Contamination Danger by Oil-Lubricated Ball Bearings in Spacecraft

WALTER WILKENS*
Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt,
Forschungszentrum Braunschweig, West Germany

The weight loss of special oil reservoirs, the sorption of oil on selected materials, and the surface migration of oil were investigated for an oil which has been successfully used for lubricating ball bearings operating in a vacuum environment and selected as one of the promising lubricants for the antenna despin system of the HELIOS spacecraft. The oil loss rates determined cannot be calculated by the relation of free molecular flow and are assumed to be greatly influenced by surface migration phenomena. The adsorption of oil vapor is considerable on ZnO and TiO_2 coated surfaces, but is not detectable on glass. Gross surface migration of oil takes place on ZnO- and TiO_2-coatings which are in direct contact with oil whereas there is no surface migration detectable on these surfaces when the oil is in a porous reservoir material.

1. Introduction

SINCE low friction, long life, and reliability are essential properties for bearings in space vehicles, oil lubrication is still among the most important methods for the lubrication of spacecraft mechanisms. By using low vapor pressure oils stored in special porous materials, as well as housings with small orifices, oil lubrication is widely used in space, e.g., in all INTELSAT spacecraft. The use of special oils and bearing housings is necessary in order to maintain the vapor pressure of the oil inside the bearing and to prevent severe oil loss into the vacuum of space.[1] However, the amount of lubricant loss is important not only because of the danger of friction and seizure, but also because of the possibility of critical surfaces being contaminated by adsorbed or condensed oil vapor or migrating oil films.[2] This contamination could cause functional failures or affect the accuracy of the spacecraft-borne instruments. This possibility is especially important for the HELIOS spacecraft† with its very sensitive experimental equipment.[3] (For instance, because of the plasma experiment, the surface potential variations must not exceed 0.2 v. Any isolating surface contaminants, such as oil films, must be eliminated in order to avoid local charge build up.) Since minute quantities of foreign materials can change optical and other surface-dependent properties significantly[4,5,6] it is most important to evaluate the oil losses from housings with small effusion channels, investigate the sorption of the oil vapor on selected surface coatings, and study the migration of oil films onto these surfaces.

2. Experimental Materials

The oil tested is the high-vacuum pumping fluid, bis(2-ethylhexyl) sebacate, which has been successfully used for lubricating ball bearings in vacuum.[7]

The oil reservoirs are made from a sintered nylon material, machined to flat rings and vacuum-impregnated with oil. The weight-increase due to the impregnation is about 300 mg or 30% of the original weight. The pore diameters of the material are between 0.6 μ and 3.5 μ, and the porosity—i.e., the ratio pore volume/total volume—is 45%.

The cages which simulate the ball bearing housings are machined from a commercial aluminium alloy (AlCuMgPb, Fig. 1). The total weight of the sintered nylon-filled cages cannot exceed 20 g because this is the maximum load for the microbalance used for determining the oil loss rates.

The surface coatings selected were zinc oxide, titanium oxide, and glass. The coatings were made from high purity ZnO and TiO_2, both bound with potassium silicate (K_2SiO_3) and applied to the targets by spraying according to the formulations and procedures presented in Ref. 8. Glass was applied by melting.

3. Apparatus and Experimental Procedure

The principle of the apparatus for measuring oil-weight-loss is shown in Fig. 1. The heart of the apparatus is a vacuum-microbalance with a maximum load of 20 g and a resolution of 10^{-6} g. The simulated ball bearing housings, with their small circular effusion channels, are suspended from the balance and surrounded by glass walls which are cooled by liquid nitrogen. The housings or cages are radiation-heated and the intensities necessary to maintain the desired cage temperatures (20°C and 60°C, within ±5°C) are determined by parallel experiments. The residual pressure in the system is less than 10^{-4} torr, and the partial pressure of the oil is negligible compared with the vapor pressure of the oil at 20°C and 60°C. The dimensions of the effusion channels of the cages simulate those of the anticipated antenna bearings. The cages can be filled with sintered nylon rings or liquid oil. Figure 1 also presents some typical phases of the weight-loss experiments.

Figure 2 shows the principle of the sorption or condensation measuring device. The main part of it is, again, a vacuum-microbalance with a maximum load of 2.5 g and a resolution

---

Received December 10, 1970; revision received May 19, 1971. The work was supported under Contract 013-081/70-H by the Gesellschaft für Weltraumforschung, GfW, Germany, to whom the writer is very grateful. He is also most thankful to H. Bentlage and E.-W. Budde for performing the weight loss and sorption experiments, and to A. Löffler, GfW, for his helpful discussions. The writer is indebted to W. Thielemann, head of the Structures and Materials Department, for his encouragement. This work was reported at the Third HELIOS Joint Working Group Meeting, Bonn-Bad Godesberg, October 1970.

Index category: Spacecraft and Component Ground Testing and Simulation.

* Physicist (Dipl.-Phys.), Chief, Materials in Space Section, Structures and Materials Department, Institut für Flugzengban.

† Project HELIOS is a cooperative space program of the United States and Germany.

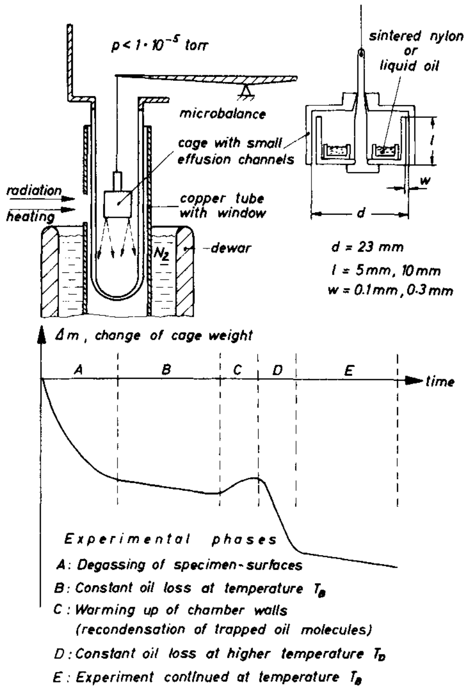

Fig. 1 Principle of the oil-weight-loss measuring arrangement with some typical experimental phases.

of 10^{-7} g. Suspended from the balance is a thin circular target of 5-cm-diam covered with the surface coatings to be tested. Beneath the target is a simulated bearing housing with its circular effusion channel facing the target (channel dimensions: diameter 23 mm, length 10 mm, width 0.1 mm). A shutter can be pulled between target and housing, thus shielding the target from oil vapor. The upper side of the shutter carries a radiation heater for degassing the target. The cage has its own controlled heating for achieving the desired cage temperatures. Inside the cage oil is stored in vacuum impregnated sintered nylon rings. The entire measuring device is surrounded by walls cooled by liquid nitrogen in a vacuum better than 10^{-7} torr. With the walls at LN_2-temperature and the cage at 60°C, the equilibrium temperature of the targets is 18°C.

Some typical phases of the sorption experiments are plotted schematically on the bottom of Fig. 2. Phase A indicates the sorption of oil molecules. The weight of the target starts to increase as soon as the shutter is opened. The shutter is closed in B, and in C the target is desorbed and its weight reduces to the starting value. After C the shutter is opened and oil vapor is again adsorbed on a clean surface.‡

The principle of the surface migration device together with a typical sequence of experimental operations is presented in Fig. 3. Inside a vacuum chamber there is a double-walled cavity with the inner wall at LN_2-temperature. The outer wall has a total orifice area of 8 cm², and is at room temperature in order to eliminate additional, but unknown, pumping speeds. The main part of the surface migration device is installed in this cavity. It consists of a shielded oil reservoir on a liftable support (height 15 mm). The support transmits its weight (50 g) to the specimen beneath by means of two knife-edges. This flat specimen has a total surface area of 70 cm², and can be moved out of the cavity into a high-frequency coil. High-frequency heating by the coil can clean or desorb the specimen from contaminants which have migrated, or have been adsorbed on it.

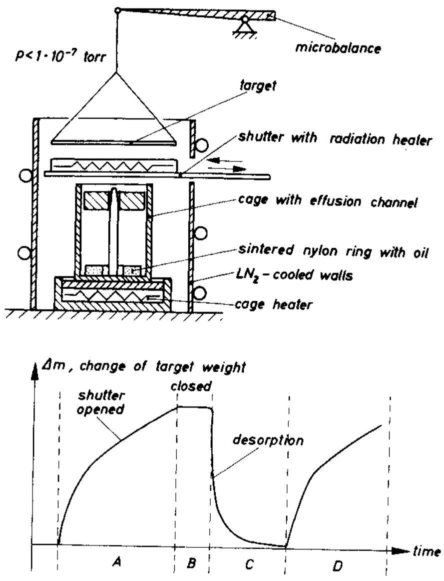

Fig. 2 Principle of the sorption measuring device with some typical experimental phases.

The sequence of the principal experimental operations is schematically presented in the lower part of Fig. 3. After the specimen is cleaned by HF-heating at 300°C, it is pulled into the cavity and cooled down until it has nearly reached the desired temperature. Thereupon the support carrying the oil reservoir is lowered to the specimen, and the desired temperature (20°C and 60°C) is maintained by controlled heaters inside the cavity. The support rests on the specimen surface for periods up to 12 hr. The support then is lifted, and the specimen pulled outside into the HF-coil where it is desorbed at 200°C. The smallest detectable amounts of desorbed vapor correspond to less than 10^{-1} monolayer.

4. Results

For the oil weight-loss measurements with simulated bearing housings, no losses could be detected at 20°C. A typical

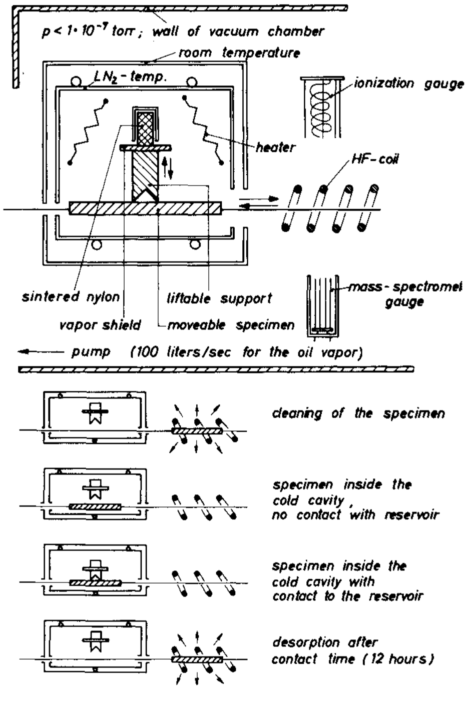

Fig. 3 Principle of the surface-migration measuring arrangement with a typical sequence of operations.

---

‡ During the sorption experiments the only radiation is infrared. However, in space ultraviolet and particle radiation can polymerize the adsorbed or condensed oil films, and it may be difficult or impossible to remove these films by heating.

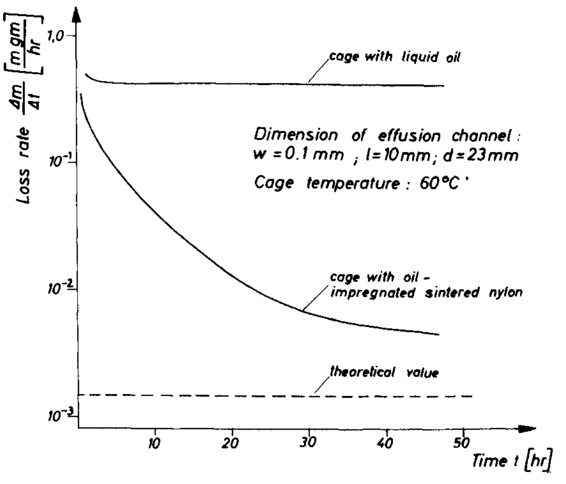

Fig. 4 Oil loss rates of a cage with liquid oil and oil in a sintered nylon reservoir.

plot obtained at 60°C, with a cage having an effusion channel 0.1-mm-wide and 10-mm-deep is shown in Fig. 4 where the loss rates of the cage with liquid oil and with oil impregnated sintered nylon are compared with the theoretical value. It can be seen in Fig. 4 that the experimental data do not correspond with the theoretical data as calculated by the Knudsen relation.[9] It is believed that the high loss rates with liquid oil are due to surface migration of the oil molecules. This conclusion is also believed valid for the reservoirs. The strong decrease of the oil loss rates with these reservoirs is probably caused by diffusion phenomena which decelerate the transportation of the oil from the inner parts of the porous reservoir material to the outer.§

When the channel width is enlarged from 0.1 to 0.3 mm, the loss rates for liquid oil remain very high compared to the rates with impregnated sintered nylon. However, the values with sintered nylon become comparable with the theoretical ones; these results are presented in Fig. 5.

The oil adsorption measurements were also conducted at housing temperatures of 20°C and 60°C. The targets were at room temperature (18°C). Results were in good accord with the oil loss measurements and no adsorption could be detected at 20°C cage temperature.

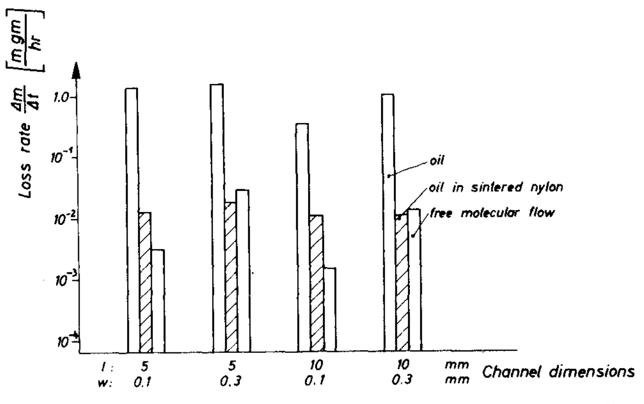

Fig. 5 Oil loss rates after 50 hr in high vacuum with impregnated sintered nylon and liquid oil for different effusion channel dimension compared with the theoretical values of free molecular flow.

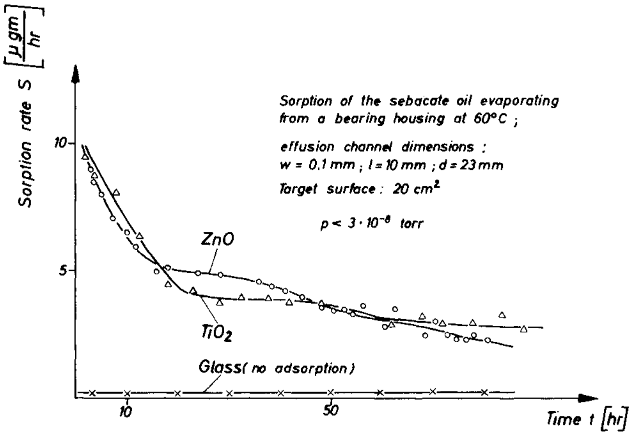

Fig. 6 Sorption rates of oil vapor on ZnO-K_2SiO_3, TiO_2-K_2SiO_3, and glass targets at 18°C.

The results obtained at 60°C are plotted in Fig. 6. The main result is that there is considerable adsorption on the ZnO- and TiO_2-surfaces but none on glass, with the sorption on ZnO and TiO_2 being very similar. After a strong decrease of the sorption rates during the first 20 hr, the rates remain nearly constant for about one day. Thereupon they start to decrease more quickly again. It is remarkable that the sorption rates remain larger than the theoretical oil effusion rates during all of the test time.

The different behavior of the oxide coatings compared to the glass surface is probably due to the following facts. Besides the temperature of the adsorbent and other parameters, the quantity of vapor adsorbed per sec and per unit area of adsorbent is greatly influenced by the heat of adsorption. Since the heat of adsorption is a property of the system adsorbent/adsorbate a change of adsorbent can alter the adsorption rates drastically. Also, large differences can result from discrepancies between the apparent and the real surface areas of adsorbents. For the present experiments the real areas of the oxide coatings are about one order of magnitude larger than those of the glass targets, which are equal to the apparent areas. With large real surface areas, the sites available for adsorption are high for a relatively long time and so are the adsorption rates.

The preceding comment assumes "monolayer adsorption," which means the oil adsorbed will not exceed that contained in one layer of molecules. This is true for the glass and also probably true for the oxides because of their large real surfaces areas. Because of this and according to the Langmuir relations,[9] the following differential equation[4] may apply to all three systems: $d\theta/dt = (1 - \theta)\alpha n/S - \theta f(t) \exp(-E/kT)$ where θ = fraction of adsorbent surface area covered with oil molecules; S = total number of sites available for adsorption of molecules; α = coefficient of the order of unity; n = number of molecules striking unit area of target per second; $f(T)$ = function of temperature T, changing only slowly compared to $\exp(-E/kT)$; k = Boltzmann's constant; and t = time.

In regard to the surface migration of the oil under investigation, preliminary experiments showed that gross oil spreading occurs on ZnO- and TiO_2-coated surfaces if these surfaces are directly in contact with liquid oil. Figure 7 demonstrates this effect for the oil spreading over the edges of the support (Fig. 3) onto a ZnO-coated surface in air. However no oil migration was observed in the case where the coatings were only in contact with impregnated reservoirs.

For investigating smaller, nonvisible quantities of oil, the vacuum-surface-migration device described before was used. But, even with this device, no significant differences could be detected between surfaces which were in contact with the reservoir and those which were not. This means that for at least 12 hr and a migration distance of 15 mm (the height of

---

§ Gaseous, as well as surface, diffusion contributes to the transportation. The ratio of gaseous diffusion to surface diffusion was not determined for the system investigated. However, both the concentration gradients causing surface diffusion and the conductances for molecular flow inside the porous material decrease as the oil evaporates from the reservoir.

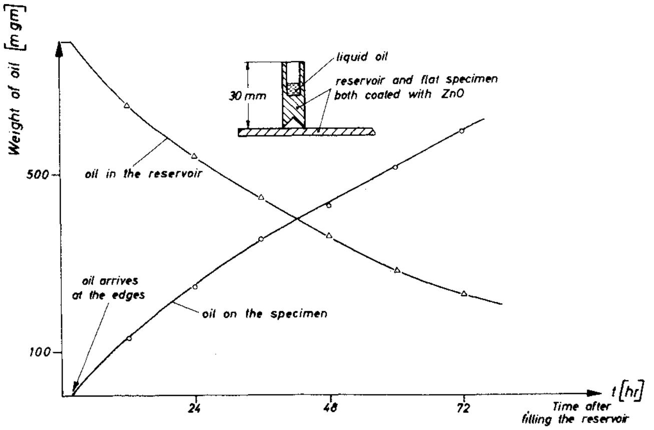

Fig. 7 Oil spreading over ZnO-coated surfaces, geometry corresponds to that in Fig. 3.

the support, which is also coated) the coatings which were used acted as oil migration barriers for both 20°C and 60°C specimen temperatures.

The quantities of oil detected by desorption and mass-spectrometry on the migration-experiment specimens (both with and without contact of the reservoirs) are in the range of 1–10 μg/cm^2, decreasing strongly with storage time in vacuum. This oil has at least partially-migrated around from the rear of the titanium shield and has evaporated onto the specimen (Fig. 3). An example of the desorption of a ZnO-coated specimen is presented in Fig. 8. The recorded molecular mass of 57 is typical for the oil investigated. The amount of gas desorbed from the specimen is about $5 \cdot 10^{-3}$ liters·torr and corresponds to nearly 10 monolayers (relative to the apparent surface area). The accuracy of these measurements of gas quantities is better than 1%. Thus, there is no surface migration for quantities larger than 10^{-1} monolayers. However, it is not believed that there is any surface migration for smaller concentrations of oil molecules.[10] As with the sorption experiments, no oil was detected on glass-covered specimens during all surface migration experiments.

5. Conclusions

The experiments conducted with the oil, bis(2 ethylhexyl) sebacate, being evaluated as a possible lubricant for the HELIOS antenna despin mechanism, have demonstrated the following. a) The oil loss rates with sintered nylon reservoirs at 60°C do not depend on the effusion channel dimensions of the cages used. No loss rates could be detected at 20°C cage temperature. b) The oil investigated is considerably adsorbed on ZnO- and TiO$_2$-coatings. The slowly-decreasing sorption rates correspond to about one monolayer per day after 100 hr test time, with a target temperature of 18°C and a cage temperature of 60°C. No adsorption could be detected on glass. There was also no adsorption at 20°C cage temperature for all surfaces. c) Although gross oil migration takes place on ZnO- and TiO$_2$-coatings directly in contact with the oil investigated, no migration was detected with these surfaces in contact with oil impregnated sintered nylon reservoirs in vacuum. This result is for contact times up to 12 hr at $2 \cdot 10^{-8}$ torr, a migration distance of 15 mm, and smallest detectable gas quantities corresponding to less than $\frac{1}{10}$ of amonolayer.

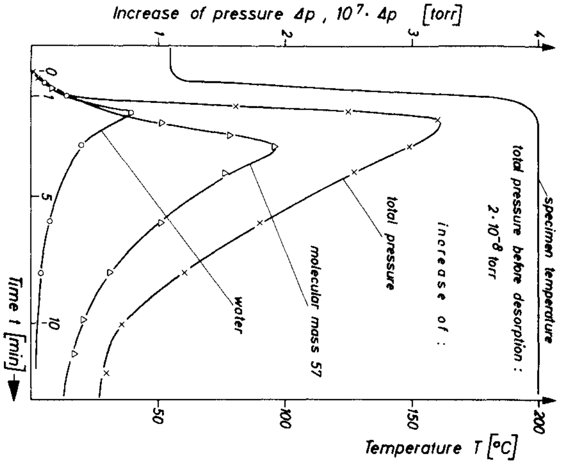

Fig. 8 Desorption of a ZnO coating after 12 hr storage time in the vicinity of the sintered nylon oil reservoir in ultrahigh vacuum (Fig. 3).

References

[1] Bisson, E. E. and Anderson, W. J., *Advanced Bearing Technology*, NASA SP-38, 1964.

[2] Poehlmann, H. C., "Outgassing and contamination threats of materials for space applications," *Proceedings of the Symposium on Long Life Hardware for Space*, 1969, NASA.

[3] Lex, J., Koppe, H. and Keller, E. W., *Helios Configuration for Close Sun Flyby*, Messerschmitt-Bölkow-Blohm GmbH, Munich, Germany, 1970.

[4] Mayer, H., *Physik dünner Schichten*, Teil I und II, Wissenschaftliche Verlagsgesellschaft, Stuttgart, 1955, pp 41–55.

[5] Scannapieco, J. F. and Griffin, R. N., "Behavior of Materials in Vacuum," CR-97 815, 1967, NASA.

[6] Mangold, V. R., "The Origin of Deposits Formed on the Surface of Thermal Control Materials by the Action of Extreme Ultraviolet Radiation," AFFDL TR-68-155, 1969, Air Force Flight Dynamics Lab., Wright Patterson Air Force Base, Ohio.

[7] Birkhold, E., Granzow, M. et al., "Erprobung von Drehmechanismen unter Weltraumbedingungen," RV4-33/05/68, Teil II, Dornier System, Friedrichshafen, Germany, 1969.

[8] Plunkett, J. D., *NASA Contributions to the Technology of Inorganic Coatings*, NASA SP-5014, 1964.

[9] Dushman, S., "Scientific Foundations of Vacuum Technique," Wiley, New York, 1962, pp. 90–104.

[10] Carman, P. C., et al., "Diffusion and Flow of Gases and Vapours Through Micropores, III. Surface Diffusion Coefficients and Activation Energies," *Proceedings of the Royal Society*, Vol. 209A, London, 1951, pp. 38–69.