas from a liquid-nitrogen storage tank typically contains more oxygen than 1 ppm. The presence or absence of water in the nitrogen gas could also play a role in surface reactions. To our knowledge, prior to our work, no systematic tests that compare liquid-lubricated MMA performance in vacuum and nitrogen gas have been reported. There have been reports in the literature of standard tests of specific lubricants that show differences in test life between vacuum and nitrogen gas [2] and between dry air and nitrogen gas environments [3]. Also, studies have been reported that show that solid-lubricated MMAs perform significantly better in nitrogen gas than in vacuum [4,5].

Hydrocarbon oils used to lubricate MMAs in spacecraft typically contain anti-wear additives to reduce the wear of the interacting metal surfaces. In previous work, we have shown that the extreme pressure additive, lead naphthenate, disappeared quickly from the lubricant in ball bearings under vacuum conditions. We determined that this was due to chemical reactions on the surface of the metal parts [6].

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We then conducted a series of experiments under vacuum and nitrogen gas conditions using hydrocarbon oils with lead naphthenate additive under several load conditions (loads resulting in Hertzian stresses of 0.36, 0.97, and 1.52 Gpa) and speeds [7]. Under the highest load conditions, the nitrogen gas tests lasted at least 10x longer without failure than the vacuum tests, which failed. Under the lower loads, there were significant differences in additive chemistry in nitrogen gas relative to vacuum [7]. We were interested in whether aryl phosphate esters would show similar behavior since they are commonly used as anti-wear additives in spacecraft applications. We undertook a series of wear-test experiments to determine whether the performance of hydrocarbon oil, formulated with aryl phosphate ester additives, is different in nitrogen and vacuum environments under the same load and speed conditions as our previous experiments with lead naphthenate additive.

## Experimental

### Lubricant

Nye 2001, a trialkylated cyclopentane synthetic hydrocarbon oil with 2% Syn-O-Ad 8478 phosphate ester additive, was used in the experiments reported here. The oil was purchased from Nye Lubricants, and is used in current spacecraft systems.

### Testing

Wear testing was performed using our in-house, eccentric-bearing wear test facility, which has been previously described [8]. A thrust ball bearing in which one of the raceways can be replaced by a flat disk comprises the interacting component of the test fixture. The remaining raceway can be mounted slightly off the axis of rotation of the disk ("eccentric mode"), resulting in increased ball sliding on the disk surface and increasing the severity of the test conditions [8]. There was a ~17% sliding component in the ball motion for the tests reported herein. It is the sliding component that accelerates failure in these tests. Ball bearing temperature was measured using a thermocouple touching the bearing race.

The ball bearing raceways and balls, and the disks, were composed of 440C stainless steel. The thrust bearings have a raceway diameter of 2.29 cm and 12 balls of 0.476-cm diameter. The average raceway surface ( $R_A$ ) was  $\leq 0.25 \mu\text{m}$ , and the  $R_A$  of the disks was  $\sim 0.015 \mu\text{m}$ . The balls were ABEC grade 5, with an  $R_A$  of  $\sim 2 \mu\text{in}$  ( $\sim 50 \text{ nm}$ ). The ball retainer was the steel ribbon retainer furnished with the thrust ball bearing. The loads on the retainer were low, so that the tests would not be impacted by reactions involving the retainer surfaces.

The metal components were cleaned using Brulin 815GD detergent (diluted with  $\text{H}_2\text{O}$ ), rinsed in distilled  $\text{H}_2\text{O}$ , and rinsed in heptane before testing. The test speeds were chosen to fall within the speed range typical of MMAs, and the load was chosen to produce a Hertzian stress at the high end of the typical range in order to result in test failure in a reasonable test time.

External cooling was provided for the testing in vacuum to keep the ball-bearing temperature relatively low due to the lack of convective cooling. Cold water ( $20^\circ\text{C}$ ) was circulated through a heat sink in good thermal contact with the ball bearing housing. The temperature was measured using a thermocouple in contact with the outside of the raceway. The temperature was maintained at  $24^\circ\text{C}$ , similar to that of the nitrogen tests.

The tests were carried out in the eccentric mode with flat disk, either in vacuum (pressure less than  $1.3 \times 10^{-4} \text{ Pa}$ ) or gettered nitrogen gas. The speed was 1800 rpm, the Hertzian stress was 1.52 Gpa, and the lubricant quantity was  $10 \mu\text{L}$ . The tribological regime was expected to be mixed or boundary [8]. The test was considered to fail when the nominal running torque increased by a factor of 1.7. Failures in this test facility are abrupt, so that the arbitrary choice of the torque increasing by the 1.7 factor does not significantly affect the test results. The tests were either run to failure, or run until a reasonable time period had elapsed without failure occurring. Six tests were run in vacuum and four under nitrogen gas conditions.

## Results and Discussion

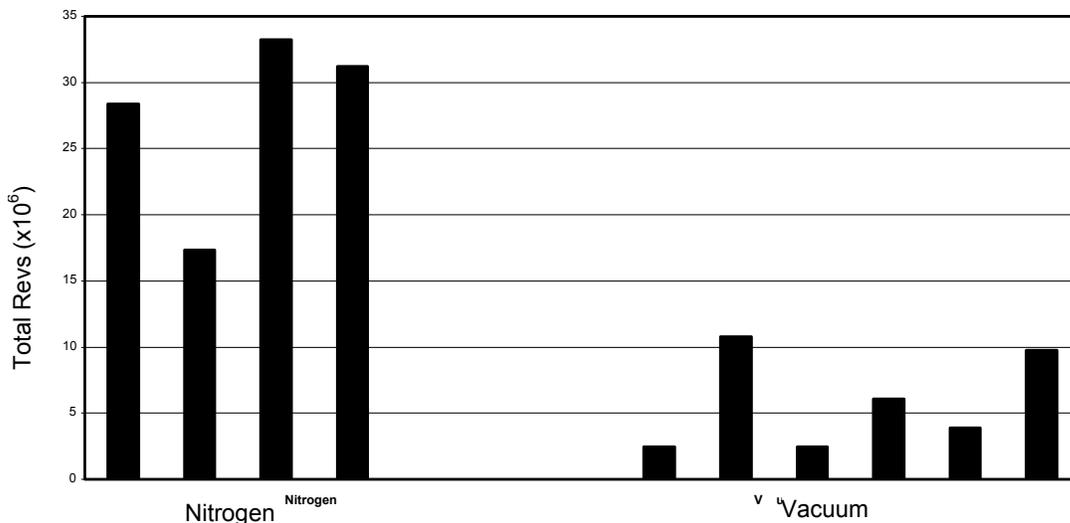
The results of the testing are given in Table 1 and illustrated in Figure 1. It is noteworthy that only one of the nitrogen gas tests failed ( $28.4 \times 10^6$  revs). The remaining three tests under nitrogen gas were stopped. We stopped one test at  $17.32 \times 10^6$  revs prematurely, compared to the other tests. If we do not include this result, the average duration for the other three tests is  $30.9 \pm 2.4 \times 10^6$  revs. Thus, we conclude that the nitrogen gas tests lasted at least a factor of 5 longer than the tests under vacuum conditions. This is similar to the results of our testing using lead naphthenate additive. Under essentially the same conditions, the lead naphthenate tests in nitrogen lasted at least a factor of 10 longer than the tests in vacuum [7]. In the case of lead naphthenate, we believe that the differences in wear life are related to the competition between oxygen and the additives for metal atom surface sites on the contacting metal parts. In nitrogen gas, the oxygen concentration is high enough that oxygen can compete with the additive for freshly exposed metal and passivate the surfaces. On the other hand, under vacuum, where the oxygen concentration is very low, the additive competes successfully for surface sites with which to react, its concentration in the oil is reduced at a higher rate than it is under nitrogen gas, and thicker Pb-containing films build up.

**Table 1. Wear Test Results**

Environment	Test Duration (revs x $10^6$ )	Ave. (revs x $10^6$ )	Failure (Y/N)
Nitrogen gas	28.4	27.5 $\pm$ 7.1* (or 30.9 $\pm$ 2.4**)	Y
	17.3		N
	33.2		N
	31.2		N
Vacuum	2.45	5.9 $\pm$ 3.6	Y
	10.79		Y
	2.45		Y
	6.08		Y
	3.92		Y
	9.76		Y

\*Including all tests.

\*\*Excluding test that was stopped prematurely at  $17.3 \times 10^6$  rev.



**Figure 1. Wear Test Results**

The mechanism of action of aryl phosphate ester additives is not completely understood. Aryl phosphate esters can react with oxidized iron and steel surfaces [9,10] at temperatures above  $100^\circ\text{C}$ , and pretreatment of bearing parts with phosphate additives at such temperatures, leaving phosphate-

containing films, is common. However, aryl phosphate esters can also react with iron metal [10,11], again leaving phosphate-containing films on the surface. The relative importance of these two reaction pathways in an operating bearing is unknown. If the reaction with iron metal is more important than reaction with oxide, there will be more reaction in vacuum than nitrogen gas since the additive will not have to compete with oxygen for metal sites. This would lead to relatively less additive in the oil, and more phosphate film on the surface than in nitrogen. If the reaction with metal oxides is more important, however, there will be more reaction in nitrogen gas than vacuum since the contaminant oxygen will prepare the exposed metal for reaction with the additive. This would lead to relatively less additive in the oil, and more phosphate film on the surface than in vacuum. The wear life itself cannot be used to distinguish between the two pathways since the test process is too complex for straightforward analysis. The tests are defined to fail at a particular increased level of torque. High torque could be due to adhesive wear due to metal on metal contact (i.e., ineffective additive function or exhaustion of additive in the oil), or to thick additive film buildup (over efficient additive function). The efficacy of the particular reaction product in extending life and the amount of additive present in the oil are also inextricably convoluted into the wear life. In future experiments, we intend to halt operation of bearings before failure, and analyze the oil and surfaces to discover the relative importance of the metal or oxide reaction pathways.

### Conclusions

The results of this study indicate that the tribological performance of MMAs lubricated with aryl phosphate ester-formulated oils will be different in vacuum and nitrogen at atmospheric pressure. Apparently, reaction between the additive and the metal surfaces of ball bearing parts is retarded in nitrogen gas compared to vacuum conditions. Thus, a nitrogen environment is not a conservative choice for life testing, despite the potential cost savings of avoiding vacuum testing. In addition, the present study involved specific conditions of sliding:rolling ratio, contact stress, and lubricant formulation; other conditions could show differences with respect to relative nitrogen/vacuum behavior, so the life extension factor of at least 5 in nitrogen cannot be used predictively for other tests. It is even possible that some systems could have better performance occurring during testing in vacuum. These uncertainties indicate that on-orbit performance would be difficult to predict from the results of our study. Therefore, we conclude that it is prudent to test an MMA under vacuum conditions when that is the environment to which the MMA will be subjected in the application.

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### References

1. Robbins, E. J., *Proc. 1<sup>st</sup> European Space Tribology Symposium, ESA SP-111, Italy, April 9-11, 1975*, p. 101.
2. John, P. J., J. N. Cutler, and J. H. Sanders, *Tribol. Lett.*, 9 (2000) 167.
3. Cutler, J. N., J. H. Sanders, J. S. Zabinski, P. J. John, J. R. McCutchen, L. S. Kastern, and K. G. Tan, *Tribol. Lett.*, 8 (2000) 17.
4. Gardos, M. N., *Tribol. Lett.*, 1 (1995) 67.
5. Fleischauer, P. D., S. V. Didziulis, and J. R. Lince, *Proceedings of the International Tribology Conference 2* (2000) p. 1109.
6. Carré, D. J., P. A. Bertrand, and J. R. Lince, *Boundary and Mixed Lubrication: Science and Applications*, Tribology Series, 40, D. Dowson, ed. (Elsevier, Amsterdam, 2000) p.147.
7. D. J. Carré, P. A. Bertrand, and J. R. Lince, "Lead naphthenate tribochemistry under vacuum and gaseous nitrogen test conditions," *Tribol. Lett.* 16(1), (2004) 207–214.
8. Kalogeras, C. G., M. R. Hilton, D. J. Carré, S. V. Didziulis, and P. D. Fleischauer, *Proc. 27<sup>th</sup> Aerospace Mechanisms Symposium, 12-14 May 1993*, NASA Conference Publication 3205, p. 197.
9. P. A. Bertrand, "Reactions of tricresyl phosphate with bearing materials," *Tribol. Lett.* 3, 367-377 (1997).

10. D. R. Wheeler and O. D. Faut, "The Adsorption and Thermal Decomposition of Tricresylphosphate (TCP) on Iron and Gold," *Appl. Surf. Sci.* 18, 106-122 (1984).
11. E. S. Forbes, N. T. Upsdell, and J. Battersby, "Current Thoughts on the Mechanism of Action of Tricresyl Phosphate as a Load-Carrying Additive," *Inst. Mech. Engrs. Tribology Convention Papers*, C64172 (1973).