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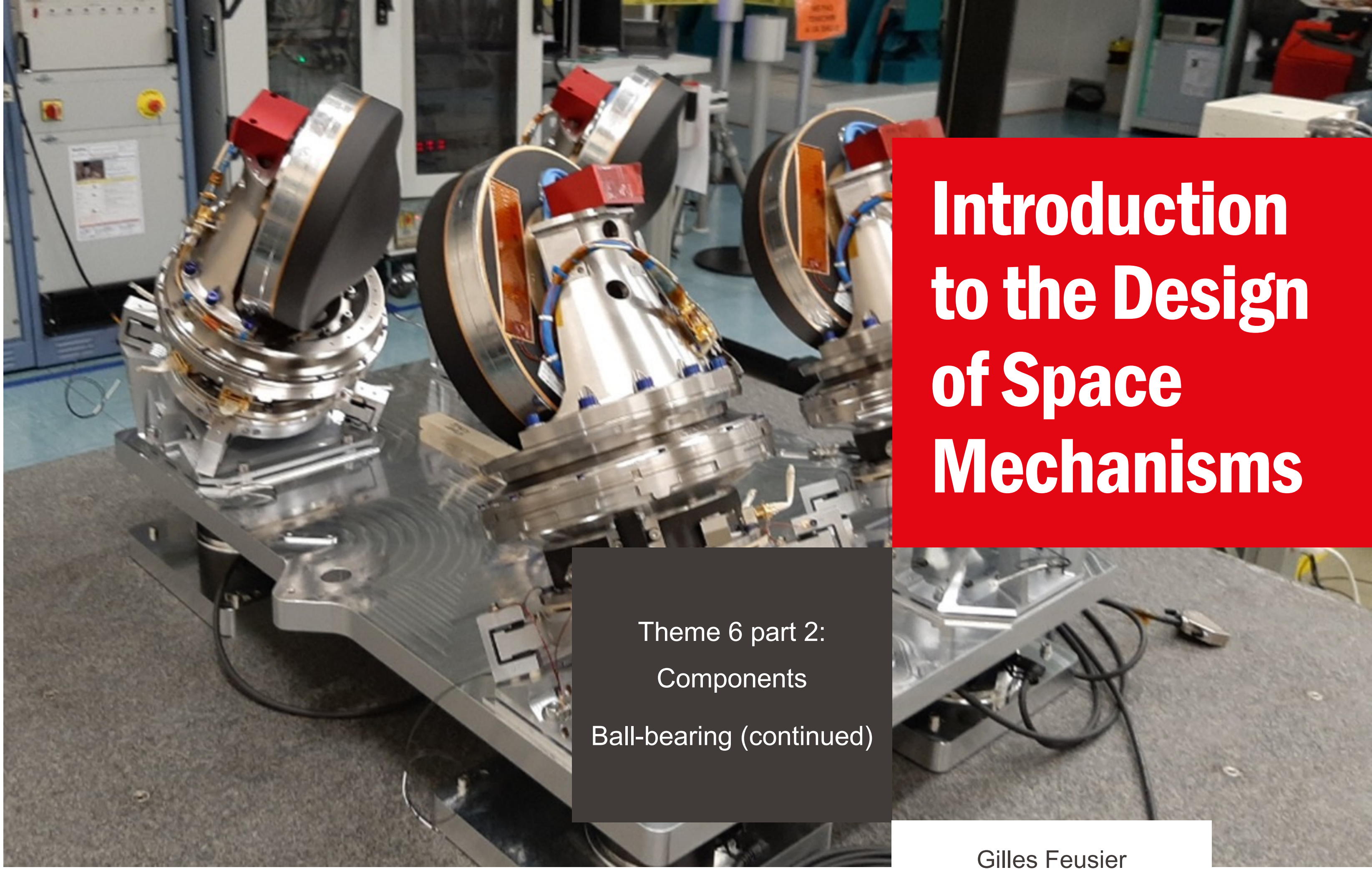


Introduction to the Design of Space Mechanisms

Theme 6 part 2:

Components

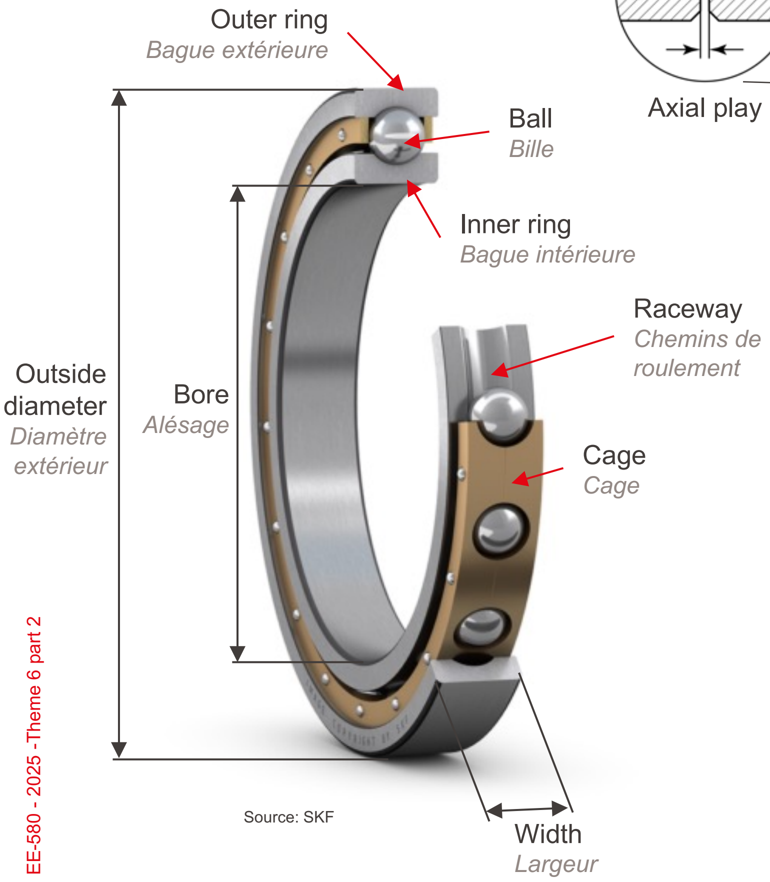
Ball-bearing (continued)

Gilles Feusier

Theme 6 Part 1 Summary

- Various type of components
  - Mechanical components (bearings, actuators, …)
  - EEE components (cables, connectors, sensors, …)
    - According to ECSS-Q-ST-60C Rev.2 and ECSS-Q-ST-60-13C
    - Classified: three classes
    - Use of COTS
- Ball-bearings
  - Usages
  - Types
  - Materials
  - Lundberg-Palmgren, life evaluation
  - Assembly
  - Preload

Ball Bearing



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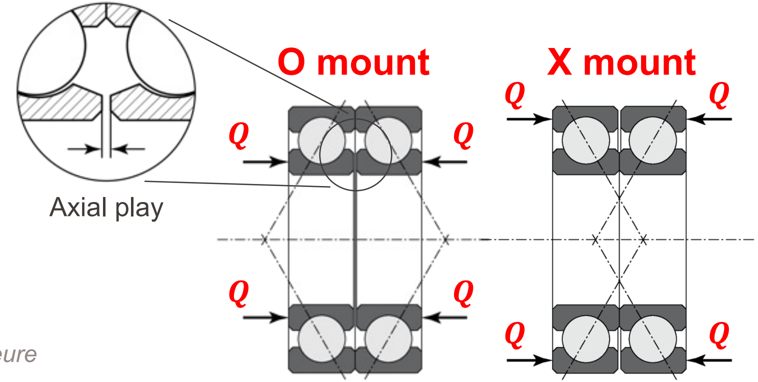
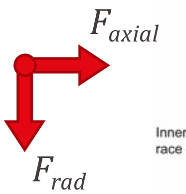
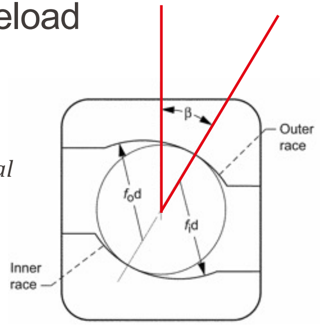
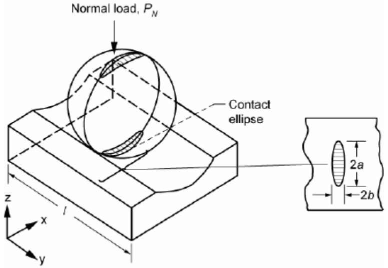


Q: preload





$$P = X \cdot F_{rad} + Y \cdot F_{axial} \quad [\mathrm{N}]$$ *Equivalent dynamic radial load*



Hertz Pressure

Lundberg-Palmgren:

$$L_{10} = \left(\frac{C}{P}\right)^3 \quad [10^6 \text{ rev.}]$$

C: Basic dynamic radial load rating

Ball bearing – Thermal Conductivity

- **Thermal conductivity:**
  - Low: only few thermal exchange between stator and rotor through the ball bearings
  - **Example**: ball bearing SAE 75 (Ø75 x Ø96 x 10 mm)
    - Thermal conductivity (dry ball bearing, no rotation):

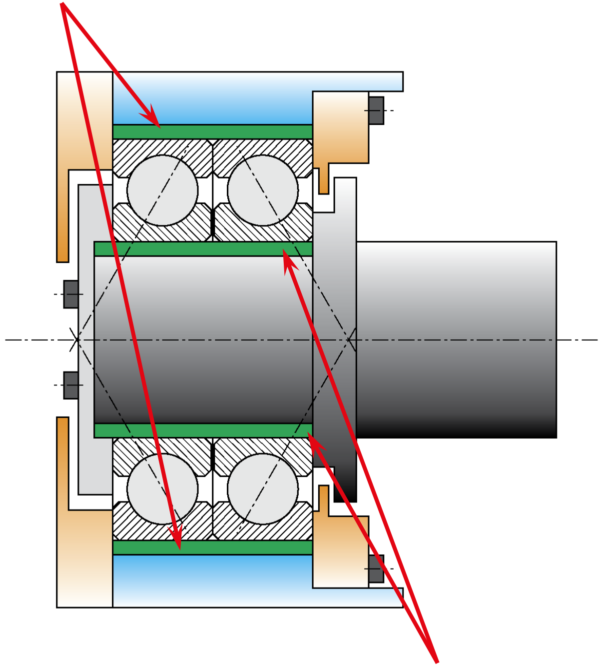
$$\lambda = 0.013 \text{ W/°C}$$

    - With a radial load: only few balls in contact, hence participating to the heat transfer
    - Thermal conductivity will increase with the preload and the axial loads
    - The lubricant: depends on lubricant type
    - With rotation there is a tendency to increase the thermal conductivity

Ball bearing – Thermal Effects

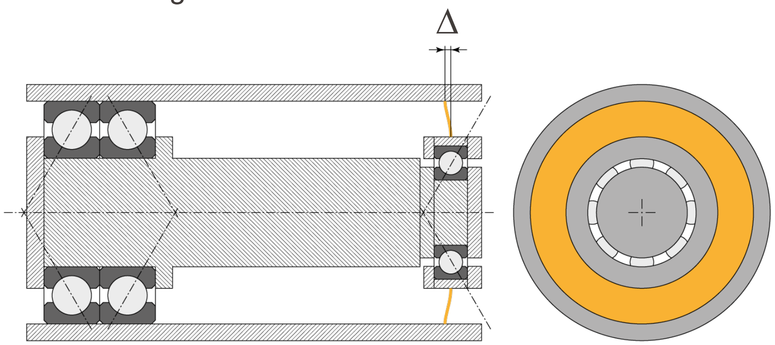
- **Radial thermal expansion**
  - Non-uniform thermal expansion of the shaft and housing if:
    - Uniform temperature but different materials
    - Thermal gradient between stator and rotor
  - Solutions
    - Utilization of materials for the rotor and stator with thermal expansion coefficients close to the one of the bearings (e.g. steel, titanium)

      ⇒ Excess mass!
    - Utilization of **intermediate rings** in steel or titanium press fitted or knocked-in in the aluminum housing/on the shaft.

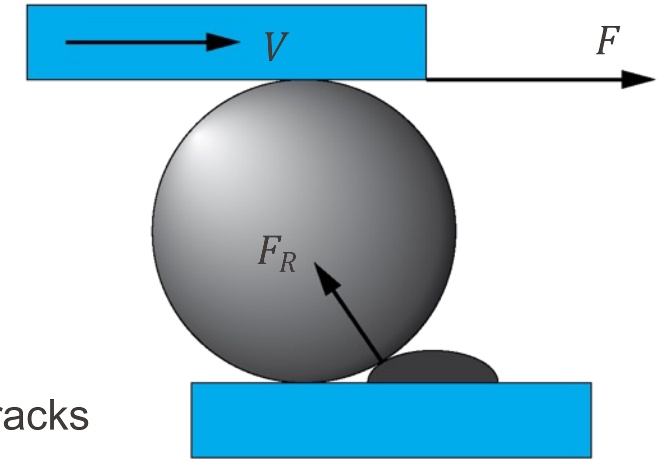


Ball bearing – Thermal Effects

- **Axial thermal expansion**
  - Change of shaft and housing length if:
    - Uniform temperature but different materials for shaft and housing
    - Shaft and housing at different temperatures
  - Effects
    - Misalignment of inner and outer ball bearing rings
    - Change of preload
    - Torque variation
    - Potential deformation of ball bearing rings and balls if the preload is too high
    - Loss of preload and creation of a gap
  - Solutions
    - **Soft preload**
      - Not appropriate for vibrations
      - Sliding between shaft and inner ring or housing and outer ring ⇒ risk of jamming
      - Soft preload applied through a membrane: highly non-linear, similar to a hard preload, without sliding.
    - **Hard preload**
      - Ball bearing pair on one side, single supporting bearing on the other side
      - Utilization of same materials for shaft and housing



Ball bearing – Torque Noise



- The torque noise depends on:
  - Preload and load
  - Rotation speed
  - Lubrication
  - Cleanliness
  - Surface finish and materials of the balls and tracks
  - Deformation of the rings
  - Non-sphericity of the balls, geometry of the tracks (tolerance classes)
  - Type of cages

- Standard manufacturer records
  - The standard conditions (load, speed, lubrication) do not necessarily correspond to the operational conditions of the mechanism
  - Results are comparable in standard conditions

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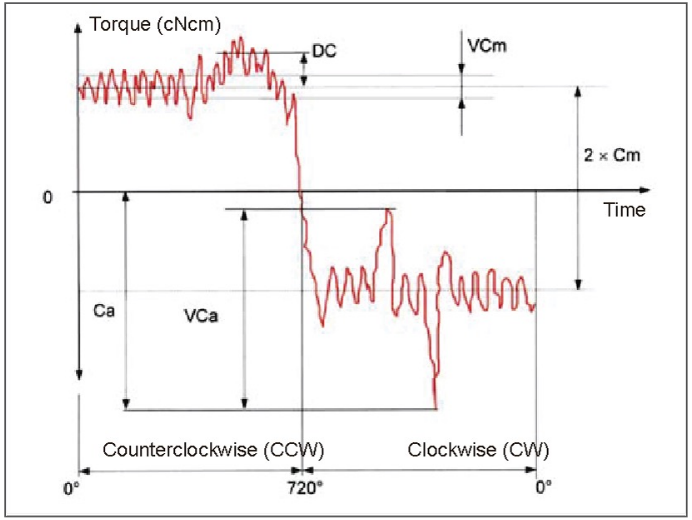
Ball bearing – Torque Noise

SCHEMATIC REPRESENTATION OF THE RUNNING TORQUE



Cm **Mean torque** during the entire measurement

Ca **Peak torque** peak coupling point

VCa **Maximum hash width** of the running torque

VCm **Average hash width** of mean torque

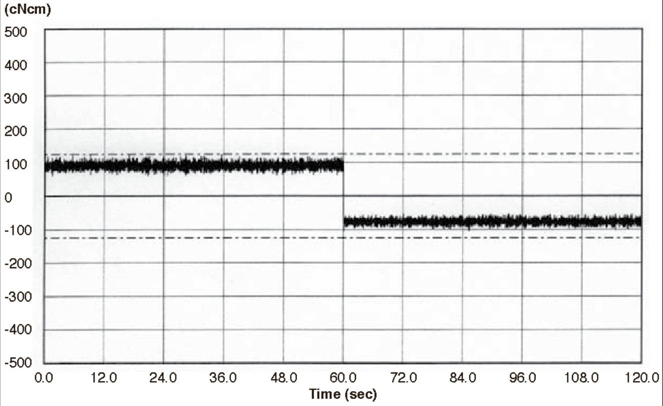
DC **Torque derivation**: maximum deviation between the running mean over 600 points and the mean value (CR)

For information: the starting torque value can usually attain twice the running torque value.

Source: ADR Catalogue [6.3]

ADR	ADR BTT10 V3.6	
	CONTROL REPORT	Date: 19/02/2008
	BEARING FRICTION TROQUE TRACE	Time: 08/10/28
		Visa: CDU

Product order: 405098				
Bearing reference: WAY30RT4DO150W201MRC44			Experimental conditions	
Bearing number: 1			Load (N):	450.
Torque (cNcm)	Measured values	Tolerances	Speed (rpm):	2.
Mean torque (Cm)	83.32	125.00	Tool radius (cm):	3.2
Peak torque (Ca)	123.57	—	Tuning masse (g):	145.
Maximum hash width (VCa)	64.51	—	Sensor n°:	J008
Average hash width (VCm)	21.81	—	Temperature (°C):	20.
Torque derivation (DC)	1.04	_	RHL (%):	—



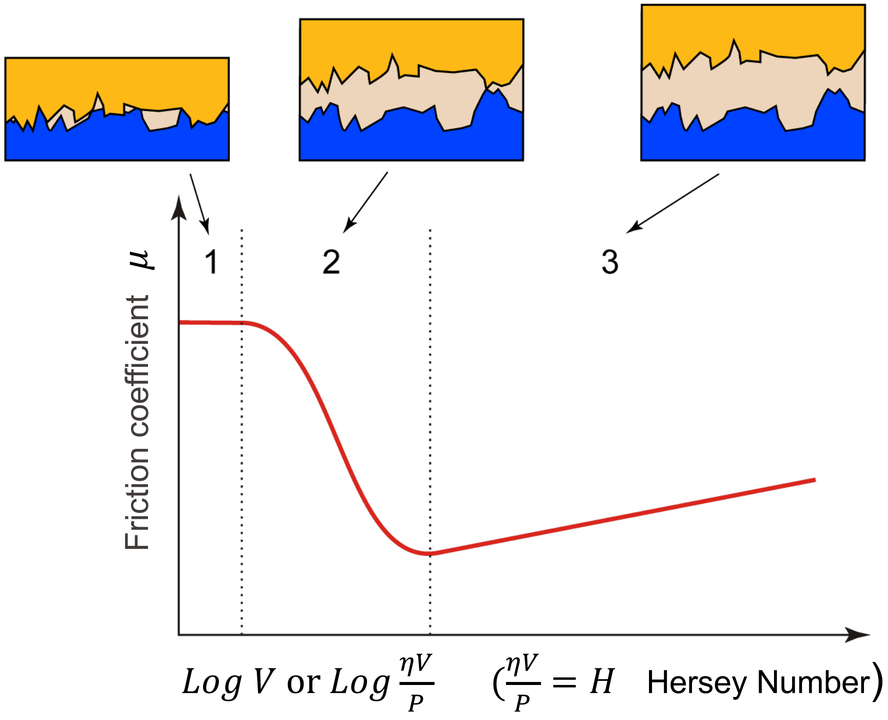
Data file name: C:\BTT10\Data\405098\ Edition date: 19/02/2008

Ball bearing - Lubrication

- **Fluid lubrication**
  - Oil, grease
  - Evaporation and migration (creep) maybe detrimental for space application under vacuum
  - Self-repair, long lifetime
  - Chemical damages (contamination as well as too high Hertz pressure)
- **Dry lubrication**
  - **MoS_2** (applied through sputtering): extended use in space applications, very sensitive to moisture (damaged by moisture)
  - **Evaporated metals**
    - Ag, Au
    - **Lead** (ESR Technology special process): extended use in space applications. Damaged when used under air. Supply and lead time.
  - Limited load capacity (Hertz pressure) when compared to fluid lubricants

Ball bearing - Lubrication

- Stribeck Curve



1. **Boundary lubrication**: Solid surfaces come into direct contact, load supported mainly by surface asperities, high friction
2. **Mixed lubrication**: Some asperity contact, load supported by both asperities and the liquid lubricant.
3. **Hydrodynamic lubrication**: Negligible asperity contact, load supported mainly by hydrodynamic pressure.

η : dynamic viscosity of the fluid
V : entrainment speed of the fluid
P : normal load per length

Ball bearing - Lubrication

- Comparative summary between dry and fluid lubricants

Source: NASA/CR-2005-213424, Lubrication for space Applications, William R. Jones, Jr., Mark J. Jansen, Ohio [6.7] *(reading)*

Table 1 - Relative merits of solid & liquid space lubricants [17]

Dry Lubricants	Wet Lubricants
Negligible vapor pressure	Finite vapor pressure
Wide operating temperature	Viscosity, creep and vapor pressure all temperature dependent
Negligible surface migration	Sealing required
Valid accelerated testing	Invalid accelerated testing
Short life in moist air	Insensitive to air or vacuum
Debris causes frictional noise	Low frictional noise
Friction speed independent	Friction speed dependent
Life determined by lubricant wear	Life determined by lubricant degradation
Poor thermal characteristics	High thermal conductance
Electrically conductive	Electrically insulating

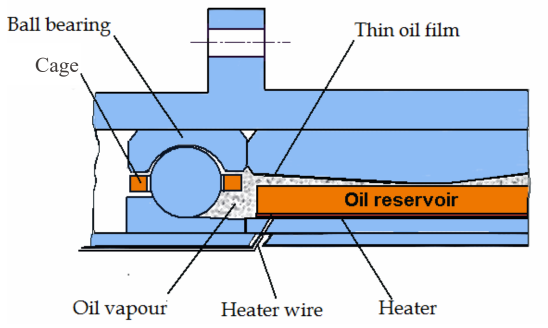
Ball bearing - Lubrication

- Fluid lubricant formulation
  - Viscous part (large molecules, more or less cross-linked)
    - Mineral oils
    - Silicone oils
    - Esters
    - **Perfluoropolyethers (PFPE)**
    - **Synthetic Hydrocarbons**
      - The **bold emphasized** oils are the most used oils in modern space applications:
        - High lubricating power
        - Very low vapor pressure
    - Ionic liquids: very low vapor pressure, high lubricating power, but risk of corrosion
  - Additive (for high contact pressure, high speed, high temperature)
    - Increase of the performances and lifetime
    - Most of the industrial additive have a high vapor pressure (evaporation and loss of properties)

Ball bearing - Lubrication

- **Grease formulation**
  - Base oil
  - Thickener: mainly PTFE (Polytetrafluoroethylene) for space applications
  - Higher resistance to high contact pressure than oil
  - Generate a higher resistive torque than oil

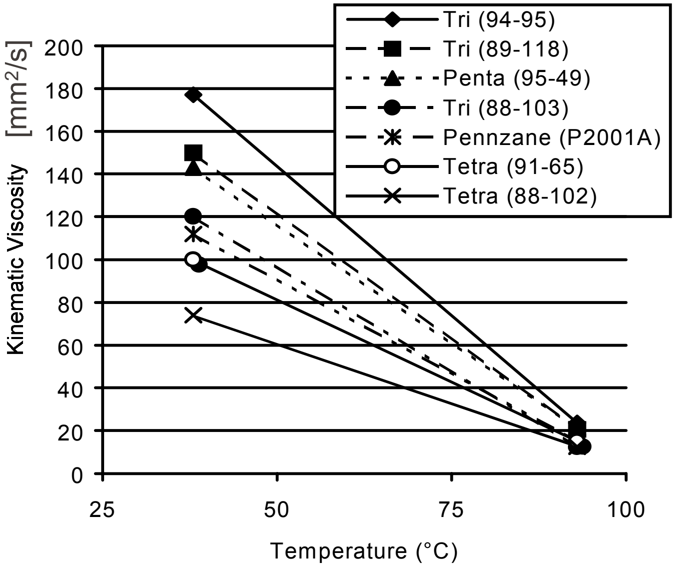
- **Combination of oil and grease:**
  - Grease is applied to the tracks and balls
  - Cages and reservoirs (if any) are impregnated with oil



Source: S. Krishnan et al. (2011). Lubrication of Attitude Control Systems, Advances in Spacecraft Technologies, Dr Jason Hall (Ed.)

Ball bearing - Lubrication

- Viscosity
  - Highly dependent on temperature
  - At low temperature, the freezing of the lubricant may block the mechanism
  - At high temperature, the lubrication power may become insufficient and can lead to the jamming of the part in friction



Slope ↗ ⇒ Changes of viscosity with temperature ↗

Note: Viscosity Index ↗ ⇒ Slope ↘
[unit less, arbitrary measure]

Source: W.R. Jones et al. "The Tribological Properties of Several Silahydrocarbons for Use in Space Mechanisms", Proceedings of the 9th European Space Mechanisms and Tribology Symposium (ESMATS 2001), September 2001.

Ball bearing - Lubrication

- **Evaporation**
  - Use of closed volumes as much as possible
  - Use of labyrinth at the openings
  - Use of reservoirs (porous materials saturated with oil)

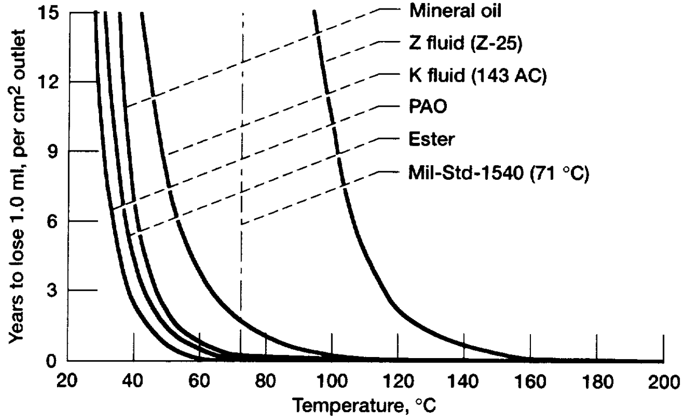


Figure 4.—Relative evaporation rates of aerospace lubricants [Conley and Bohner, 1990].

Source: W.R. Jones et al. "Space Tribology", NASA / TM-2000-209924

- **Migration (creep)**
  - Use of anti-creep barriers
  - Use of sharp edges if possible

Ball bearings

- Material of the rings
  - Space bearing: mainly stainless steel AISI 440C
- Material of the balls
  - Stainless steel
  - Coated steel
    - TiC (hard coating, avoid cold welding)
    - Lubricant (MoS_2): rapid wear, but self-repair through material transfer
  - Ceramic (Si_3N_4, ZrO_2)
- Cages
  - Impregnated phenolic resin (MoS_2 for dry lubrication, oil for fluid lubrication)
  - Metallic (bronze, steel) Note: steel is not very popular for space applications
  - Vespel® PTFE, PEEK, Torlon®, etc

Source: The Barden Corporation Ltd

Theme 6 - Ball-bearings. Summary

- Usages
- Types: load capacity, including under vibrations
- Materials: resistance to corrosion
- Lundberg-Palmgren, life evaluation
  - Nominal life L_{10}
  - Equivalent loads
  - Allowable Hertz pressure: ground application standards, space applications
- Assembly and preload
  - Hard and soft preload
  - Gapping
- Thermal performances
- Torque noise
- Lubrication
  - Oil, grease, solid lubricants