Proper Lubricant Selection for Rolling Bearing Applications

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Abstract: *Proper selection of lubricant is a decisive task in achieving the maximum possible bearing life for a certain application. In this paper a theoretical part concerning bearing lubrication and the RKB software dedicated to the proper lubricant selection are presented.*

Key words: *lubricant selection, reference/actual kinematic viscosity, viscosity index*

1 Introduction

It is well known that at least 60% of premature bearing failures are due to incorrect lubrication. Even high quality bearings can exhibit best performance only when they are lubricated correctly. Rolling bearings must be lubricated to prevent the harmful metal-to-metal contact between the rolling elements, raceways and cage and to protect the bearing from corrosion and wear as well. In addition, bearing lubricant has to ensure dissipation of heat, elimination of contaminants, flushing away of wear debris, lubrication of the seal lips and filling of labyrinth seal gaps. It is worth mentioning here that the function of lubricant in seals is different from that in bearing itself and therefore it is better to lubricate bearings and seals separately, choosing the best lubricant for each, even if, unfortunately, this solution is rarely implemented, because of high costs, possibility of making mistakes by substituting one lubricant with another, etc.

The general principles of hydrodynamic lubrication can be applied, within certain limits, to explain lubrication of rolling bearing elements. However, in the case of rolling bearings, the contact area is extremely small and, consequently, the load pressures may reach high values, in the range of 1–3 GPa. Under such extremely high pressures, an elastic deformation of the contacting surfaces occurs, the load-bearing area increases and the oil is totally squeezed from between mating surfaces. Consequently, the oil pressure increases by several orders of magnitude and, therefore, a thin viscoelastic lubricant film, which becomes capable of supporting the external load, is maintained between the surfaces. This special lubrication regime is known as *elastohydrodynamic lubrication* in which the friction and film thickness between the two bodies in relative motion are determined by the geometry and the elastic properties of the bodies, by the relative speed, and by the viscosity of the lubricant at the actual pressure, temperature and rate of shear.

In the particular case of rolling bearings, the thickness and load carrying capacity of the lubricant film mainly depend on the viscosity and other oil properties and on the bearing internal geometry, speed, and size. When the bearing starts to run, the contact between mating surfaces of rolling elements and raceways is mostly metal-to-metal, because the oil film thickness is small, in relation to surface roughness, hence a large number of metallic asperities come into contact. As speed increases, the lubricant film thickness also increases and fewer asperities make contact. In order to reach the desirable lubricant full film, bearing geometry, application conditions (speeds and loads), and lubricant properties have to combine to form an oil layer so thick that even the highest peaks do not penetrate the film and do not come into contact with each other. If this situation is achieved during operation, the subsurface stress will be the only responsible for the bearing fatigue failure and a long bearing life is expected. In this context the role of the temperature cannot be excluded. The most appropriate working temperature for a rolling bearing is the temperature that requires the minimum lubricant quantity necessary for an optimal lubrication.

2 Oil or Grease Lubrication?

Among other important factors (especially those connected to operating and environmental conditions), bearing loads and speeds are of crucial importance when selecting the appropriate type of lubricant for a certain application. As a basic orientation in using grease lubrication, equation (1) can be used. If the mentioned condition is not fulfilled, oil lubrication can be chosen.

$$\frac{P}{C} \le \left(\frac{P}{C}\right)_{lim} \tag{1}$$

where:

- P – dynamic equivalent radial/axial load, kN;
- C – basic dynamic radial/axial load rating, kN;
- $(P/C)_{lim}$ – load ratio limit for grease lubrication. The load ratio limit for grease lubrication is a function of bearing type, size, and speed and is given by the following approximate but useful equation:

$$\left(\frac{P}{C}\right)_{lim} = \frac{1}{8} \cdot \frac{10^6 - F}{10^5 + F} \tag{2}$$

where:

- F – adjusted speed index, $mm \cdot min^{-1}$:

$$F = K_b \cdot D_{pw} \cdot n \tag{3}$$

- K_b – bearing type factor (1 for radial or thrust ball bearings and cylindrical roller bearings, 2 for tapered or spherical roller bearings, 3 for full complement cylindrical roller bearings and cylindrical roller thrust bearings);
- n – bearing speed, rpm;
- D_{pw} – bearing pitch diameter, mm. For simplified but well approximated calculation, instead of the pitch diameter D_{pw} one can use the bearing mean diameter D_m (mm):

$$D_m = \frac{D + d}{2} \tag{4}$$

- D – bearing outer diameter, mm;
- d – bearing bore diameter, mm.

The advantages and disadvantages of certain mineral or synthetic oils to lubricate specific applications must be carefully considered when selecting a lubricant and designing a lubrication system. Oil lubrication is suitable when high speeds or operating temperatures make difficult or even impossible the use of grease and when it is important to quickly evacuate the heat from the bearing and housing. For high-speed operation, since the heat generated in rolling bearings increases with oil viscosity, it is necessary to select low-viscosity oil (otherwise the bearing temperature would increase too much). On the contrary, for very slow speeds, viscous oils are used to ensure a sufficiently strong oil film. On the other hand, insufficient oil viscosity may result in metal-to-metal contact and therefore possible premature failure.

Since the key elements in choosing the appropriate grease for a bearing application are the characteristics of the grease base oil, hereinafter we will use only the generic term "oil" and the reader is asked to understand that we refer, as appropriate, to the oil itself (as direct lubricant) or to the base oil of the lubricating grease.

3 Oil Main Properties

3.1 Viscosity

The most important characteristic of oil is its viscosity. Among a large number of viscosity types, in the lubricant industry the most used is the kinematic viscosity (ν) – hereinafter called simply viscosity – and its usual unit of measure is mm^2/s (also known as cSt). Since viscosity varies with temperature it is a common practice to indicate the viscosity of oil at a certain reference temperature. Most often this reference temperature is 40 °C and the oil viscosity at this temperature is designated by ν_{40}.

The work of The British Standards Institution (BSI) and the American Society of Lubrication Engineers (ASLE) was concretized in the ISO viscosity classification system [9], which it is now highly recommended for all kinds of industrial applications. The ISO viscosity classification consists of a series of 18 viscosity ranges (Table 1) extracted from the viscosity interval 1.98 –1 650 mm^2/s. Each interval is defined by a number called Viscosity Grade (VG) that represents the rounded value of the mid-point of the respective grade range. As a general rule, each subsequent VG is approximately 50% higher than the previous, whereas the minimum and maximum values of each grade range are by 10% less and higher than the mid-point, respectively. For example, ISO VG 220 refers to a viscosity grade range of

220 mm^2/s ± 10% (at 40 °C). The ISO system is also adopted by ASTM standards [5] and since the American Gear Manufacturers Association (AGMA) has issued [3] own specifications for gear lubricants used in various types of gear application, Table 1 contains the ISO-AGMA grade equivalence also.

Table 1 – ISO classification of industrial oils and AGMA/ANSI equivalence

ISO 3448:1992 Viscosity Grade	Kinematic viscosity at 40°C [mm^2/s = cSt]			AGMA/ANSI 9005-D94 Grade
	Mid-point	Minimum	Maximum	
ISO VG 2	2.2	1.98	2.42	-
ISO VG 3	3.2	2.88	3.52	-
ISO VG 5	4.6	4.14	5.06	-
ISO VG 7	6.8	6.12	7.48	-
ISO VG 10	10	9.00	11.00	-
ISO VG 15	15	13.5	16.5	-
ISO VG 22	22	19.8	24.2	-
ISO VG 32	32	28.8	35.2	0
ISO VG 46	46	41.4	50.6	1
ISO VG 68	68	61.2	74.8	2
ISO VG 100	100	90.0	110	3
ISO VG 150	150	135	165	4
ISO VG 220	220	198	242	5
ISO VG 320	320	288	352	6
ISO VG 460	460	414	506	7
ISO VG 680	680	612	748	8
ISO VG 1000	1 000	900	1 100	8A
ISO VG 1500	1 500	1 300	1 650	9

It is important to know that the oil kinematic viscosity decreases substantially with temperature and the standardized [6] and commonly used variation law is based on the so called Ubbelohde-Walther equation [2]:

$$\log\log(\nu + 0.7) = A - B \cdot \log(t + 273.15) \tag{5}$$

where:

- ν – kinematic viscosity, mm^2/s (cSt);
- t – temperature, °C;
- log – logarithm to base 10;
- A, B – constants.

This equation is valid in the range $2–2\cdot10^7$ mm^2/s and it is obvious that it will allow the calculation of the kinematic viscosity for a given oil at a certain operating temperature in the most of the instances required by bearing applications. The constants A and B individualize the oil viscosity-temperature behavior and can be evaluated from two data points. Most often, the kinematic viscosities at 40 °C (ν_{40}) and 100 °C (ν_{100}) are used. As aforementioned, almost all lubricant manufacturers provide the value of the kinematic viscosity at 40 °C (ν_{40}); not the same can be said about the kinematic viscosity value at 100 °C (or at temperatures other than 40 °C). Many reliable lubricant manufacturers provide also the value of the viscosity index (VI, see paragraph 3.2), by which it is possible to calculate ν_{100} and then the constants A and B. From here, one can calculate the value of the kinematic viscosity of oil at any operating temperature.

3.2 Viscosity Index

The viscosity of oils decreases as temperature increases, but some oils feature a favorable viscosity-temperature behavior, meaning that their viscosity varies less with temperature than the viscosity of other oils. An arbitrary but much used measure for the change of viscosity with temperature is the (kinematic) viscosity index (VI), whose scale was set up by the Society of Automotive Engineers (SAE). Although this scale was originally ranged from 0 to 100, today's mineral oils can attain values beyond 100 and synthetic oils can reach even values over 400. The current standard method [6][8] for determining the VI is based on the method of Dean and Davis [1] and involves the comparison of the kinematic viscosity of the oil with those of two reference oils at 40 °C and 100 °C, respectively.

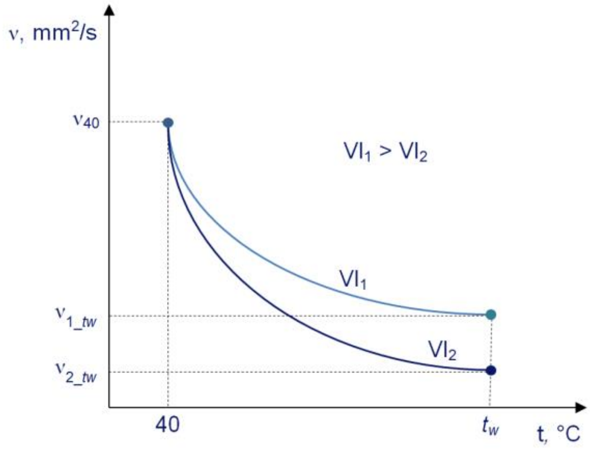


Fig. 1 – Oils having different VIs experience different variations of viscosity with temperature

As one can see in Fig. 1, two different oils having the same viscosity at 40 °C, but with different viscosity indexes, will reach different values of viscosity at the operating temperature (t_w). Thus, the higher values of VI represent lower degrees of oil viscosity change with temperature. Lubricating oils are frequently classified by their kinematic viscosity index and they are accordingly grouped into very high (VHVI), high (HVI), medium (MVI) and low (LVI), as in Table 2.

Table 2 – Classification of lubricating oils by viscosity index

Group	Viscosity Index
Low viscosity index (LVI)	Below 35
Medium viscosity index (MVI)	35–79
High viscosity index (HVI)	80–110
Very high viscosity index (VHVI)	Over 110

Since, the VI calculation procedure in its present form is widely used to compare lubricants however it suffers a major drawback in that it is unusable for lubricants with a kinematic viscosity below 2 mm²/s at 100 °C.

3.3 Additives

A large part of bearing lubricating oils (grease base oils) is represented by the additivated oils. They comprise special compounds called *additives* that by chemical and/or physical action contribute to the improvement of the lubricant properties and transmit better performance characteristics to the lubricants. The major bearing oil additive families are:

- *Anti-oxidants (AO) or oxidation inhibitors*: additives which retard the appearance of oxidation products and therefore considerably extend lubricating oil life.
- *Corrosion inhibitors or rust inhibitors*: chemical compounds that, when added to oil, diminish metal corrosion rate, preventing rust formation on metallic part surfaces during inactive periods. Formation of a coating and passivation layer that covers the metallic surfaces and does not allow the access of corrosive substances (moisture and atmospheric oxygen) to them represents the background of the

corrosion inhibiting mechanism. Oil composition, amount of water, and many other factors contribute to the corrosion inhibiting efficiency.

- *Anti-wear (AW) additives*: complex substances that reduce wear in the mixed friction/lubrication regime. They form a film to surround metallic parts and, if the loads are light, they succeed in separating the surfaces and avoiding their metal-to-metal contact. Under extreme pressure conditions, the AW additives become ineffective, therefore appropriate EP additives are necessary.
- *Extreme pressure (EP) additives*: similarly to AW additives, they adhere to metallic surfaces, preventing them from touching even at high or very high pressure and therefore decrease the wear and the probability of part seizure. When a thin oil film between two surfaces of small area endeavors very high pressure for a very short period of time, called relaxation time, its behavior becomes rheological (viscoelastic behavior, almost as a solid body). This fact helps keep apart the two surfaces and avoid the metal-to-metal contact. A major role of EP additives is to increase the relaxation time from picosecond to nanosecond range. EP oils perform well over a large range of temperatures, speeds and bearing sizes and prevent damage of the parts during starting and stopping of the application.
- *Detergents*: additives used to clean and neutralize oil impurities (which otherwise would accumulate in deposits) by emulsifying the oxidation products, they maintain them in suspension, and prevent them from attaching to lubricated surfaces. Even if many detergents have the same effect as several other additives, it is totally unrecompensed to use them as universal additives.
- *Friction modifiers*: additives (mostly solid particles, such as graphite, molybdenum disulfide, wolfram disulfide, etc.) added to lubricants with the purpose to reduce the friction between the lubricated part surfaces.
- *Dispersants*: additives which keep fine contaminant particles in suspension (to avoid their coagulation) until they are retained by filters (if case be) or removed together with the oil when replaced. Water is also held in suspension as a stable emulsion.
- *Metal deactivators or metal deactivating agents (MDA):* additives which contribute to oil stabilization by deactivating metal ions appeared in lubricants as a result of the oxidative processes with the metallic surfaces and therefore inhibit the action of metallic (especially copper) particles as catalysts in the oxidation processes. They also retard the formation of gummy residues.
- *Defoamers or anti-foaming agents*: chemical additives, generally insoluble in foam, that prevent the production of air bubbles and foam in the oil which could lead to lubricity loss, pitting, and even corrosion when oil embedded air comes into contact with metallic surfaces. Having low viscosity, they rapidly spread on foamy surfaces where they cause air bubbles rupture and surface foam breakdown.
- *Viscosity index improvers*: additives which reduce the decreasing rate of the oil viscosity with increasing temperature. At high temperatures, they increase the viscosity, and at low temperatures they improve the oil fluidity.
- *Emulsifiers*: additives which help form and stabilize an emulsion (mixture of insoluble substances), usually mineral oils with water.
- *Pour point depressants*: additives which improve the fluidity of oil at lower temperatures (lower the pour point).
- *Seal conditioners*: additives which cause gaskets and seals swell and therefore prevent oil leakage.
- *Thixotropic additives*: compounds which improve the grease property to soften when mechanically stressed and to return to its initial consistency when left to rest. Special additivated preserving oils are also thixotropic.

The special and unfavorable conditions (low-speed and highly loaded large size bearings, hardly axially loaded roller bearings, etc.) in which rolling bearings operate have to be considered also. In such conditions it is more likely that the non-additivated oil film is inappropriate, but if additives (especially EP additives) are used, they form a separating film between mating parts (rolling elements and raceways, cage and guiding lips, respectively) in order to prevent wear and premature fatigue breakdown. EP additives must be even more used, as the bearings are in situations where they are subjected to combined loads so that $P/C > 0.15$ or/and the operating viscosity ν_{tw} is lower than the reference (rated) kinematic viscosity ν_1 (see paragraph 4.1).

In addition, oil additives should provide, if necessary, oxidation stability, anticorrosive protection, foam reduction and fine distribution of insoluble contaminants in suspension. For applications where bearings are subjected to great thermal stressing, high-temperature oils with superior non-deterioration properties must be used and, where temperatures vary within a large range, oils with VI improvers are appropriate. For extremely high temperatures, synthetic oils (polyglycols or polyalphaolefins) are preferred because they are very resistant to deterioration (aging).

Note that there are some other oil properties such as flash point, pour point, neutralization number (NZ), saponification number (VZ), carbon residue, etc. that could be very important in many specific applications.

4 Oil or Grease Base Oil Selection

4.1 Reference Kinematic Viscosity

Selection of the appropriate oil or grease to lubricate a certain bearing application mainly means the selection of the proper oil (or grease base oil) viscosity so that the oil forms the elastohydrodynamic lubricant film between rolling elements and raceways able to withstand the bearing loads. This procedure is based on the expected operating temperature, speed, and bearing geometry. According to ISO 281:2007 [7], taking into account the bearing speed (n) and size (D_{pw}), the oil has a certain reference (rated) viscosity at the operating temperature. This reference kinematic viscosity ν_1 can be calculated using equation (6) or the diagram in Fig. 2 a.

$$\nu_1 = \begin{cases} 45\,000 \cdot n^{-0.83} \cdot D_{pw}^{-0.50} & \text{if } n < 1\,000 \text{ rpm} \\ 4\,500 \cdot n^{-0.50} \cdot D_{pw}^{-0.50} & \text{if } n \geq 1\,000 \text{ rpm} \end{cases} \quad (6)$$

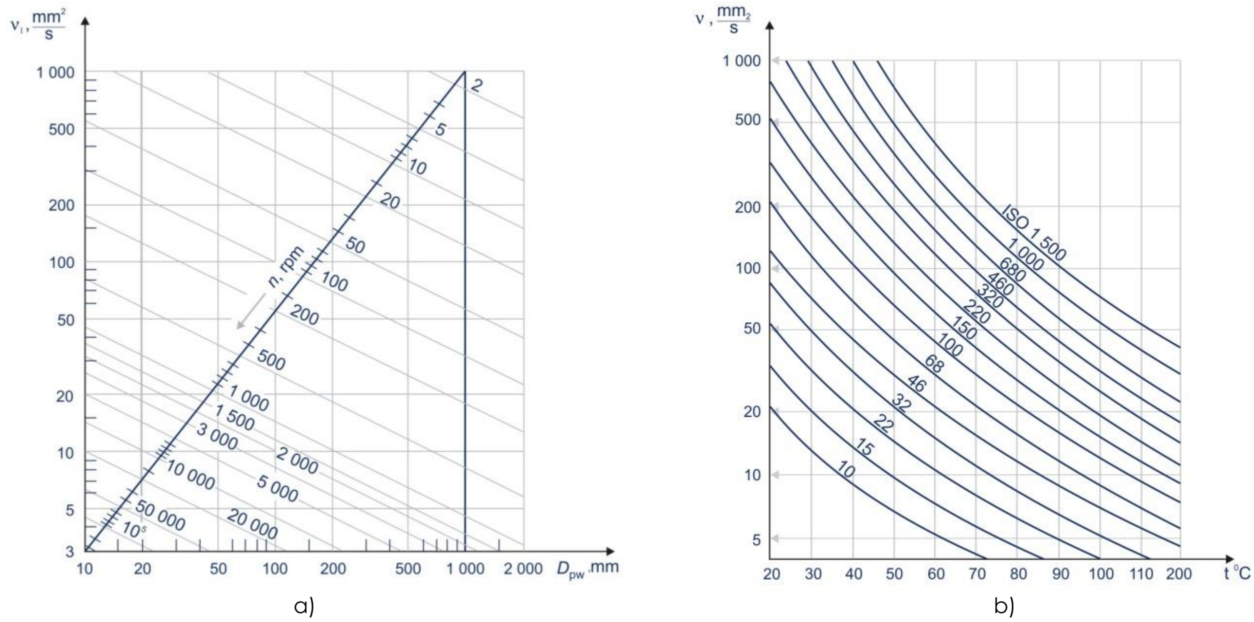


Fig. 2 – Choosing the appropriate oil: a) reference kinematic viscosity (at operating temperature) depending on bearing size and speed (according to ISO 281:2007); b) viscosity vs. temperature diagram for ISO grade mineral oils

Again a good approximation can be made by using in the above equation the bearing mean diameter D_m instead of the pitch diameter D_{pw}. Bearings should be generally lubricated with oil whose operating viscosity ν_{tw} (at working temperature) is higher than the rated viscosity ν_1. The condition of the lubricant separation is described by the viscosity ratio κ, as the ratio of the actual kinematic viscosity ν_{tw} to the reference kinematic viscosity ν_1:

$$\kappa = \frac{\nu_{tw}}{\nu_1} \quad (7)$$

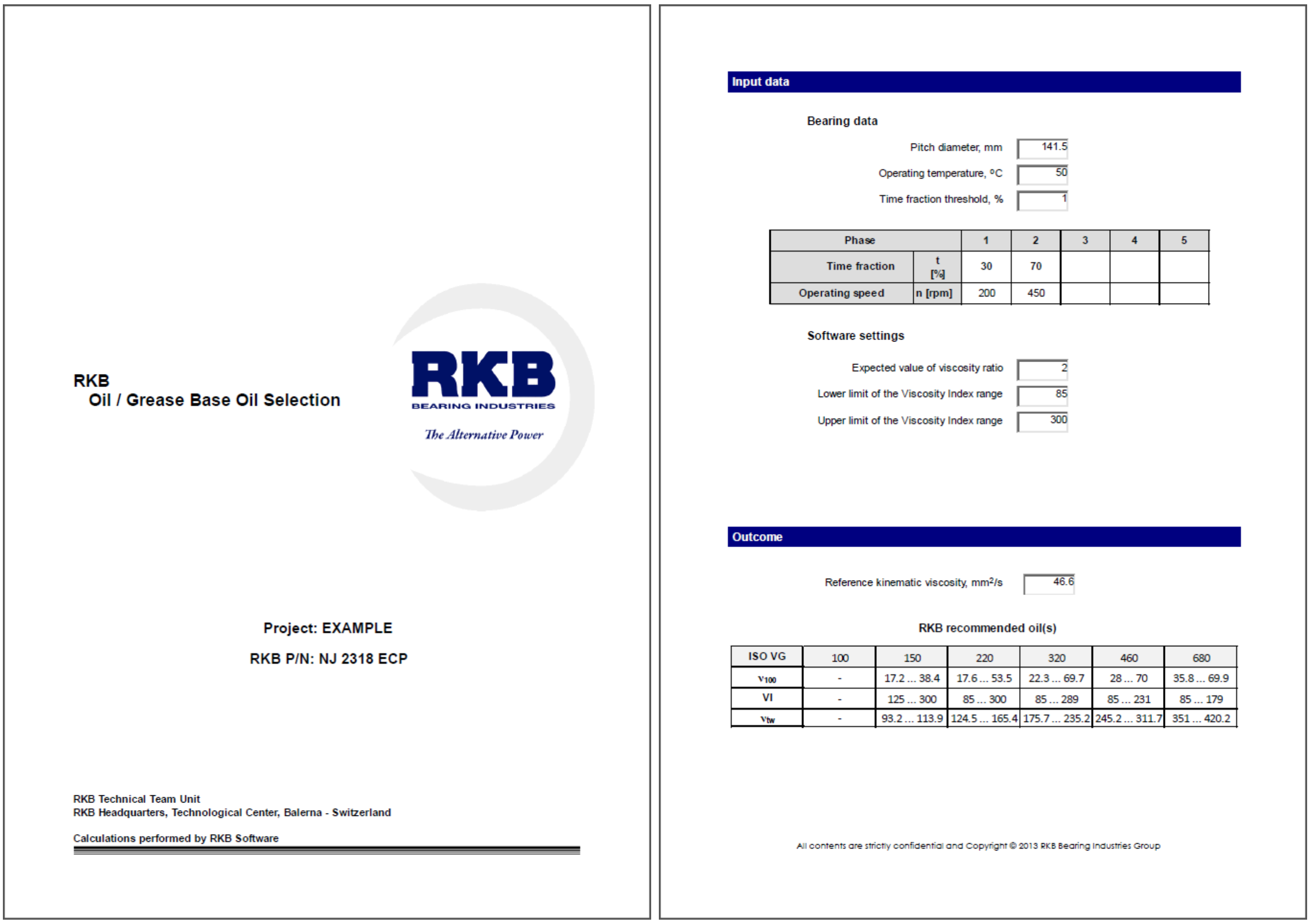
As common knowledge, a full elastohydrodynamic lubricating film between the rolling bodies and the raceways of the bearing rings is obtained for a value of the viscosity ratio higher than 4, but this almost always implies high costs with the lubricant, therefore lower values are often preferred by end users.

4.2 Quick Procedure of Mineral Oil Selection

With the values of the reference (rated) kinematic viscosity ν_1 and the estimated working temperature t_w and using the diagram in Fig. 2 b, it is possible to determine the reference viscosity of oil at the reference temperature (40 °C) and the appropriate ISO viscosity grade of the chosen oil to be used for bearing lubrication. Note that the diagram in Fig. 2 b is valid only for mineral oils with a viscosity index of about 95. For different oils please ask RKB Technical Team Unit for correct calculation and recommendations.

4.3 RKB Oil Selection Original Software

The main problem with the lubricant selection is that, even if the reference (rated) kinematic oil viscosity (ν_1) at the operating temperature is known, the effective choice consists in opting, among a practically infinite number of instances, for an oil – characterized by two numbers, ISO VG (i.e. ν_{40}) and ν_{100} or VI, unknown at the selection moment – which has to assure at the operating temperature such a viscosity that the viscosity ratio (κ) has an expected reasonable value. Obviously, here there are multiple choices, but the minimal values are interesting.



RKB
Oil / Grease Base Oil Selection

The Alternative Power

Project: EXAMPLE

RKB P/N: NJ 2318 ECP

RKB Technical Team Unit
RKB Headquarters, Technological Center, Balerna - Switzerland

Calculations performed by RKB Software

Input data

Bearing data

Pitch diameter, mm: 141.5
Operating temperature, °C: 50
Time fraction threshold, %: 1

Phase		1	2	3	4	5
Time fraction	t [%]	30	70			
Operating speed	n [rpm]	200	450			

Software settings

Expected value of viscosity ratio: 2
Lower limit of the Viscosity Index range: 85
Upper limit of the Viscosity Index range: 300

Outcome

Reference kinematic viscosity, mm²/s: 46.6

RKB recommended oil(s)

ISO VG	100	150	220	320	460	680
ν_{100}	-	17.2 ... 38.4	17.6 ... 53.5	22.3 ... 69.7	28 ... 70	35.8 ... 69.9
VI	-	125 ... 300	85 ... 300	85 ... 289	85 ... 231	85 ... 179
ν_{tw}	-	93.2 ... 113.9	124.5 ... 165.4	175.7 ... 235.2	245.2 ... 311.7	351 ... 420.2

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Fig. 3 – RKB oil (grease base oil) selection original software (Variant 1)

RKB Technical Department has developed its original software able to provide his customers with recommendations in order to choose the appropriate oil for their bearing applications. There are two RKB software variants available: Variant 1 (Fig. 3) in which the lubricant selection is performed for a single bearing operating at a single speed, and Variant 2 (Fig. 4), the most complex, in which are involved several bearings subjected to variable operating conditions but lubricated with the same oil (e.g. same oil bath).

As one can see in Fig. 3, given the bearing (pitch or mean diameter) and the operating conditions (operating temperature and speed), and setting the expected value of the viscosity ratio and the range of viscosity index, the reference kinematic viscosity is displayed and, the most important, the required properties of the recommended oil(s) are provided. In both software variants time fraction threshold means the value phase duration up to which the operation conditions are not taken in consideration (e.g. start-up phase). For the bearing application presented in Fig. 3 (input data section) user can chose either an oil ISO VG 150 but with the minimum VI of 125 (i.e. a minimum kinematic viscosity of 17.2 mm²/s at 100 °C), or an oil ISO VG 220 with the minimum VI of 85 (i.e. a minimum kinematic viscosity of 17.6 mm²/s at 100 °C).

RKB
Oil / Grease Base Oil Selection
Several Bearings / Same Lubricant

The Alternative Power

Project: EXAMPLE

RKB P/N: **32020 X**
32316 AE
32956 P6AES1
NJ 324 EMAC3

RKB Technical Team Unit
RKB Headquarters, Technological Center, Balerna - Switzerland

Calculations performed by RKB Software

Input data

Bearings:

	RKB P/N	Bearing type	Pitch diameter D_{pw} [mm]
B1	32020 X	Single row tapered roller bearing	125
B2	32316 AE	Single row tapered roller bearing	125
B3	32956 P6AES1	Single row tapered roller bearing	330
B4	NJ 324 EMAC3	Single row cylindrical roller bearing	190

Operating conditions:

Operating temperature, °C: 45

Time fraction threshold, %: 1

Phase			1	2	3	4	5
Time fraction		t [%]	20	30	30	10	10
B1	Operating speed	n [rpm]	250	1000	2000	3000	4000
B2			200	800	1600	2400	3200
B3			150	600	1200	1800	2400
B4			100	400	800	1200	1600

Software settings:

Expected minimum value of viscosity ratio: 2

Lower limit of the Viscosity Index range: 95

Upper limit of the Viscosity Index range: 300

Outcome

Reference kinematic viscosity, mm²/s: 71.4

RKB recommended oil(s) / grease base oil(s)

ISO VG	150	220	320	460	680	1000
ν_{100}	-	18.8 ... 53.5	24 ... 73.3	30.3 ... 98.4	39.1 ... 133.6	49.9 ... 178.5
VI	-	95 ... 300	95 ... 300	95 ... 300	95 ... 300	95 ... 300
ν_{tw}	-	165.5 ... 190.2	237.2 ... 275.1	336.2 ... 392.8	489.5 ... 575.6	708.5 ... 838.1

2

Fig. 4 – RKB oil (grease base oil) selection original software (Variant 2)

In the case presented in Fig. 4 the four bearing types used in the design of a speed reducer should be lubricated with the same oil. The operation cycle of bearings is taken also in consideration. RKB recommendation goes to an ISO VG 220 with the minimum viscosity index of 95 (i.e. a minimum kinematic viscosity of 18.8 mm²/s at 100 °C). Now user can compare this with other lubricant requirements (e.g. those from the gearing lubrication), and can eventually make a correct choice from the immense offer of the lubricant manufacturers.

References

[1] E.W. Dean and G.H.B. Davis (1929), *Viscosity Variations of Oils with Temperature*, Chemical and Metallurgical Engineering, Vol. 36, p. 618-619.
[2] C. Walther (1928), *The Variation of Viscosity with Temperature–I, II, III*, Erdol und Teer, Vol. 5, p. 510, 526, 614.
[3] ANSI/AGMA 9005-D94, *Industrial Gear Lubrication*.
[4] ASTM D2270 –10e1, *Standard Practice for Calculating Viscosity Index From Kinematic Viscosity at 40 and 100°C*.
[5] ASTM D2422-97(2002), *Standard Classification of Industrial Fluid Lubricants by Viscosity System*.
[6] ASTM D341– 09, *Standard Practice for Viscosity-Temperature Charts for Liquid Petroleum Products.*
[7] ISO 281:2007(E), *Rolling bearings – Dynamic load ratings and rating life*.
[8] ISO 2909:2002, *Petroleum products – Calculation of viscosity index from kinematic viscosity*.
[9] ISO 3448:1992, *Industrial liquid lubricants – ISO viscosity classification*.