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ROLLING ELEMENT BEARINGS IN SPACE

J. W. Kannel* and K. F. Dufrane*

The paper discusses some of the advances in tribology that have been associated with aerospace mechanisms. The needs of aerospace have been the dominant forces leading to improvements in understanding and applying tribology technology. In the past two decades improvements in understanding bearing torque, elastohydrodynamic lubrication, lubricant distribution, cage stability, and transfer film lubricants have been made. It is anticipated that further developments will be made in response to future aerospace requirements.

INTRODUCTION

The development of aerospace mechanisms has required considerable advances in the science of friction, wear, and lubrication (tribology). The aerospace industry has been the dominant driving force in tribology and has given tribology the popularity and respectability it now enjoys. Further, many of the tribology techniques developed for aerospace have been applied to mechanical components for non-aerospace systems and have been a benefit to all technology. Figure 1 shows a qualitative chart which illustrates the growth of tribology problems with aerospace and the advances that have been made. Despite significant advances in tribology, the insatiable demands of aerospace systems seem to grow faster than the solutions.

Major tribology advances have been made in several areas, with rolling element bearings being a particularly important example. Without the advance made in rolling-bearings or alternative concepts, many of the space systems would not be possible. The paper discusses a small part of their advances and how these advances can be applied to assist design. The paper discusses bearing torque for small and medium sized bearings, cage stability, lubricant distribution, and transfer film lubrication. The paper does not deal with the emerging area of high temperature tribology, which is an area needing major advances to permit the practical use of engines and mechanisms at high temperatures.

TRIBOLOGY DEVELOPMENT

Gyroscope Bearing Lubrication

Early in the space program the need for special lubricants for precision gyroscope systems became apparent. The most popular lubricant soon became KG-80, which was a replacement for the original fluid Teresso V-78. Interest in fluids at various viscosity levels prompted the development of

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*Battelle Columbus Division, Columbus, Ohio.

the Super Refined Gyroscope (SRG) lubricants. These SRG fluids represent a homologous group that allows the users to select a specific viscosity, and the researchers to vary viscosity, in controlled experiments with a reasonable degree of confidence. Selecting the proper viscosity involves several important considerations depending on the application.

Operating torque is one important consideration in selecting the viscosity. Typical viscosity-temperature data are given in Figure 2 for the SRG fluids. Several experiments have been conducted with an R-6 bearing to define the torque and lubrication capabilities of the SRG lubricants. Figure 3 shows torque as a function of viscosity. This bearing was lubricated with a few milligrams of the selected lubricant by using a Freon carrier. The Freon evaporates and leaves a residual film of lubricant. The torque is related to the shearing of the viscous layer between the balls and races. Figure 3 clearly shows the torque penalty associated with increasing the viscosity of the bearing lubricant.

One advantage of increasing viscosity is illustrated in Figure 4. Lift-off speed is defined as the speed at which a lubricant film is formed that completely separates the balls and races in the bearing. The lubricant film condition is monitored by an electrical continuity approach. The dynamic electrical resistance of the bearing is interpreted in terms of percentage of lubrication, i.e., the percentage of the time no electrical shorting occurs. At a temperature of 60 C the R-4 bearing would generate a good elastohydrodynamic (ball race) lubricant film at a speed of 80 rpm if a KG-80 fluid were used. If an SRG-40 fluid were used, the speed required for good lubrication would be 160 rpm. The higher viscosity fluid would be preferred if the primary bearing operating speed was to be in this range. However, if the operating speed is much higher, the lower viscosity lubricant may be preferable because of the associated lower operating torque.

The lubricant viscosity is also a factor in evaporation rates, which can be important for vacuum applications where extended life is desired. In general, evaporation rates for a given type of fluid decrease as the viscosity is increased. For example, Table 1 presents measured evaporation rate data for two different lubricants at different viscosities. For long-life applications the lower loss rates associated with higher viscosities are desirable, but the high viscosity lubricants have the accompanying disadvantage of higher operating torques.

Cage Stability

Gross bearing torque can be controlled by proper selection of the lubricant and lubricant quantity in the bearing. However, bearing torque variations are much more difficult to control. Small torque variations in a gyroscope of a despun antenna support in space can result in intolerable errors in positioning and control. One major source of torque variation is erratic motions of the cage separating the balls. Under ideal conditions the cage simply rotates with the balls. However, under some conditions the cage incurs rapid secondary motion, which is known as cage instability. Cage instability generates erratic friction in a bearing, which is observed as erratic torque. Figure 5 is an example of torque fluctuation measured in a bearing operating in an unstable mode.

The key to cage stability lies in the tangential stiffness of the ball-race interfaces and the rate at which energy can be absorbed at these interfaces. When the cage strikes a ball, the ball will slip and generate a reactive force against the cage. If the slip occurs easily, such as when the balls and races are completely separated by a film of low viscosity fluid, the reaction force is small. Under such conditions the cage energy is absorbed by shear losses in the lubricant film. Conversely, if the ball and races are separated by a highly viscous fluid, the ball slippage will be small, the shear losses much less, and the cage motion will be undamped. Depending on the parameters of the particular bearing, cage instability can be a serious problem.

A cage stability criterion is given by:

$$Dp = \frac{32C_{\mu}^{2}}{M\,C_{sl}} \tag{1}$$

where

$C\mu$ is a ball-race traction parameter inversely related to film thickness
C_{sl} is the ball-cage spring rate (linearized)
M is the cage mass

$$C\mu \approx \mu_{avg} A/h \tag{2}$$

where

μ_{avg} is the average contact zone viscosity ($\sim 10^6$ Cp for a mineral oil)
A is contact area
h is film thickness

As h gets small or μ_{avg} gets large, $C\mu$ gets large.

The larger the value of Dp the higher the likelihood the cage will be unstable. An approximate criterion for cage stability is given in Figure 6. To check stability, values of the ball-cage friction coefficient, f, and a factor e_f must be known, where:

$$e_f = \exp(-\pi/Dp-1) \tag{3}$$

An accurate assessment of cage stability requires analyses of the cage motions using comprehensive computer models.

Lubricant Distribution

Large spacecraft starting with Skylab have brought a new set of tribological problems. Smaller spacecraft could be stabilized by spinning the spacecraft or by the use of control jets. The large extended mission spacecraft require large control moment gyroscopes (CMG's), which are capable of handling large slew loads resulting from astronauts moving around the crafts and from changing the orientation. The large CMG's have considerable weight and operate at high speeds. Small bearings using lubricant-impregnated retainers no longer suffice for these units; positive lubrication of large bearings is required. The lubrication has to be highly reliable, but extremely compact to meet weight and space requirements.

One major tribological challenge is insuring that the lubricant gets into the bearing to lubricate the ball-race interfaces. Devices such as centrifugal oilers attached to the rotating shaft were successfully used in some applications. However, positive lubricators in space require a hard look at how lubricant migrates around the bearing cavity in a vacuum environment. Typical results of creep tests are shown in Figure 7.

A drop of lubricant approximately 0.5 mm in diameter was positioned on a polished steel plate in a 10 mPa (10^{-5} torr) vacuum chamber. The spreading of the drop was monitored over a period up to 400 hours. For the two lubricants shown in Figure 7, the rate of creep would decrease over an extended time period. The higher viscosity fluid, SRG 160, tended to creep much more slowly than the low viscosity fluid, SRG 60. The lubricants would not creep around sharp edges or over a debris track of Synthane. Lubricant tended to creep in the direction of a thermal gradient of 4C, as shown in Figure 8. Lubricant would not creep against the thermal gradient. These results demonstrated that the lubricant must be resupplied directly to the ball tracks on the races or to the balls themselves. Since the quantity of make-up lubricant is very small, the delivery system must be arranged for the centrifugal force field to permit direct impingement on the races, as opposed to controlling the direction through a jet. The tribology technology developed for large CMG's permitted the design of automatic lubricators that functioned for extended missions.

Transfer Film Lubrication

One major key to the success of the NASA space efforts has been the use of highly efficient systems and the minimization of weight. Large tribology devices cannot be tolerated and every effort must be given to optimizing system performance. In some applications, such as the liquid oxidizer and fuel pumps in the Space Shuttle main engine, the bearings must be cooled and lubricated with the cryogenic fluid. Cryogenic fluids tend to be good for bearing cooling, but are poor lubricants. One method to lubricate bearings in this environment is by transfer film lubrication.

Transfer film lubrication implies that the lubricating cage material is transferred to the ball and, in turn, to the races, Transfer film technology is in its infancy as a tribological science and little is known about materials or operating conditions required to optimize this type of lubrication. In most applications, transfer films are difficult to achieve and even more difficult to substantiate. Enough is known about transfer films to realize both their importance and their limitations.

Figure 9 shows the results of transfer film studies with Rulon-A and 5 percent MoS_2. A 440C ball (Figure 10) was loaded against an oscillating 440C cylindrical ring. A Rulon-A wiper was loaded against the ball to create a transfer film for the ball-race interface. As the load (contact stress) between the ball and ring was increased, the roughness of the ring wear track decreased slightly. At a mean stress level of 1.38 GPa (200,000 psi) the transfer film was insufficient to prevent roughening of the surfaces. The experiments imply that there is a limiting stress for effective transfer film lubrication.

The traction associated with solid surface films can be computed using elasticity theory for the traction of surface layers, as shown in Figure 11. The smaller the value of γ in the Figure, the lower is the surface film elasticity. Values of γ of 0.01 might be associated with MoS_2, and values of γ of 0.002 would be indicative of a PTFE coating. The traction-slip curves are, in many respects, similar to those for liquid lubricants. An effective viscosity for a transfer film can be expressed:

$$\mu_{eff} = \frac{2p_o h}{3V} \frac{C_T V}{\Delta V} \tag{4}$$

where

p_o is the maximum contact pressure
C_T is the traction coefficient
h is film thickness
V is rolling velocity
ΔV is slip velocity

For a solid-film-lubricated bearing, Equation 4 in conjunction with Equations 1-3 show the factors affecting cage stability. Large values of the traction coefficient, for a given value of slip, can product an unstable cage. The lower the resilience of the surface film, the greater the probability for cage unstability.

CONCLUSIONS

Numerous tribology problems have been encountered in the development of aerospace mechanisms. These problems have led to research activities which have not only yielded solutions to the problems but have also aided in overall technology development. Examples of aerospace tribology advances include better understanding of bearing torque, elastohydrodynamic lubrication, lubricant distribution, cage stability, and transfer film lubrication.

There are several tribology related problems currently facing industry and specifically the aerospace industry. For example, lack of tribology materials and lubricants are major limitations to high temperature engine development. Lack of low temperature lubricant technology is a limitation to cryogenic lubrication. Bearing precision is a limitation to very accurate mechanical control devices. The research required to address these and other problems promises to insure a productive future in tribology.

TABLE 1. EFFECT OF VISCOSITY ON EVAPORATION RATE OF TWO LUBRICANTS IN A 0.133 MPa (10^{-6} TORR) VACUUM

Fluid	Published Viscosity at 40C, 10^{-6} m^2/s	Weight Loss Rate at 40C mg/cm^2-hr
Super-refined Paraffinic Mineral Oil (SRG 30)	14	18
Super-refined Paraffinic Mineral Oil (SRG 40)	27	13
Perfluoro Ether	8	2.2
Perfluoro Ether	28	0.19
Perfluoro Ether	357	0.0002

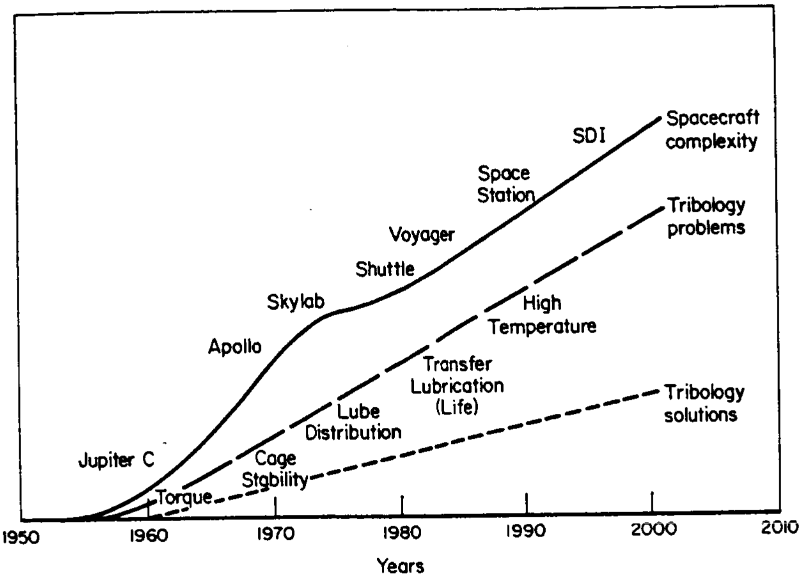


Figure 1. - Tribology challenge.

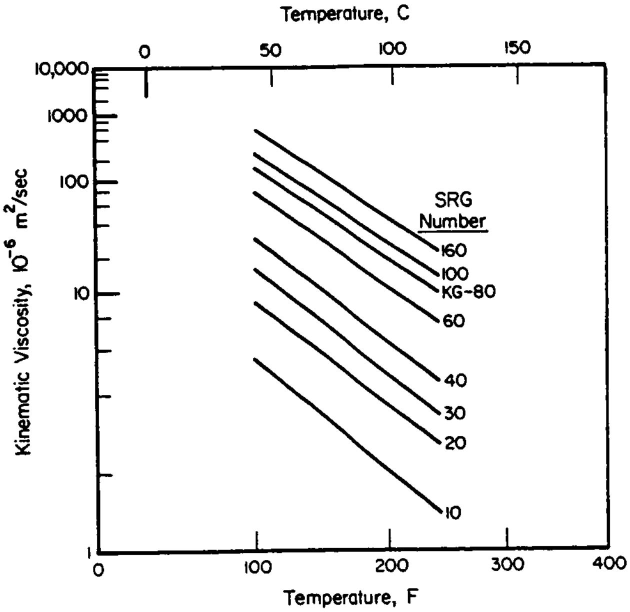


Figure 2. - Viscosity versus temperature for a homologous series of super-refined mineral oils.

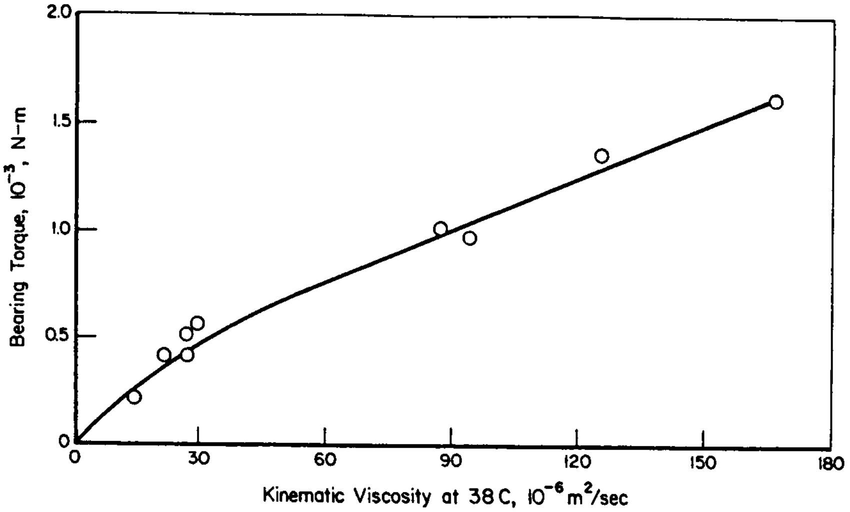


Figure 3. - Measured bearing torque as a function of lubricant viscosity for various lubricants at 25C for an R-6 bearing at 480 rpm.

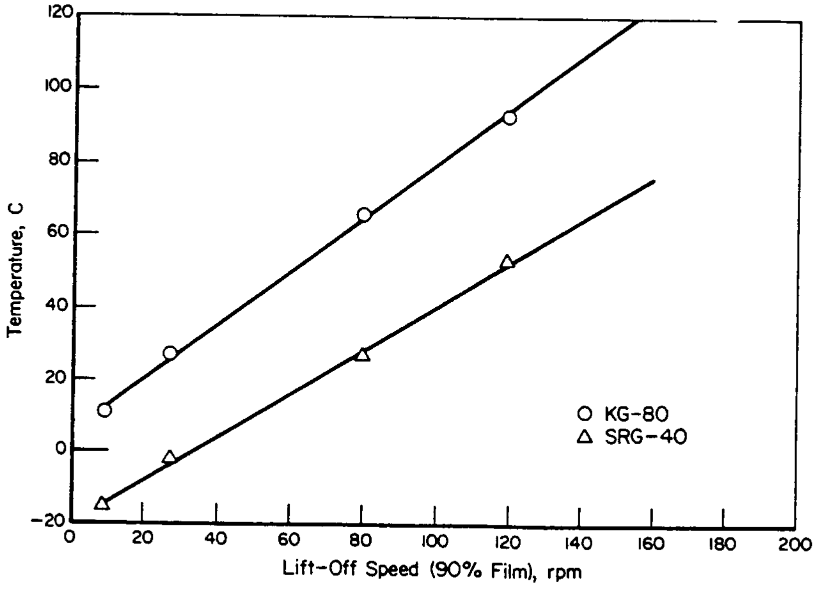
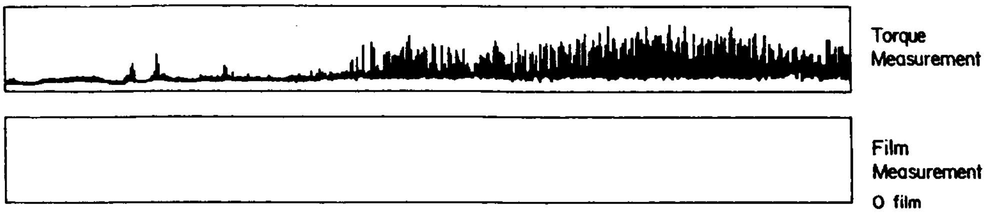
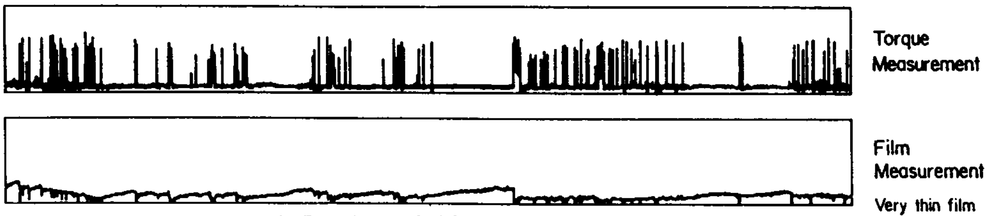


Figure 4. - Lift-off speed as a function of temperature for an R-6 bearing loaded to 980 MN/m^2 maximum Hertzian contact stress (inner race) and lubricated with two superrefined mineral oils.



a. Dry bearing.
Chart speed: 1 div = 5 sec (left to right)



b. Two drops of oil in bearing.
Chart speed: 1 div = 5 sec (left to right)

Figure 5. - Bearing torque and film thickness measurement with no lubricant and meager lubricants. Torque spikes imply instability.

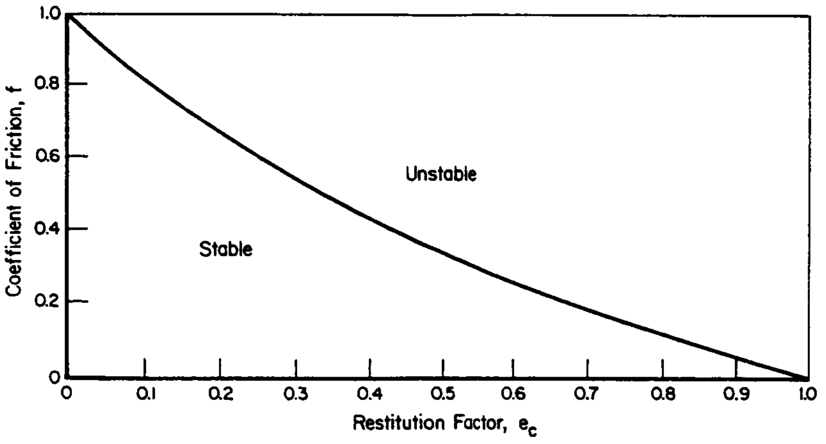


Figure 6. - Quick check of cage stability.

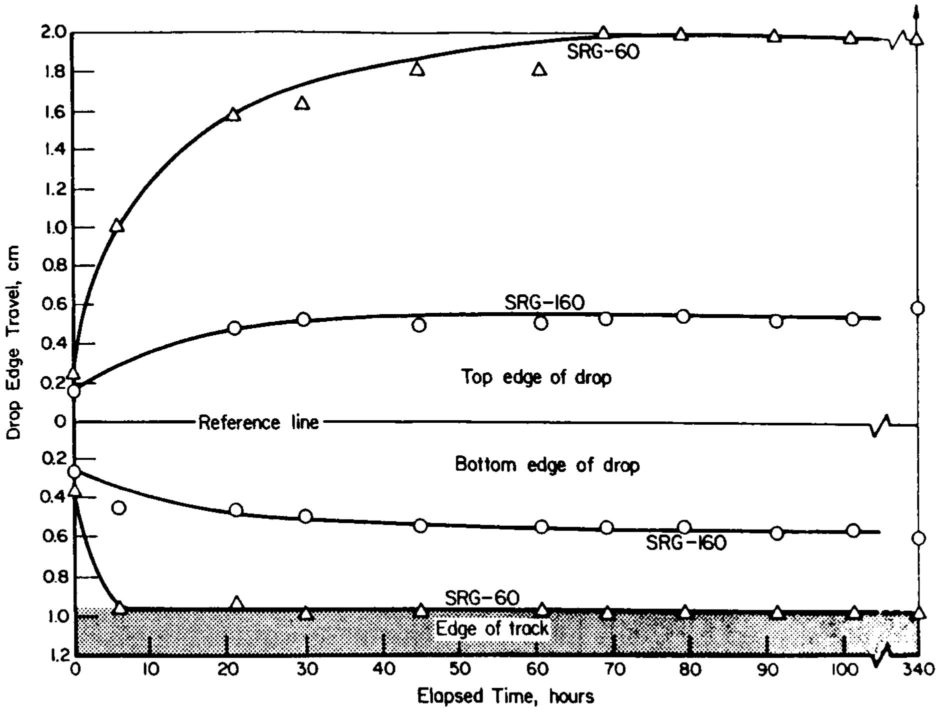


Figure 7. - Results of creep experiments in presence of a synthane transfer film SRG-60 and SRG-160 oils.

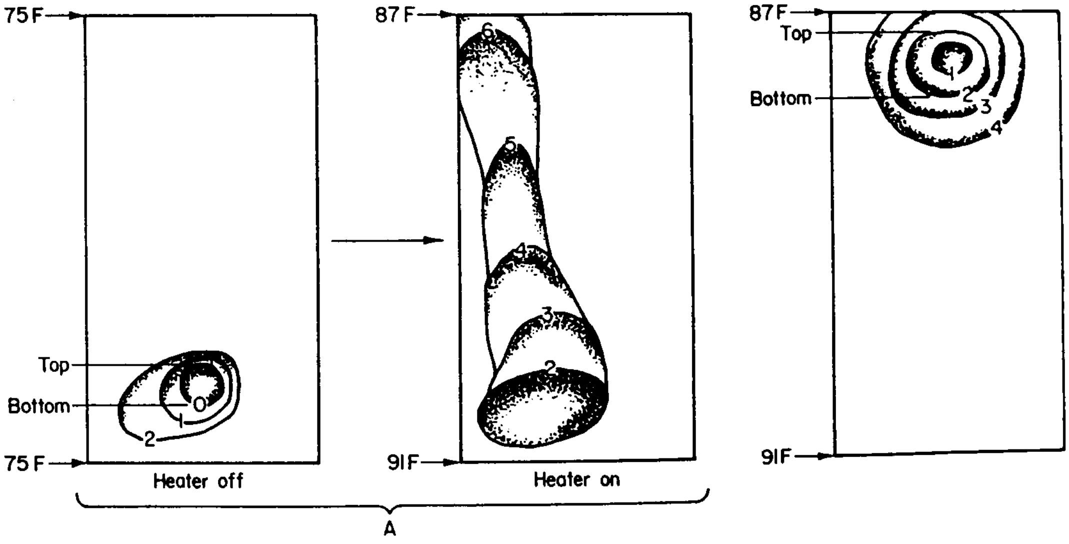


Figure 8. - Sketch showing migration patterns of KG-80 in the presence of a 4 F thermal gradient.

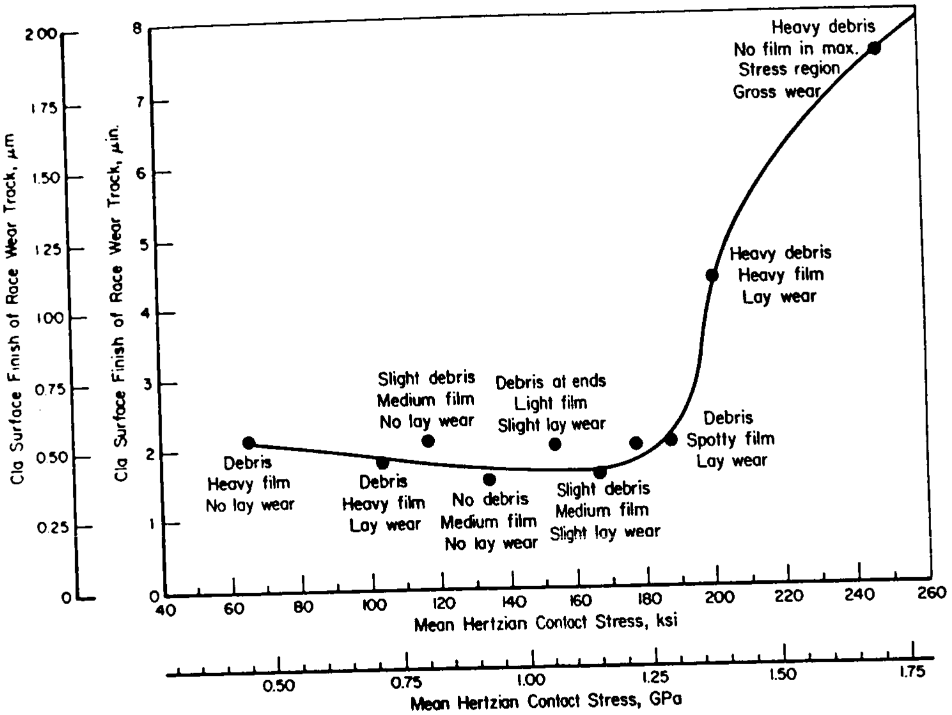


Figure 9. - Relationship between race wear track surface finish and ball-race contact stress for a race lubricated with a rulon-A + 5 percent MoS_2 transfer film.

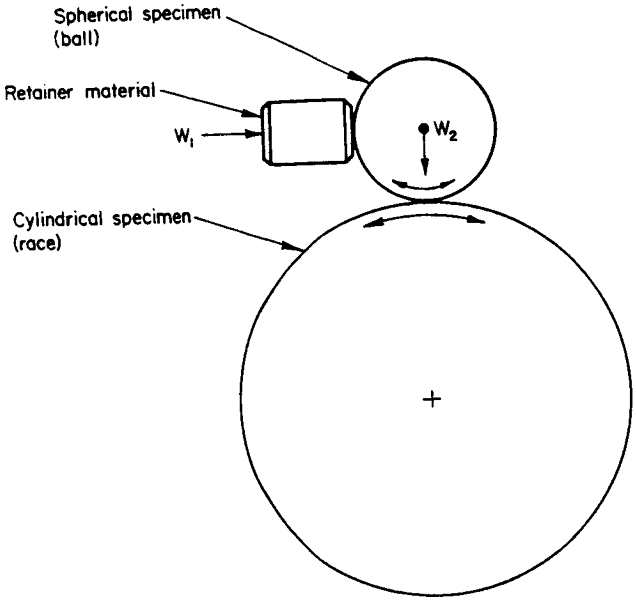


Figure 10. - Schematic drawing of apparatus for transfer analysis.

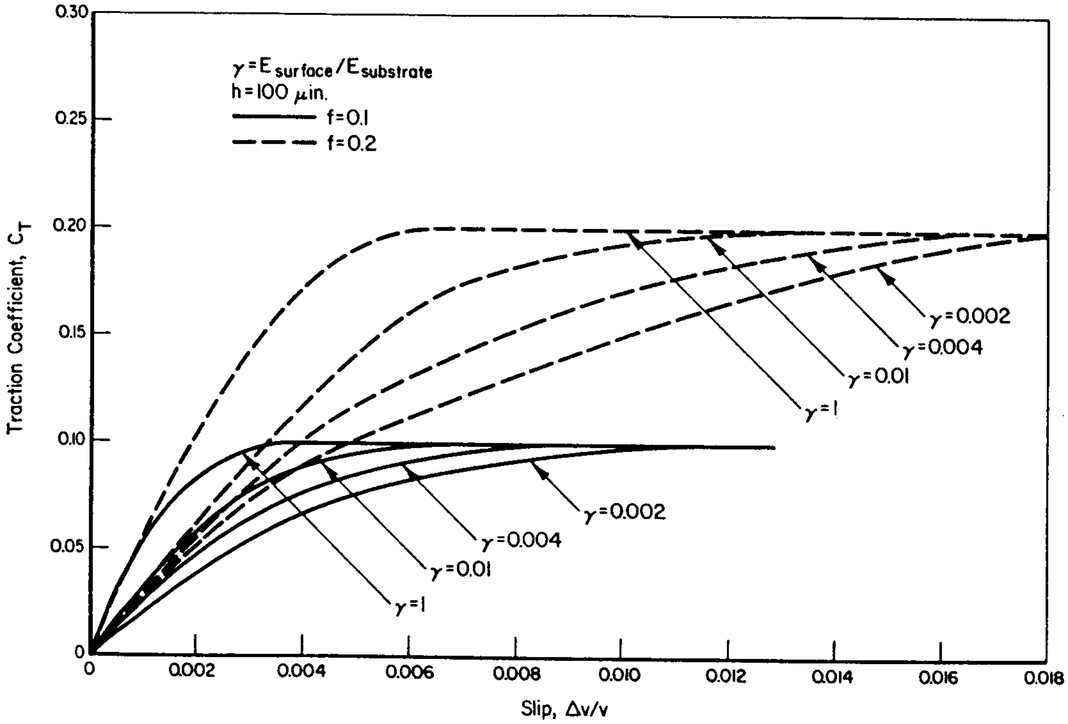


Figure 11. - Theoretical traction slip curves for various coatings.