



Effect of Ceramic Ball and Hybrid Stainless Steel Bearing/Wheel Combinations on the Lifetime of a Precision Translation Stage for the SIM Flight Project

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ABSTRACT

A study of hybrid material couples using the Spiral Orbit Tribometer (SOT) [1]-[3] was initiated to investigate both lubricated (Pennzane[®] X2000 and Brayco[™] 815Z) and unlubricated Si₃N₄, 440C SS, Rex 20, Cronidur X30 and X40 plates with Cerbec SN-101-C (Si₃N₄) and 440 C balls. The hybrid wheel/bearing assembly (Figure 2) will be used on the Linear Optical Delay Line (LODL) stage (Figure 1) as an element of the NASA Space Interferometry Mission (SIM). SIM is an orbiting interferometer linking a pair of telescopes within the spacecraft and, by using an interferometry technique and several precision optical stages, is able to measure the motions of known stars much better than current ground or space based system. This measurement will provide the data to “infer” the existence of any planets, undetectable by other methods, orbiting these known stars.

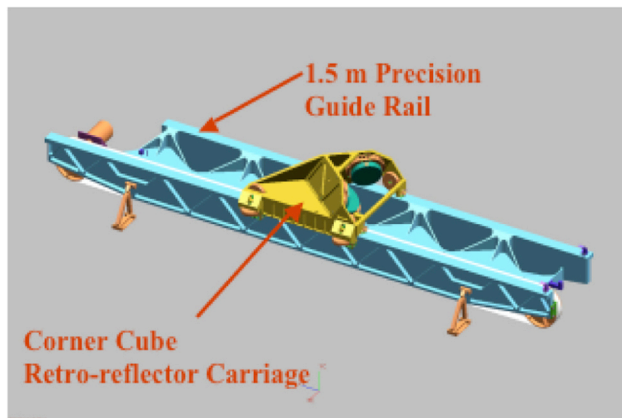


Figure 1 – Linear Optical Delay Line

The LODL is a motor driven, band drive rail system carrying a Corner Cube Retro-Reflector Carriage system running on a 1.54 m guide rail system as conceptualized. Three Integrated Hybrid Duplex Angular Contact Bearing Wheel Assemblies (Figure 2), running on the precision rail system, are used to locate the carriage system on the rail, with preload wheel assemblies opposite to these assemblies. The

requirement is a 5-year mission lifetime with a goal of 10 years total, using little or no lubricant in order to reduce contamination to the nearby optics. The SOT result indicates accelerated lubricant consumption rate between the ceramic ball and 440C SS and 52100 bearing steel, but promising trend with the newer Cronidur X30 and X40 bearing steel. The use of dry or no lubricant will require further investigation.

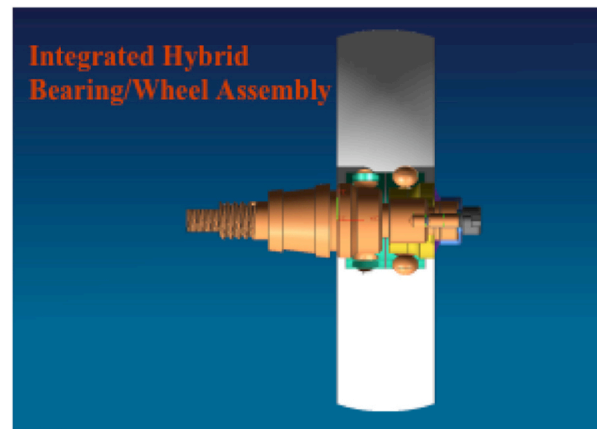


Figure 2 – Integrated Hybrid Bearing/Wheel

1. EXPERIMENTAL

A Spiral Orbit Tribometer (SOT) [1]-[3] (Figure 3) was used to study the lubricated lifetime of these material couples. In addition, friction coefficients and wear measurements (using profilometry) were studied for the unlubricated material combinations. The SOT measures lubricant consumption in the boundary lubrication regime. The tribometer simulates rolling and pivoting seen in angular contact bearings and other lubricated contacts. For unlubricated tests, because of the stick/slip action when the rolling ball strikes the guide plate, both force data and scrub lengths were used to calculate friction coefficients. In these tests, plates were either made of Si₃N₄, 440C SS, Rex 20, Cronidur X30 or X40. In all cases, a 12.7 mm (1/2”) Si₃N₄ ceramic bearing ball was used. Tests were performed with no lubricant, or either Pennzane X-2000 (containing only an antioxidant) or Brayco 815Z

dissolved in hexane or Freon and applied to the bearing balls, resulting in a deposition of approximately 50 μg of lubricant after solvent evaporation. Tests were run in ultrahigh vacuum ($< 10^{-6}$ Pa), room temperature, and ball speeds from 20 to 100 RPM. A normalized lubricant lifetime was determined by dividing the number of ball orbits at failure (friction coefficient of 0.28) by the amount of lubricant deposited on the ball. This yields a lifetime in orbits/ μg of lubricant. In addition, ball specimens were analyzed post-test by X-ray Photoelectron Spectroscopy (XPS).

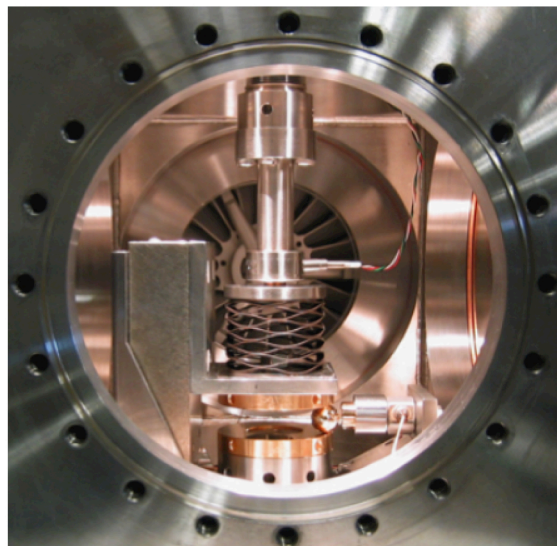


Figure 3 – The Spiral Orbit Tribometer

2. RESULTS AND DISCUSSIONS

2.1 Unlubricated Ceramic Ball/Ceramic Plate

Initial testing with an unlubricated silicon nitride ball on a silicon nitride plate yielded erratic behavior with the friction coefficient rising quickly after 20 orbits at 1.5 GPa as shown in Figure 4.

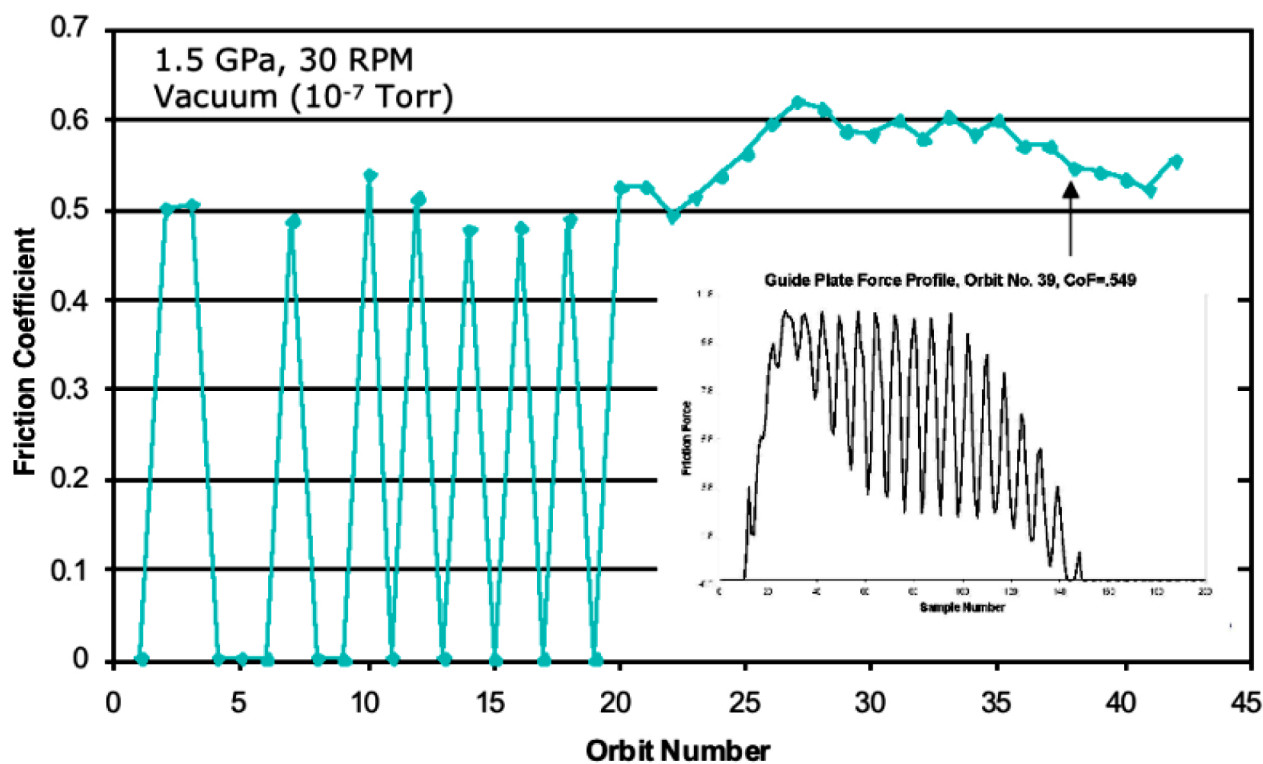


Figure 4 – Unlubricated Ceramic/Ceramic SOT Test

2.2 Unlubricated Ceramic Ball/Metal Plates

Subsequent unlubricated tests with silicon nitride balls and other candidate metallic plates at 30 RPM resulted in a higher number of orbits, with friction coefficients as high as 2.5 after 15K to 45K orbits, as indicated in Table 1.

Table 1 – Unlubricated Ceramic/Metal SOT Test

Plate Material	Mean Hertzian Stress (GPa)	Number of Orbits	Friction Coefficient Range
440C	0.80	15K	1.0-2.5
440C	0.80	30K	0.2-2.2
REX20	0.85	15K	1.1-2.3
X40	0.80	45K	0.2-1.6
X40	0.80	45K	0.2-1.6
X40	1.5	45K	0.4-1.1

A typical friction trace from an unlubricated test is illustrated below in Figure 5.

(Si₃N₄ Ball, 10⁻⁸ Torr, 30 RPM, X40/0.8 GPa Test)

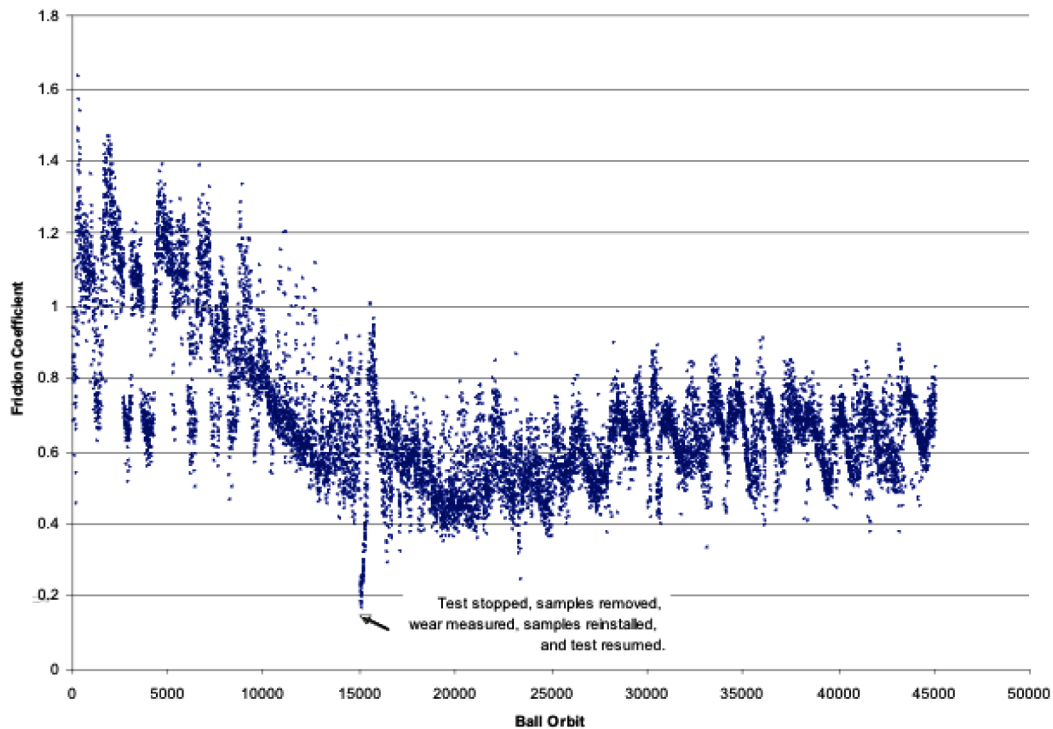


Figure 5 – Typical Unlubricated Ceramic/Metal Trace

2.3 Hybrid Wheel Design with Toroid Balls

With the higher than expected friction coefficients from the unlubricated SOT tests, it would be difficult to design a consistent wheel system with any of these unlubricated pairs. However, the SOT test is designed such that there is always a sliding action when the test ball contacts the vertical guide plate producing an area on the stationary plate called the scrub. This sliding action, between the extremely hard ceramic ball and the “softer” metallic plate will not be present in an actual bearing pair. Based on this, Cerobear designed

the first generation of SIM LODL test wheel, illustrated on Figure 2, with the most promising combination, X40 and Si₃N₄ balls. In addition, for the full 16 ball complement without a ball separator, a toroid ball concept was used, with every other ball having a slightly smaller diameter to act as a separator. The delivered wheel assembly, 3 months after completion of the SOT tests, ran smoothly without any lubrication. However, at that time, SIM was directed by NASA to stand down and the planned drive wheel life test was cancelled.

2.4 Lubricated Ceramic Ball/Metal Plates

While the wheel was being manufactured at Cerobear, a set of lubricated SOT tests with ceramic balls and metallic plates was completed, with emphasis on Pennzane X2000 and some reference tests with Brayco 815Z. This is much less than the desired 4 tests minimum for each combination to bracket statistical variations. The limited tests do show some trends, with the reference 440C SS plates yielding an average normalized lifetime of 275 orbits/ μg with Pennzane at 1.5 GPa. This is more than an order of magnitude less than lifetimes observed with 440C/440C. The lubricated data is illustrated in Table 2.

Table 2- Lubricated Ceramic/Metal SOT Test
(Si_3N_4 Ball, 10^{-8} Torr, 30-100 RPM, Pennzane X2000)

Plate Material	Mean Hertzian Stress (GPa)	Normalized Life (Orbits/ μg)	Averaged Norm. Life
440C	0.80	867	562
440C	0.80	256	
440C	1.5	135	275
440C	1.5	327	
440C	1.5	364	
REX20	0.85	478	537
REX20	0.85	596	
X40	1.5	14,081	14,081
Cronidur X30	1.5	7,821	8318
Cronidur X30	1.5	8,814	
440C*	1.5	17	25
440C*	1.5	32	

* Tests with Brayco 815Z

The same data is presented in Figure 6 in normalized life (orbit/ μg) form for easier comparison.

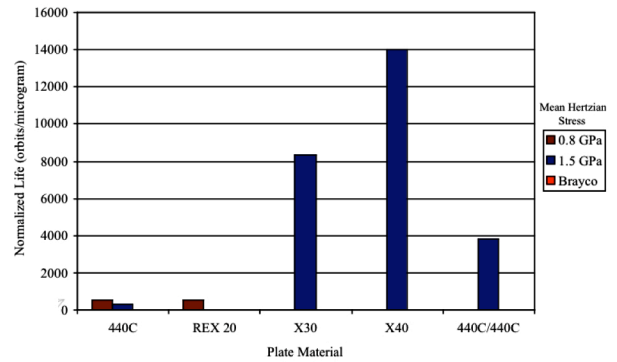


Figure 6 – Lubricated Ceramic/Metal SOT Test

The SOT test data showed that the most promising combination with the ceramic ball is with the newer X40 material. Although only a single test, the 14,081 orbit/ μg with Pennzane result is almost a factor of four times greater than a Pennzane/440C/440C combination. This yields the possibility of using minimal lubricant for this contamination sensitive project. However, this “speculation” needs to be life tested when future funds became available. Nevertheless, this is very promising since this combination can be applied in other “starved” mechanisms, such as NASA JWST observatory (with Northrop Grumman Space Technology as lead contractor) with mechanisms operating at near liquid helium temperature, or future rovers roaming on the “dark” side of the moon. A typical friction trace of the lubricated ceramic ball/X30 SOT test is presented below:

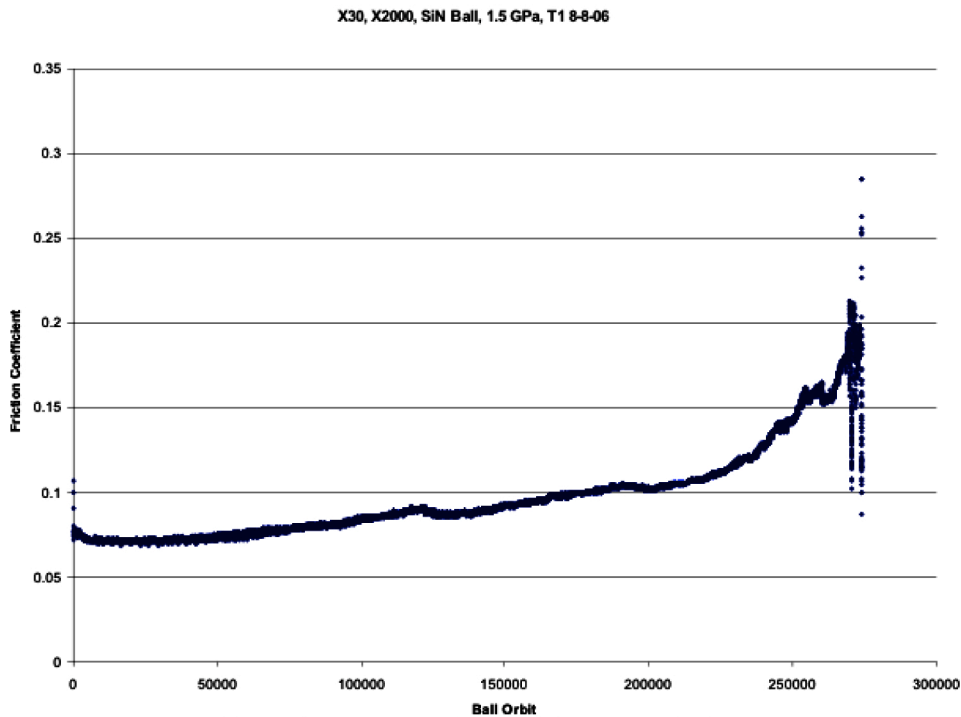


Figure 7 – Typical Lubricated Ceramic/X30 Trace

2.5 Ceramic Ball/"Nano-Coated" Metal Plates

The SOT testing thus far has produced mixed results, with some combinations yielding an unexpected lower lifetime than the 440C SS/440C SS pair, while others (ceramic/X40 pair) yielded an extended lifetime. Cerobear then suggested coating some test plates with their proprietary fluorocarbon nano-coating process on the X30 and X40 test plates. The hypothesis is that if a source of lubricant is applied on the combination with the lowest lubricant consumption rate, then it is

possible that only a very small amount of lubricant may be needed for this contamination sensitive project.

The single fluorocarbon "nano-coated" SOT test partially proved this theory is correct, with very low friction coefficient (0.1 to 0.25) for the first few orbits. However, the minute amount of lubricant is quickly consumed by the tribological action between the ceramic ball and the X40 test plate, and the friction coefficient rises quickly and stabilized at around 0.42, as illustrated in Figure 8.

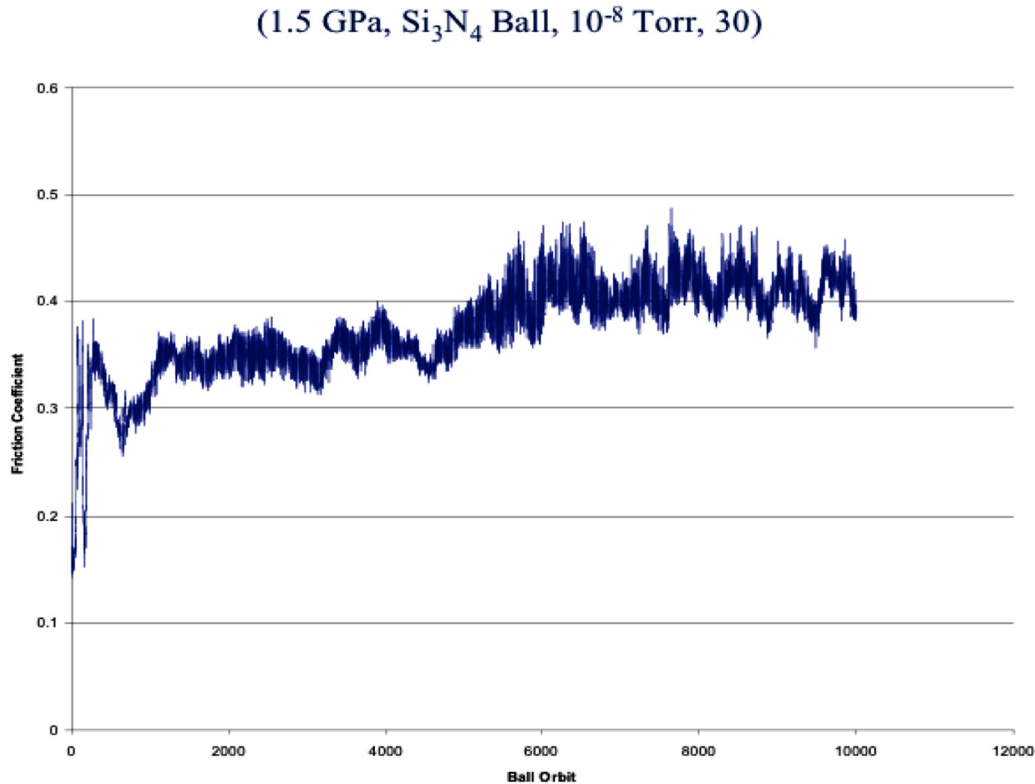


Figure 8 – Fluorocarbon "Nano-Coated" X40

This steady state friction is lower than the unlubricated silicon nitride/X-40 combination. An alternate method of providing a source of additional fluorocarbon lubricant was in progress when the test program was terminated in June 2006. The plan was to use a fluorocarbon composite guide plate for the SOT tests to simulate a composite bearing cage.

3. TEST SUMMARY

3.1 Unlubricated Tests

The Silicon nitride on silicon nitride couple yielded erratic friction coefficients during the scrub region of the SOT tests. Regardless of stress level, a material buildup in the wear track region is observed on the

fixed (lower) plate. Regardless of stress level, some wear, with a buildup on the inside of the wear track, is observed on the upper (rotating) plate. Most wear occurs in the scrub (sliding) region. Severe stick/slip between the ball and the plate is observed around the scrub region. This effect yields an average friction coefficient value, which is lower than the 'real' value seen in the rolling part of the track. Since scrub length is directly related to the friction throughout the ball orbit, the average friction coefficient can be calculated using the scrub length. For the 0.8 GPa tests, the scrub length equates to an average friction coefficient of 1.6. Regardless of stress level, a steady state friction eventually occurs. Limited data at 1.5 GPa indicates that Cronidur X-40 has slightly less wear than 440C or Rex 20 in the unlubricated SOT tests.

3.2 Lubricated Tests

Silicon nitride balls lubricated with Pennzane X-2000 or Brayco 815Z on either 440C or Rex 20 plates yield shorter lifetimes compared to a 440C/440C couple. **Silicon nitride balls lubricated with Pennzane X-2000 on Cronidur X-30 and X-40 yield longer lifetimes than 440C/440C.** Fluorocarbon “nano-coated” Cronidur X-40 and a silicon nitride ball yields high friction after only 60 ball orbits. However, the steady state friction for the coated plate/ceramic ball couple is lower than for unlubricated silicon nitride on untreated X-40 plates.

4. CONCLUSIONS

All steels showed some wear when coupled with ceramic ball in this limited series of SOT tests. Preliminary data at 1.5 GPa indicates X40 yields slightly lower wear than 440C or REX20 in an unlubricated couple. Si_3N_4 balls lubricated with Pennzane on REX20 and 440C yield shorter lifetimes than 440C on 440C. Si_3N_4 balls lubricated with Pennzane on X40 yield longer lifetimes than 440C on 440C. Fluorocarbon “Nano-Coated” X40 yielded high friction at 1.5 GPa after only 60 orbits.

5. FUTURE WORK

More SOT tests should be performed to expand the data base at 0.8, 1.0 and 1.5 GPa for the Si_3N_4 ball/X40 plate combination. A minimum of four SOT tests for each material combination and conditions should be run to bracket statistical variations. The Fluorocarbon “Nano-coated” technique, when coupled with a “donor” lubricant source, could be an acceptable substitute for unlubricated option. This can be demonstrated by using a fluorocarbon composite for the guide plate to simulate the cage in SOT.

6. CONCLUDING REMARKS

The Spiral Orbit Tribometer can provide a rapid assessment of various ceramic/metal and metal/metal combinations both lubricated and unlubricated.

7. ACKNOWLEDGMENTS

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