

ASSESSING LUBRICANT LIFETIME IN SPACECRAFT MOVING MECHANICAL ASSEMBLIES

David J. Carré and Patricia A. Bertrand

The Aerospace Corporation
2350 E. El Segundo Blvd., El Segundo CA 90245
Mail Station: M2-271
Telephone: 310-336-6761/FAX: 310-336-1636
E-mail: david.j.carre@aero.org/ patricia.a.bertrand@aero.org

ABSTRACT

The advent of longer-lived satellites and spacecraft has resulted in the requirement for a greater understanding of lubricant loss pathways. At The Aerospace Corp., we have been engaged in research to understand these phenomena. In this paper, we will present a review of this work which includes the following topics: vapor pressure modeling of oils and additives for loss rate prediction, additive effectiveness, and oil uptake into cotton-phenolic ball retainer material. These studies allow us to make much more accurate estimates of lubricant lifetime in moving mechanical assemblies.

1. INTRODUCTION

A decade ago, satellite lifetimes were short, 3-5 yr, and were generally limited by the lifetimes of non-mechanical systems, such as batteries and electrical components. More recently, improvements in other systems have led to satellite lifetimes often being limited by the lifetime of moving mechanical assemblies (MMAs). Many satellite systems now have expected lifetimes of 10-15 yr. To meet these expectations, improvements in mechanical components and lubrication have to be made. In addition, a more thorough understanding of the various lubrication phenomena that limit MMA life (such as oil evaporation, creep, and centrifugal loss) and more accurate methods of predicting life of a lubrication system have to be developed.

2. DISCUSSION

2.1 Oil Evaporation Modeling

We have developed a computer model that allows us to calculate the evaporative loss of oil from MMAs (Ref. 1). The model uses supercritical fluid chromatography (SFC) data to provide a distribution of oil components as a function of retention time and detector response. (Under the SFC conditions, retention time is a function of solubility in the supercritical carbon dioxide carrier fluid which is proportional to molecular weight. Typically, the SFC data consist of more than 1000 detector response

values equally spaced on the retention time axis.) Linear hydrocarbons are also analyzed under the same SFC conditions to provide a molecular weight (carbon number) vs retention time calibration. High temperature literature vapor pressure data for the linear hydrocarbons are extrapolated to a temperature representative of the application conditions. This results in a vapor pressure vs carbon number calibration of the SFC data at a specific temperature. Unfortunately, extrapolations of vapor pressure data over large temperature ranges are not accurate due to non-linearity of the Clausius-Clapeyron relationship. In order to correct for the errors in extrapolation, the loss rate as a function of percent oil evaporated is determined in a laboratory experiment in which the loss of oil as a function of time, under vacuum conditions, is gravimetrically determined. From these data, vapor pressure vs percent loss can be determined and used to normalize the vapor pressures used in the model to the temperature of interest. As a result, the oil is modeled as a set of more than 1000 data points representing oil components at equal carbon number intervals, each assigned a unique vapor pressure.

The loss of oil for a specific application is modeled using the geometry of the MMA. The initial SFC derived data are used as the starting point. Using the vapor pressures for the individual components and the loss rates derived from them as additional inputs, the simulated oil evaporation is run on the computer using a program written in IDL® (Interactive Data Language). The oil distribution (amount vs. carbon number) can be calculated as a function of time. For the calculations, we typically divide the time into 500 equal time intervals so that the calculation results in 500 distributions and 500 oil vapor pressures as a function of time. The vapor pressure of the oil is determined from the oil distribution component mole fractions and vapor pressures using Raoult's law.

Figure 1 gives plots of oil distributions as a function of oil loss for a light petroleum-based oil, SRG40. (The distribution that is farthest to the left in the figure represents the initial distribution based on the SFC data.)

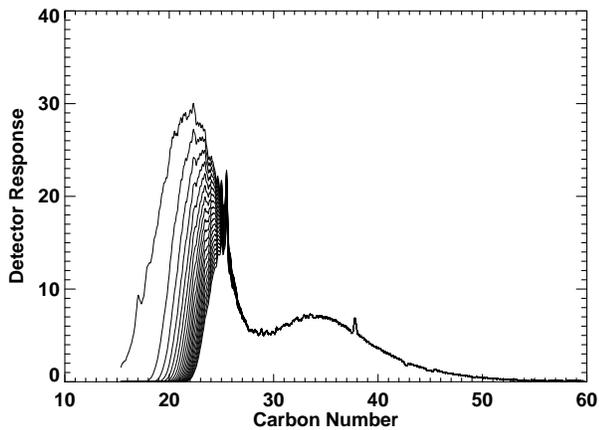


Figure 1. Oil distributions as a function of oil loss for SRG40 oil.

In the figure, the distributions are shown at every 25 time intervals to keep the figure from becoming too complex. It is clear that as the lighter, more volatile oil components evaporate, the rate of evaporation diminishes and succeeding distributions are closer together. The total loss of oil at the end of this simulation was 55%.

The effect of oil loss on vapor pressure is given in Figure 2. The vapor pressure diminishes with loss as expected.

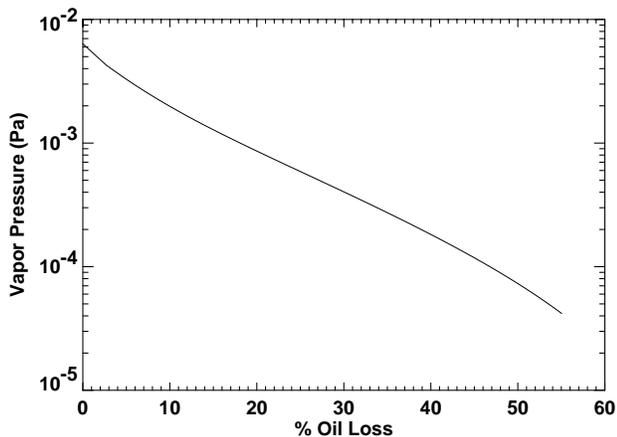


Figure 2. Vapor pressure as a function of oil loss for SRG40 oil.

Unfortunately, there is a dearth of spacecraft oil loss data from actual satellite flights. The one exception is the oil loss data from the reaction wheel that was returned from the Hubble Space Telescope (HST) after 7 years of operation (Ref. 2). We had the opportunity to analyze the lubricant from the spin ball bearings. These bearings showed very little loss of oil, which was in agreement

with our computer simulation. The conditions under which the HST operated were very benign in terms of temperature and tribology, consistent with the low oil loss.

We can test our model on two sets of data: one from a terrestrial test of a ball bearing cartridge assembly lubricated with a petroleum oil and another from loss of petroleum oil from satellite reaction wheel spin bearings during storage (Ref. 1). The first example is illustrated in Figure 3.

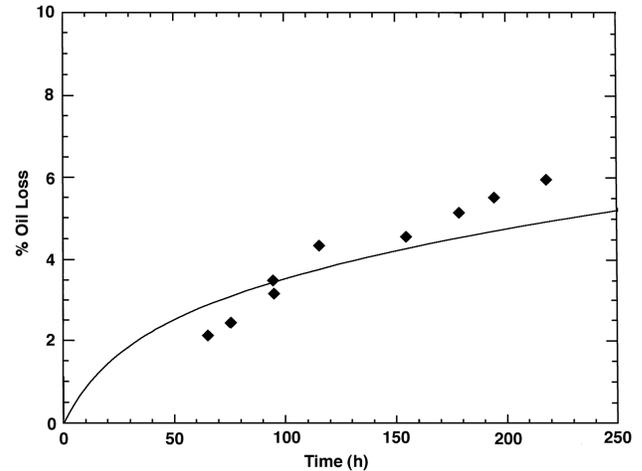


Figure 3. Loss of oil from a ball bearing cartridge system under vacuum at 70°C; model (-), empirical data (♦). (Reprinted by permission of the Society of Tribologists and Lubrication Engineers.)

Oil loss from the cartridge was determined gravimetrically at specific time intervals. There were no measurements before 65 h and the test was terminated at 6% loss of oil. The symbols are the loss data, and the solid line is the model prediction. The model predicts the loss of oil within 1% of the empirical loss data.

In the second example, the ball bearings in a satellite system suffered excessive lubricant loss during storage. This is shown in Figure 4. The conditions were ambient temperature with a background pressure of 0.5 atm of He gas. The data are for five satellites stored 3, 5, and 7 yr and were obtained by comparison of chromatographic data for the storage oil samples with data for the unused oil. Standard diffusion calculations and an average storage temperature of 25°C were used for the model. As before, the symbols are the loss data, and the solid line is from the model. The data do not start at 0% oil loss, because some oil was lost during the build and acceptance procedures for the MMAs. The correspondence between the model and the empirical data is very good considering that the chromatographic data are only good to a few

percent. These data indicate that it is possible to model the oil loss from satellite MMAs within a few percent of the actual loss using our method, which is much more accurate than previously used techniques.

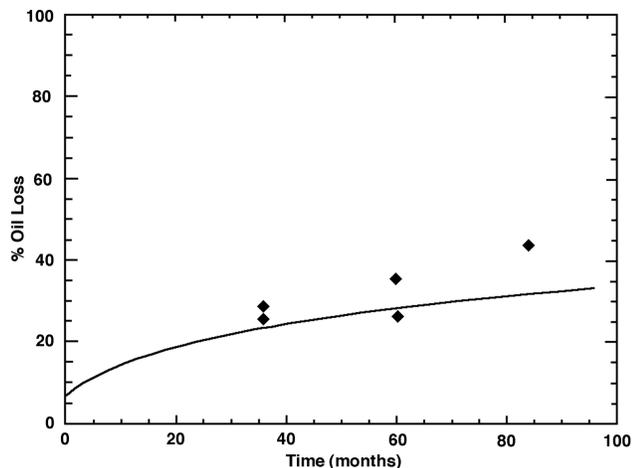


Figure 4. Oil loss from satellite MMAs during storage at ambient temperature; model (-), empirical data (\blacklozenge). (Reprinted by permission of the Society of Tribologists and Lubrication Engineers.)

2.2 Aryl Phosphate Additives

Longevity of MMAs can depend on the presence of appropriate lubricant additives over the lifetime of the mission. For spacecraft, the presence or absence of antioxidants is not normally a concern because the MMAs typically operate under orbital conditions, i.e., low pressure with very little oxygen or water present. However, for the boundary lubrication tribological regime, the presence of antiwear additives can be critical. Not only must the additives perform their intended function, they also must remain in the areas where they are needed.

We previously measured the vapor pressure of tricresyl phosphate (TCP) at 50°C in our laboratories (Ref. 3). The measured vapor pressure is high enough (2.6×10^{-5} Pa) that its loss via vapor transport must be taken into consideration. There are commercially available mixtures of aryl phosphate ester additives that have components that are higher in molecular weight than TCP and, as a result, have lower vapor pressures and loss rates. We measured the vapor pressure of one of these mixtures by performing a laboratory weight loss measurement under vacuum conditions and using our oil evaporation model to fit the shape of the percent loss vs. time curve for the experiment. The result is shown in Figure 5. The shape of the curve is very sensitive to the vapor pressures of the components and the composition of the mixture.

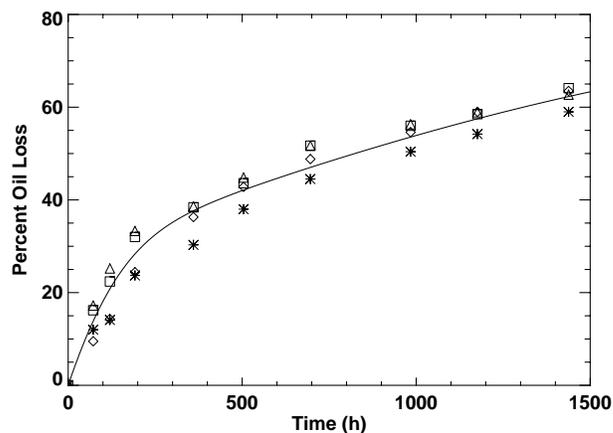


Figure 5. Percent loss vs time data for an aryl phosphate ester mixture at 50°C. The symbols represent individual sample data; the line is the fit obtained from the model. (Reprinted by permission of the Society of Tribologists and Lubrication Engineers.)

We used the manufacturer's specifications for the composition of the mixture as a starting point and adjusted the composition and the vapor pressures of the components until the shape of the model curve fit the empirical data. The fit of the model to the data is very good. The final composition was within the manufacturer's specification.

The calculated vapor pressures for the four aryl phosphate ester additives in the mixture in order of increasing molecular weight are: (triphenyl phosphate) 3.1×10^{-4} , (t-butylphenyldiphenyl phosphate) 2.1×10^{-5} , (di-[t-butylphenyl]phenyl phosphate) 2.1×10^{-6} , and (tri-[t-butylphenyl] phosphate) 2.1×10^{-7} Pa. The vapor pressure of TCP is less than that of the most volatile component, and approximately the same as the second most volatile component. The remaining two components in the mixture are considerably less volatile than TCP and would be expected to remain in the lubricant much longer than TCP. As a result, if the tribological action of these aryl phosphate ester additives is comparable to that of TCP, longer wear life would be expected.

The relative wear test performances of TCP and tri-(t-butylphenyl) phosphate (TBP) additives were determined in our laboratories in a ball bearing tester that operates under boundary lubrication conditions and elevated temperature in vacuum (Ref. 4). The additives were tested at a concentration of 1%(v/v) in a multiply alkylated cyclopentane (MAC) synthetic hydrocarbon (Pennzane[®]) under the same conditions of load and speed. The results of the testing are shown in Figure 6. It is clear

that the less volatile aryl phosphate additive (TBP) performed better than TCP under the test conditions. This

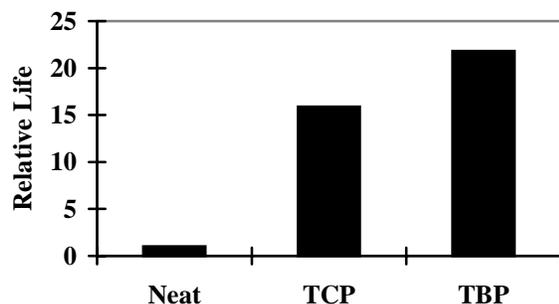


Figure 6. Relative wear test performance of MAC oil neat and with additives.

is a reflection of the lower vapor pressure of the higher molecular weight additive. It remains in the contact area longer and thus provides for a longer performance lifetime.

2.3 Oil Absorption into Cotton-Phenolic Retainers

Many ball retainers (also called cages) in MMAs are made of cotton-phenolic material. The material is porous, and is impregnated with lubricant before use. If the material is not fully impregnated, it could absorb oil from the ball bearing during storage and use, resulting in less oil available to the moving parts. We have determined the mechanism of oil absorption into the material, and have found that the oil absorption process can require several years for completion.

In our experiments (Ref. 5), small, wedge-shaped pieces of material were cut from cotton-phenolic tubes. They were cleaned by Soxhlet extraction in heptane, dried by baking in a vacuum oven, and impregnated by submersion in oil baths. The pieces were removed and weighed periodically to determine the amount of oil absorbed into the material. The absorption of oil is a two-step process: a fast first step which we attribute to filling of the capillaries associated with the cotton threads, and a slow second step which we attribute to diffusion of oil into the phenolic resin matrix.

The results for a typical petroleum oil are given in Figure 7. Three regions are marked. Capillary fill takes place in regions 1 and 2. Due to the shape of the pieces, there are two lengths of cotton threads in each piece, and thus two lengths of capillaries. During the time labeled as region 1, both sets of capillaries are filling; during the time labeled as region 2, only the longer set is filling since the shorter set has finished. Diffusion of oil from the capillaries and the bath into the bulk resin takes place in region 3.

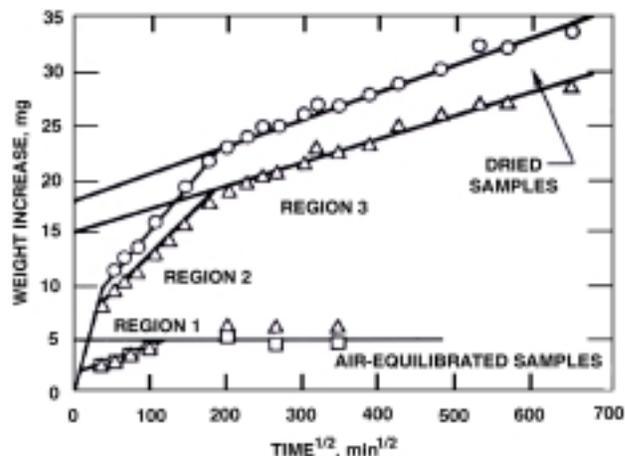


Figure 7. Oil absorption into cotton-phenolic material. The different symbols correspond to different test samples. (Reprinted by permission of the Materials Research Society.)

The data from the first two regions can be modeled by a capillary fill process. The weight increase of the samples due to capillary fill is proportional to the square-root of time, and depends upon the density, surface tension, and viscosity of the oil, as well as the capillary geometry. The number and length of the capillaries can be estimated from the number and length of the cotton threads. Various oils of different viscosities, densities, and surface tensions were used in the experiments, and the capillary fill model fit the data well. The amount of oil absorbed by the material was about 2 to 3% (v/v), which is typical for cotton-phenolic retainer material used in spacecraft ball bearings (in special cases, greater porosity can be obtained).

The data from region 3 can be modeled as a diffusion process. For the initial stages of diffusion, the weight increase can be fit to a simple square-root of time dependence (this is why region 3 appears linear in Figure 7). In our experiments, we carried out the measurements until the samples were saturated with oil, and fit the data to the complete solution of the diffusion equation for saturation of sheet samples. Saturation took almost 2 years to achieve. The diffusion coefficient obtained compares well to that of large molecules in polymer matrices, when we consider the volume into which the diffusion takes place to be the volume between the capillaries. That is, the oil is not diffusing into the phenolic resin only from the outer surfaces of the samples, but from the interior surfaces also. In our experiments, an additional 2-3% (v/v) of oil was absorbed in this step.

Another important effect is illustrated in Figure 7. Samples which were equilibrated with air (about 50% relative humidity) before submersion in oil, show much less oil absorption than dry samples. It is well-known that cotton-phenolic material is very sensitive to water. In the experiments reported in Figure 7, the water vapor from the air has absorbed into the material and formed a barrier to oil absorption. This result clearly shows the necessity of drying cotton-phenolic retainers completely before impregnation with oil.

Oil can be absorbed into an incompletely impregnated retainer even in an operating bearing (Ref. 6). In order to explore this effect, retainers were partially impregnated (to about 60% of their capillary capacity) with a poly- α -olefin oil, then operated in a bearing lubricated with a neopentyl polyol ester oil. After a chosen length of time (from 1 h to 49 d), each retainer was removed from its bearing, and the oil within it was extracted and analyzed. There was more oil in the retainers after use than before, and the collected oil contained a large fraction of the ester oil (about 40% of the collected oil was ester after several days of operation). The oil collected from the metal parts had only a few percent of the poly- α -olefin oil, showing that very little oil left the retainer. Identical results were obtained when the initial locations of the two oils were reversed.

Oil absorption into cotton-phenolic ball-bearing retainers can be a significant loss pathway for oil in a bearing. However, this pathway can be mitigated by careful treatment of the retainers before use and an adequate oil supply to the bearing during use. Retainers should be very dry before impregnation, and should be left in oil as long as feasible to ensure as complete impregnation as possible. Enough oil should be supplied to the bearing for storage and use to accommodate any additional absorption into the retainer due to the long term, diffusion-related process.

3. CONCLUSIONS

The lifetime of lubricated ball bearing systems can be affected by the loss of lubricating oil and additives. Loss of oil and additives via evaporative transport must be taken into consideration when the MMAs are designed and the lubricants selected. We have shown that the loss of oil and additives can be modeled if the vapor pressures of the components are known. In addition to evaporative loss, oil can be lost from the working surfaces in a ball bearing by absorption into cotton-phenolic ball retainer material. The retainer material will absorb oil for extended periods of time and this effect must be taken into

consideration when determining the quantity of oil with which to lubricate the ball bearings in an MMA.

4. REFERENCES

1. D. J. Carré and P. A. Bertrand, "A Model to Calculate Evaporative Oil Loss in Spacecraft Mechanisms," *Tribol. Trans.*, 42(2), 282 (1999).
2. D. J. Carré and P. A. Bertrand, "Analysis of Hubble Space Telescope Reaction Wheel Lubricant," *J. of Spacecraft and Rockets*, 36(1), 109 (1999).
3. D. J. Carré and P. A. Bertrand, *Modeling and Measurement of Aryl Phosphate Ester Vapor Pressures at 50°C*, The Aerospace Corporation, El Segundo, CA, TR-98(8565)-3, 30 September 1998.
4. S. V. Didziulis and R. Bauer, *Volatility and Performance Studies of Phosphate Ester Boundary Additives With a Synthetic Hydrocarbon Lubricant*, The Aerospace Corporation, El Segundo, CA, TR-95(5935)-6, 20 December 1995.
5. P. A. Bertrand, "Oil absorption into cotton-phenolic material," *J. Mater. Res.*, 8(7), 1749-1757 (1993).
6. P. A. Bertrand, D. J. Carré, and Reinhold Bauer, "Oil Exchange Between Ball Bearings and Cotton-Phenolic Ball-Bearing Retainers," *Tribol. Trans.*, 38 (2), 342-352 (1995).