



American
Gear Manufacturers
Association®

AGMA 955-A22

AGMA Information Sheet

Guidance for Industrial Gear Lubrication

AGMA 955-A22

**American Gear
Manufacturers
Association**

Guidance for Industrial Gear Lubrication
AGMA 955-A22

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ABSTRACT

This information sheet provides lubrication guidelines for enclosed and open gearing installed in general industrial power transmission applications. It is not intended to supplant specific instructions from the gear manufacturer.

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Foreword

[The foreword, footnotes, and annexes, if any, in this document are provided for informational purposes only and are not to be construed as a part of AGMA Information Sheet 955-A22, *Guidance for Industrial Gear Lubrication*.]

During development of ANSI/AGMA 9005-F16 the AGMA Lubrication Committee decided that information on lubrication should be in a separate document from information on lubricants. This document, AGMA 955-A22, was created as the first step of separating ANSI/AGMA 9005-F16 into two documents. AGMA 955-A22 provides fundamental, generalized lubrication information, whereas the future edition of ANSI/AGMA 9005 is planned to cover only information on lubricants. The first draft of AGMA 955-A22 contained text from ANSI/AGMA 9005-F16. These sections were greatly expanded on by the committee to produce AGMA 955-A22.

The end user is encouraged to work with their equipment builder and lubricant supplier to achieve the most reliable system for their needs.

The first draft of AGMA 955-A22 was created in March 2016. It was approved by the Technical Division Executive Committee (TDEC) in August 2022.

Suggestions for improvement of this standard will be welcome. They may be submitted to tech@agma.org.

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American Gear Manufacturers Association – Guidance for Industrial Gear Lubrication

1 Scope

This information sheet provides fundamental, generalized lubrication information. It is intended as a reference source, in conjunction with AGMA 9005, in AGMA application specific standards. This information sheet is prepared as a guide for gear designers and manufacturers in the selection of suitable commercially available liquid lubricants for open and enclosed gear drives. These recommendations may be of assistance to users in the selection of an acceptable lubricant and lubrication system in the absence of specific manufacturers' recommendations.

This information sheet applies to both open and enclosed metallic gearing that has been designed and rated in accordance with applicable AGMA Standards. The applicable gear types include involute profiles of spur, helical including double helical and herringbone, worm, non-offset bevel, and face gears. The guidelines apply to both open gearing, where bearings are lubricated separately, and enclosed gearing, where bearings and gears share a common lubrication system. The special regulatory requirements associated with food or drug handling applications are not addressed in this information sheet. Hypoid gears are not covered by this document. See AGMA ISO 22849 [1]. Greases and solid lubricants are not discussed in detail in this document.

This information sheet is not intended to replace any existing application standards such as aerospace, automotive, marine, industrial enclosed drives, high speed applications, mill, kiln, wind turbines, flexible couplings, or splines. See applicable AGMA application standards for lubrication specific guidelines.

This information sheet is intended for use by the experienced gear designer with an understanding of the lubricant and lubrication needs of the application being reviewed.

2 Normative references

The following standards contain provisions, which through reference in this text, constitute provisions of this information sheet. At the time of publication, the editions listed were valid. All standards are subject to revision, and parties to agreements based on this information sheet are encouraged to apply the most recent editions of the standards indicated below:

AGMA 925, *Effect of Tribology and Lubrication on Gear Surface Distress*

ANSI/AGMA 1012, *Gear Nomenclature, Definition of Terms with Symbols*

ANSI/AGMA 9005-F16, *Industrial Gear Lubrication*

Both ISO and ASTM standards are listed in this document. When reporting a result, the standard and method used should also be reported.

3 Terms and definitions

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ANSI/AGMA 1012 as well as the following apply.

3.1.1 Abnormal operating temperatures

Unexpected change in typical operating temperature of a gearbox during normal operating conditions.

3.1.2 Ambient temperature

In general, the installed gears may be exposed to an ambient temperature range of -40°C to $+55^{\circ}\text{C}$ (-40°F to $+131^{\circ}\text{F}$). the ambient temperature is defined as the dry bulb air temperature in the immediate vicinity of the installed gears. Specific type and viscosity grade of lubricant will be determined, in part, by ambient temperature.

3.1.3 Antiscuff lubricants

These lubricants contain additives that provide protection against scuffing. These lubricants are typically formulated with mineral or synthetic base fluids. Antiscuff lubricants were formerly known as extreme pressure, EP, lubricants.

3.1.4 Asperity

Tribological surfaces are never perfectly smooth but consist of peaks and valleys called surface roughness. An asperity is a peak within the surface roughness.

3.1.5 Bearing manufacturer

Legal entity who is responsible for the design and the application engineering of the gearbox bearings.

3.1.6 Dwell time

Time that the lubricant remains in the reservoir before it is recirculated.

3.1.7 Elastohydrodynamic lubrication (EHL) film thickness

Lubricant film between nonconforming surfaces that is formed because of the high pressure viscosity relationship of the entrained lubricant.

3.1.8 Filter

Device to remove and contain contaminants from the lubricant.

3.1.9 Gear (wheel)

A gear (wheel) is a machine component with gear teeth. In a gear pair, the one with the greater number of teeth is called the gear, bull gear, girth gear, or wheel.

3.1.10 Gearbox

A mechanical device comprised of gears, bearings, and shafts that changes speed and torque in a system.

3.1.11 Gearbox manufacturer

The entity responsible for designing, specifying manufacturing requirements, and warranting the gearbox and its components.

NOTE: It is possible that several legal entities may be involved in this process, which is not further reflected in this information sheet.

3.1.12 Gearbox owner

Entity that purchases and is responsible for operating the gearbox.

NOTE: In practice, the owner may contract different legal entities to operate, service, and maintain the gearbox. This distinction is not further reflected in this information sheet.

3.1.13 High temperature performance

Ability of the lubricant to resist oxidation or thermal decomposition in high temperature operation.

3.1.14 Hydroprocessing

Any of several chemical engineering processes including hydrogenation, hydrocracking, and hydrotreating, especially as part of oil refining.

3.1.15 Inline filter

A filter installed in the main lubrication system that reduces contaminants within the lubricant supplied to the gears and bearings.

3.1.16 Interface

Defined boundary of the gearbox that is either a physical mount to another system subcomponent or a path of exchange such as control signals, hydraulic fluid, or lubrication system.

3.1.17 Involute

An involute is the locus of a point on a taut cord being unwound from the circumference of a stationary circular disc. Alternatively, it is also the locus of a point on a straight line that rolls without slipping round the circumference of a stationary circular disc [2]. This form is used frequently due to the favorable meshing engagement of teeth.

3.1.18 Lambda ratio

See **Specific film thickness**.

3.1.19 Low temperature performance

Ability of the lubricant to flow or circulate in low ambient temperature.

3.1.20 Lubricant manufacturer

Entity that designs, manufactures, and warrants lubricants for gearboxes.

3.1.21 Non-offset bevel gear

Bevel gear with intersecting axes including straight, Zerol®, spiral, skew, on-center face, and Beveloid®. See Table 1.

NOTE: Zerol® and Beveloid® are registered trademarks of the Gleason Works.

3.1.22 Normal operating temperatures

Expected rise in temperature of a gearbox (above ambient temperature) as a result of internal losses and external heat sources during normal operating conditions.

3.1.23 Offline filter

A filter independent of the main lubrication system, typically with a separate pump, that typically operates continuously to improve lubricant cleanliness. Other names are bypass filter, kidney loop filter, or side stream filter.

3.1.24 Oxidative stability

Oxidative stability refers to the ability of a lubricant to resist chemical reaction with oxygen. It may be improved by the presence of antioxidant additives. Reaction with oxygen can be accelerated by unoxidized metal surfaces, water, and other types of catalysts. This term is often incorrectly linked with thermal stability.

3.1.25 Pinion

A pinion is a machine part with gear teeth. In a pair of gears that run together, the one with fewer teeth is called the pinion.

3.1.26 Pump

Mechanical device that delivers lubricant from either the reservoir or sump into tubes or channels directing the fluid to bearings and gear mesh(es). May be motor driven or mechanically coupled to a gear or pinion in a gearbox.

3.1.27 Rust and oxidation inhibited, R&O, lubricants

Mineral or synthetic lubricant with additives limited to rust inhibitors, oxidation inhibitors, and antifoam additives. See ANSI/AGMA 9005 for more information.

3.1.28 Reservoir

External vessel that holds the gearbox lubricant.

3.1.29 Specific film thickness

Specific film thickness, also known as the Lambda (λ) ratio, is the ratio of the elastohydrodynamic lubrication (EHL) film thickness calculated for smooth surfaces divided by the composite surface roughness. The equations for EHL film thickness and composite surface roughness vary with the source. See AGMA 925 for more information.

3.1.30 Sump

Interior space at the bottom of the gear housing that collects lubricant that drains from the gearbox internal components.

3.1.31 Sump, dry

Reservoir provided by a tank that is separate from the sump.

3.1.32 Sump, wet

Reservoir integral with the gear unit housing.

3.1.33 System

The arrangement and combination of individual components, such as couplings, the driver, and the driven equipment, that make-up a complete machine or process.

3.1.34 System integrator

Entity responsible for specifying the requirements for the gearbox for the system in accordance with applicable standards and specifications.

NOTE: Typically, the system integrator will design, manufacture, and furnish the system where the gearbox is used.

3.1.35 Thermal Stability

Thermal stability refers to the ability of a lubricant to resist decomposition by temperature alone. It is not altered by lubricant additives. This term is often incorrectly linked with oxidative stability.

3.1.36 Traction coefficient

A parameter describing the force developed by shearing of an EHL film between contacting bodies. It is a function of the contact area, local viscosity, and sliding velocity (shear rate).

3.1.37 Viscosity Index (VI)

Viscosity index, as measured by ASTM D2270, is a single number indicating the effect of temperature on kinematic viscosities measured at 40°C and 100°C.

3.1.38 Wheel

See **Gear**.

3.2 Symbols and units

Symbols and units used within this document are listed in Table 1.

NOTE: The symbols used in this document may differ from other AGMA documents. The users should assure themselves that they fully understand the terms, definitions, and symbols as contained in this document.

Table 1 – Symbols

Symbol	Term	Units	Where first used
C_p	specific heat capacity of lubricant	kJ/[kg·K]	Eq. 1
P	total transmitted power	kW	Eq. 1
Q	lubricant flow rate	L/min	Eq. 1
t_D	dwel time	minutes	Eq. 3
V	volume	L	Eq. 3
v_{r1}	rolling velocity of the pinion	--	4.5.1
v_{r2}	rolling velocity of the wheel	--	4.5.1
v_{s1}, v_{s2}	sliding velocities	--	4.5.2
v_{ss1}, v_{ss2}	specific sliding ratios	--	4.5.3
ΔT	difference between lubricant inlet and outlet temperature	K or °C	Eq. 1
η	gearbox efficiency	--	Eq. 1
λ	specific film thickness	--	Clause 4
ρ_{oil}	lubricant density	kg/m ³	Eq. 1

4 Gear lubrication overview

The lubrication requirements of spur, helical, straight-bevel, and spiral bevel gears are essentially the same. For this class of gears, the magnitudes of the loads and sliding speeds are similar, and requirements for viscosity and antiscuff properties are virtually identical. Mineral oils without antiscuff additives are suitable for high-speed lightly loaded gears where the high entraining velocity of the gear teeth develop thick elastohydrodynamic (EHL) films. In these cases, the most important property of the lubricant is its viscosity. Slower speed gears, especially carburized gears, tend to be more heavily loaded, and these gears generally require higher viscosity lubricants with antiscuff additives. Hypoid gears, such as those used in automotive axles, are especially prone to scuffing because they are heavily loaded and have high sliding velocities. For these reasons, hypoid gear lubricants have the highest concentrations of antiscuff additives. Worm gears have high sliding velocity, which generates significant frictional losses. Their tooth loads are relatively light, and they are successfully lubricated with mineral oils that are compounded with lubricity additives, or synthetic lubricants with low traction coefficients.

While these guidelines will generally provide satisfactory selections, a detailed engineering analysis is always preferred, especially in critical applications and high speed gearboxes. Such an analysis is beyond the scope of this information sheet.

In the case of wormgear drives, ambient temperature is used because operating temperature is generally not known at the time of installation.

The primary function of gearing lubrication is to keep the tooth surfaces separated during operation. A measure of the separation of tooth surfaces is specific film thickness, λ , see AGMA 925.

4.1 Gear lubrication

Gears require lubrication to reduce friction, dissipate heat, prevent surface distress such as scuffing and mitigate micropitting and wear, but the choice of lubricant and the details of lubricant delivery are complex because the interrelationship of many factors that should be considered such as:

- gear tooth geometry;
- gear tooth motion (kinematics);
- gear tooth forces (static and dynamic);
- gear tooth material and surface characteristics (physical and chemical);
- lubricant characteristics (physical and chemical);
- environmental characteristics (physical and chemical).

Consequently, the gear designer should consider all aspects of tribology if the gears are to have adequate strength, wear resistance, and scuffing resistance to meet the requirements of a given application.

4.2 Lubricant classifications

For the purposes of this document, lubricants are considered to be in one of three distinct classes: inhibited, antiscaff, or compounded. See ANSI/AGMA 9005 for more information.

4.3 Lubrication regimes

The functioning of mechanical components such as gears and bearings involves relative motion of surfaces in contact, under load. Separation of the surfaces by a thin film of fluid is a key factor in achieving smooth operation and acceptable service life. Lubrication regimes, as defined by the lambda-ratio, λ , are hydrodynamic (HL), elastohydrodynamic (EHL), mixed (ML) and boundary (BL) lubrication. The theory of EHL was developed to explain the interplay between the elastic deformations and the formation of the fluid film, and to analyze its behavior under various rolling and sliding contact operating conditions.

Development and operational influence of the EHL fluid film depends on lubricant characteristics, lubricant inlet conditions, load intensity, operating pitch line velocity, surface conditions, metallurgy, and oil cleanliness. See AGMA 925 for more information.

4.3.1 Hydrodynamic lubrication

Hydrodynamic lubrication exists when there is complete separation of the sliding and rolling contact surfaces achieved by a continuous lubricant film. Hydrodynamic lubrication films are formed generally under light loads and moderate pitch line velocities, and low or high loads with high pitch line velocities. The specific film thickness also plays a significant role.

4.3.2 Elastohydrodynamic lubrication

EHL exists in highly loaded sliding and rolling contacts when fluid film formation is influenced by elastic deformation of the contacting surfaces.

4.3.3 Mixed lubrication

Lubrication regime where the load is shared between lubricant films and direct contact with surface asperities.

4.3.4 Boundary lubrication

Boundary lubrication exists when the sliding and rolling surfaces are wetted with fluid but the lubricant film thickness is small compared to the sliding and rolling surface roughness. Boundary lubrication occurs under heavy loads, low pitch line velocities, or low viscosity lubricants.

4.4 Gear types

Cylindrical gears with non-intersecting parallel axes in a plane consist of spur, single helical, double helical, or herringbone. Conical gears with axes in a plane that intersect at a right angle or arbitrary angle are straight bevel, Zerol® bevel, spiral bevel, skew bevel, face, and Beveloid®. Gears with non-intersecting axes in separate planes include hypoid, single-enveloping worm, double-enveloping worm, crossed-axis helical, and Spiroid.

Table 2 summarizes gear types.

Table 2 – Types of gears

Parallel axes (external or internal)	Intersecting axes	Non-intersecting crossed axes
Spur	Straight bevel	Hypoid ¹⁾
Single helical	Zerol® bevel	Single-enveloping worm
Double helical	Spiral bevel	Double-enveloping worm
Herringbone	Skew bevel	Crossed-axis helical
	On-center face gear	Offset face gear
	Beveloid®	Spiroid
NOTE: ¹⁾ Hypoid gears not covered by this document. See AGMA ISO 22849 [1].		

4.5 Gear kinematics

All the gears shown in Table 2 have line contact except crossed-axis helical gears, which have point contact. However, most bevel, and face gears are manufactured with crowning in both the profile and lengthwise directions that results in point contact under zero load.

Parallel axis and intersecting axis gears have very similar rolling and sliding velocities, whereas non-intersecting axis gears have additional lengthwise sliding that generally results in more severe tribological contact and lower efficiency.

Gear teeth both roll and slide on one another. Figure 1 shows that the rolling velocity of the pinion, v_{r1} , and the rolling velocity of the wheel, v_{r2} , linearly increase from zero at the interference points to a maximum at each end of the path, Start of Active Profile (SAP) and End of Active Profile (EAP), of contact.

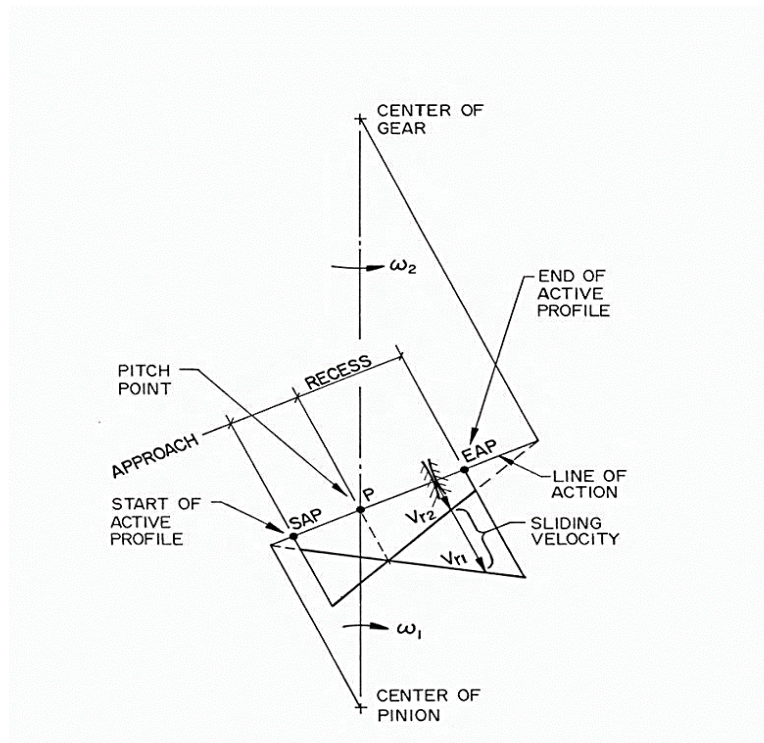


Figure 1 – Rolling and sliding velocities

The distance between the v_{r1} and v_{r2} lines represents the sliding velocity. The amount of sliding is proportional to the distance from the pitch point, P, and is zero when the gear teeth contact at the pitch point, and largest at the ends of the path. Sliding is oppositely directed on either side of the pitch point.

4.5.1 Rolling velocities v_{r1} , v_{r2}

Increasing rolling velocity entrains more lubricant between contacting teeth, increases oil film thickness, and reduces the number and severity of asperity contacts.

4.5.2 Sliding velocities v_{s1} , v_{s2}

Sliding velocity impacts heat generation, efficiency, and asperity distress. High sliding velocity generates frictional power loss by shearing the oil film and shearing boundary films on contacting asperities. High sliding velocity also increases flash temperature and risk of scuffing.

4.5.3 Specific sliding ratios v_{ss1} , v_{ss2}

Specific sliding ratio is the ratio of the sliding velocity to the rolling velocity at a particular point on a gear tooth profile ($v_{ss1} = v_{s1} / v_{r1}$, $v_{ss2} = v_{s2} / v_{r2}$). The specific sliding ratio is a contact severity parameter that is:

- a dimensionless ratio dependent on tooth geometry and independent of pitchline velocity;
- positive in addendum ranging from zero at the pitch point to +1 at the interference point of the mating gear;
- negative in dedendum ranging from zero at the pitch point to $-\infty$ at the interference point of the mating gear.

Generally, $|v_{ss1}| < 1.0$ is recommended, and $|v_{ss1}| \leq 0.5$ is preferred, for good resistance to macropitting, micropitting, and scuffing. Specific sliding ratio is also called slide/sweep ratio. Figure 2 shows a typical plot of specific sliding ratio. $v_{ss1} = -1.15$ at the pinion SAP, and $v_{ss2} = -0.963$ at the pinion EAP for this example.

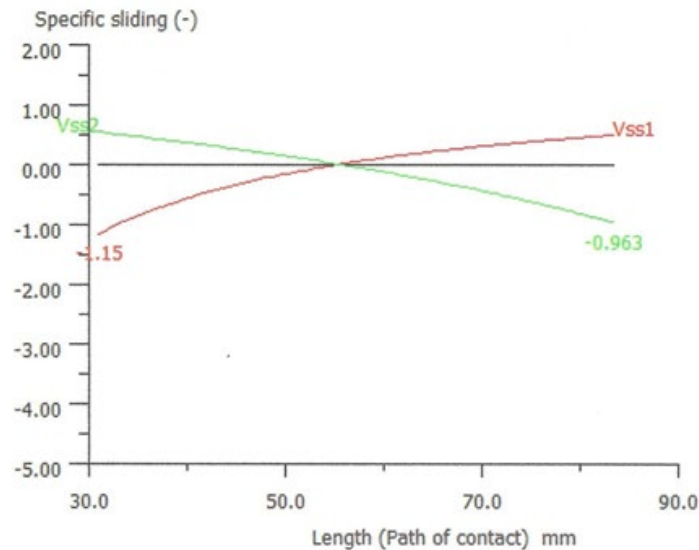


Figure 2 – Specific sliding velocity

4.6 Hertzian stress

Figure 3 shows how the Hertzian stress varies along the path of contact. The maximum stress for this example occurs at the lowest point of single tooth contact (LPSTC). In other cases, it can occur at the highest point of single tooth contact (HPSTC). ANSI/AGMA 2101 [3] uses the maximum Hertzian stress to determine the durability rating of a gearset.

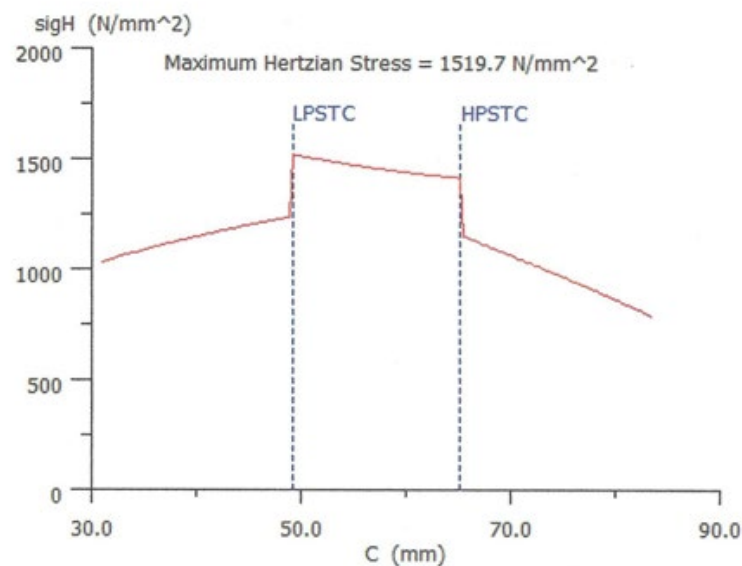


Figure 3 – Hertzian stress

Figure 4 shows how Blok's [4] contact temperature varies along the path of contact. The maximum contact temperature for this example occurs at the pinion SAP. The contact temperature is a minimum at the pitch point where it is equal to the tooth flank temperature because the sliding velocity and flash temperature rise are both zero at the pitch point. AGMA 925 uses the maximum contact temperature to assess the risk of scuffing.

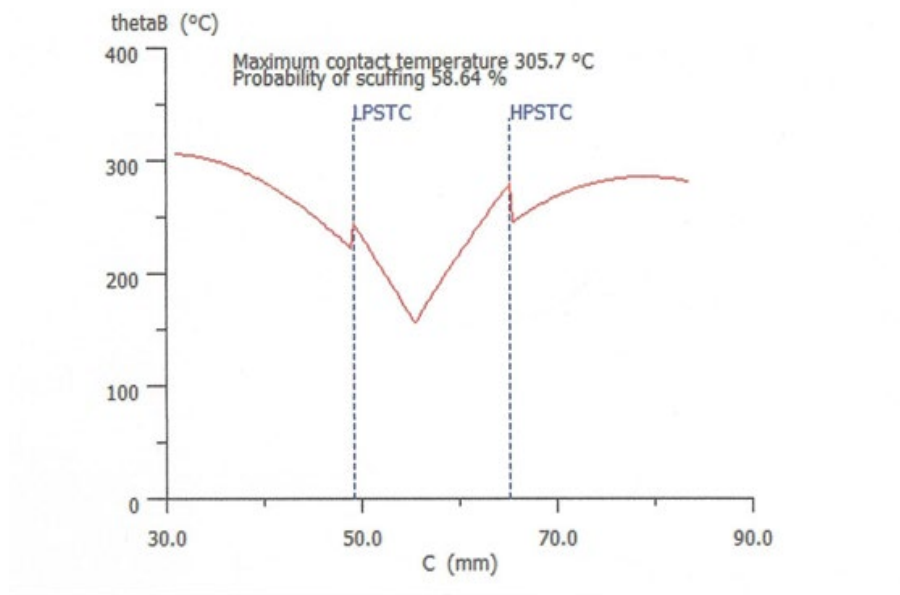


Figure 4 – Blok's contact temperature

4.7 Gear tooth meshing at first point of contact

Figure 5 shows that scraping of the lubricant at the first point of contact hinders the development of the EHL film. The intersection between the undercut and involute forms a cusp on the pinion flank at point A'. Furthermore, if the driven wheel has inadequate tip relief or the driving pinion has inadequate root relief, tip-to-root interference occurs. Figure 6 shows how the wheel tip corner approaches the pinion involute along a trochoidal path that intersects the pinion involute at a point above the usual pinion SAP. Contact between the wheel corner and the pinion involute results in very high Hertzian stress especially if the wheel has sharp corners at tips of its teeth. The high stress and scraping action of the wheel corner undercuts the pinion involute by removing the material shown shaded in Figure 5 and plowing material toward the pinion root.

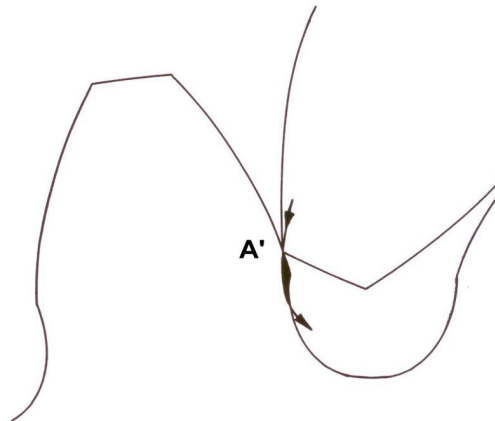


Figure 5 – Tip to root interference between wheel tip and pinion root

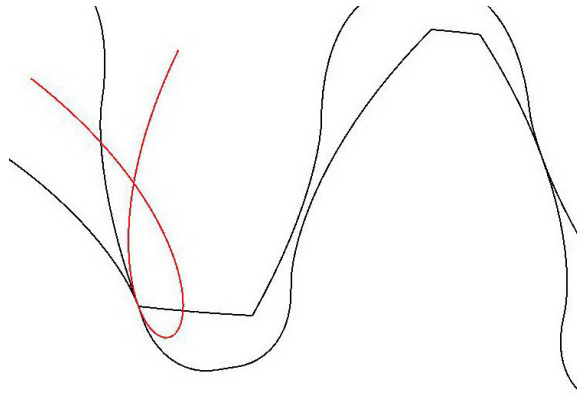


Figure 6 – Trochoidal path of wheel tip corner

The lubricant selection should be appropriate for the gears, and also consider other lube system and mechanical components such as bearings, seals, and auxiliary equipment.

4.8 Specific film thickness, λ

The primary function of gearing lubrication is to keep the tooth surfaces separated during operation. A measure of the separation of tooth surfaces is specific film thickness, λ , which is a ratio of fluid film thickness to the composite surface roughness of the driver and the driven gears. See AGMA 925 for more information. The parameters that influence fluid specific film thickness are geometry, load, speed, lubricant dynamic viscosity, and pressure viscosity coefficient.

Figure 7 shows how the specific film thickness varies along the path of contact. The minimum specific film thickness for this example occurs at the LPSTC. AGMA 925 uses the specific film thickness to predict the probability of wear.

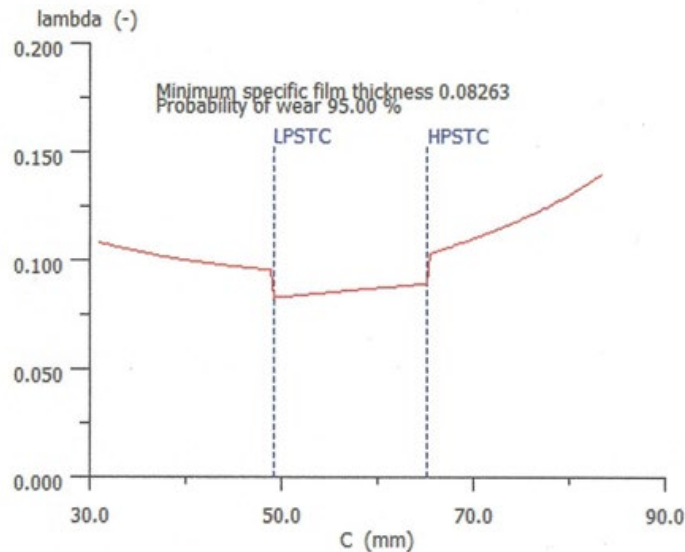


Figure 7 – Specific film thickness

4.9 Lubrication-related failure modes

ANSI/AGMA 1010 [5] classifies all forms of gear tooth failure and discusses the morphology of each failure mode and suggests potential remedies. It includes the following lubrication-related failure modes:

- adhesion;
- abrasion;

- polishing;
- corrosion;
- fretting;
- cavitation;
- erosion;
- electric discharge;
- scuffing (severe adhesion);
- plastic deformation;
- Hertzian fatigue.

For more information on gear tooth failure modes see ANSI/AGMA 1010 [5].

5 Lubricant properties

The sections below discuss various lubricant properties.

5.1 Lubricant base oil

A key element of a finished lubricant is the base oil. Base oil comes primarily from two sources: mineral or synthetic. The term mineral usually refers to base oils that have been refined from a crude oil source. Synthetics are usually the product of a chemical reaction of one or more selected starting materials. In 1993, the American Petroleum Institute (API) assigned a Group number according to the fluids properties to further define base oils, see Table 3 derived from Appendix E of API 1509 [6].

Moving from Group I through Group II and Group III the crude oil manufacturing process goes from traditional solvent processing, which removes wax and improves pour point, to moderate and severe hydroprocessing. These processes remove sulfur, nitrogen, polar material, and olefins. They also rearrange the molecular structure to improve thermal and oxidative stability and raise the viscosity index.

Table 3 – API base oil group numbers

API Group	Saturates %	Sulfur %	Viscosity Index	Lubricant type
I	< 90	> 0.03	80–119	Mineral
II	≥ 90	< 0.03	80–119	Mineral
III	≥ 90	< 0.03	≥ 120	See 5.1.3
IV	–	–	–	PAO Synthetic
V	–	–	–	All other base lubricants not included in Groups I–IV

As the Group number increases from I to IV, the solvency of the base oil generally decreases for additives and degradation products. The change in solvency can be accommodated by judicious selection of additives, and by use of co-base oil to improve solvency.

Finished lubricants can contain mixtures of one or more base oil types. Partial synthetic fluids contain mixtures of mineral and synthetic base oils. Full synthetic fluids can be mixtures of two or more synthetic base oils. As an example, mixtures of polyalphaolefins and esters are commonly used in synthetic formulations. Mixtures are generally used to tailor the properties of the finished fluid for a specific application or need.

Lubricants are formulated for specific performance characteristics. Compositions will vary and general labels, such as PAO/synthetic, may not fully describe the lubricant.

Table 4 below defines general properties for base oils used in lubricants. The table does not account for inclusion of different additives or use of different viscosities within the groups that change the properties of the finished lubricant.

Table 4 – General properties of base oil chemistry

General properties				
Base oil type	Mineral	Polyalphaolefin (PAO)	Diester and polyol ester	Polyglycol (PAG)
API Group	I, II, III ¹⁾	IV	V	V
Typical use temperature	-20 to 100°C	-50 to 140°C	-60 to 180°C	-30 to 160°C
Typical pour point	Down to -40°C	Down to -50°C	Down to -50°C	Down to -50°C
Miscibility with other oils or water	Mineral, PAO, or Ester	Mineral, PAO, or Ester	Mineral, PAO, Ester, or PAG	Ester, PAG, or up to 5% water depending upon EO/PO ratio of PAG oil
Additive solubility ⁵⁾	3,4,5	5	3	3
General guidelines				
Seal ²⁾ compatibility	Compatible: NBR, HNBR, FKM, ACM, AU;	Compatible: HNBR, FKM, ACM; test compatibility: NBR;	Compatible: FKM; test compatibility: NBR, HNBR, ACM, AU;	Compatible: FKM, EPDM; test compatibility: NBR, HNBR, ACM, AU;
Thermal stability ⁵⁾	4,4,4	2	2,1	1
Relative oxidation resistance of base oil ^{3) 5)}	4,3,2	2	3,2	3
Resistance to residue formation ⁵⁾	4,3,2	2	2,2	1
Relative lubricity, friction coefficient	Changes significantly when fully formulated			
Relative wear protection of base oil	Changes significantly when fully formulated			
Gearbox application notes	1) Limited viscosity temperature behavior; 2) Limited oxidation resistance, more likely to form residue	1) Seals can shrink	1) Paint compatibility should be checked; 2) Seals can swell	1) Not intended for lubrication of aluminum containing alloys; 2) Paint and seal compatibility should be checked
Biodegradability standards ⁴⁾	Does not comply	Does not comply	Some comply with EAL, VGP, and EU Ecolabel standards	Does not comply
NSF H1 Food Grade Compliance	Only white Oil	Some types	Some types	Some types
NOTES: 1) Group III is considered synthetic in North America. 2) Seal types include: ACM – Polyacrylic; AU – Polyester Urethane; EPDM – Ethylene Propylene Diene Terpolymer; FKM – Fluoroelastomer; HNBR – Hydrogenated Nitrile; NBR – Nitrile. 3) Incorporation of antioxidant additives can improve oxidation resistance above the base oil properties. 4) Biodegradability standards include: EAL – Environmentally Acceptable Lubricants [6]; EU Ecolabel – Label of environmental excellence awarded to products and services meeting high environmental standards throughout their life cycle: from raw material extraction, to production, distribution and disposal [7]; VGP (Vessel General Permit) – Standards for biodegradability, minimal toxicity, and non-bioaccumulating standards set in Appendix A of the U.S. EPA's 2013 VGP [8]. 5) 1 = Excellent, 2, = Very Good, 3 = Good, 4 = Moderate, 5 = Poor				

5.1.1 API Group I

API Group I base oils are mineral oils that receive the least amount of refining, which may result in a shorter operating life. Group I based gear lubricants typically have the lowest viscosity index.

5.1.2 API Group II

API Group II base oils undergo additional, more complicated, refining than Group I oils. This refining removes additional contaminants such as sulfur and provides more saturation of the hydrocarbon molecules. Compared to Group I oils, Group II oils have increased oxidative stability and decreased solvency for additives and degradation products.

5.1.3 API Group III

API Group III oils undergo a more intense hydroprocessing than Group II oils. The result is a higher VI and a lower concentration of unsaturated hydrocarbons and sulfur. Group III oils derived from crude oil are sometimes described as synthesized hydrocarbons. Compared to Group II oils, Group III oils have increased oxidative stability and decreased solvency for additives and degradation products.

Gas-To-Liquids (GTL) base oils are included in API Group III and are defined as synthetic base oils. GTL starts with natural gas and, through a series of processes, produces defined molecules used as fuels and lubricants.

5.1.4 API Group IV – Polyalphaolefin (PAO) lubricants

Polyalphaolefins, or olefin polymers, are paraffin-like liquid hydrocarbons that are synthesized to achieve a combination of high temperature viscosity retention, low volatility, very low pour point and a high degree of oxidation resistance along with low traction coefficients that can improve equipment efficiency. These characteristics result from the wax-free combination of moderately branched paraffinic hydrocarbon molecules of predetermined chain length. They have a high viscosity index making them suitable over a very wide temperature range.

Compared to API Group I and Group II base oils, Group IV PAO lubricants generally have lower solvency for additives and for sludge that may form as the oil ages. Lubricant manufacturers usually add a higher solvency fluid, such as ester or alkylated aromatic fluids, in order to keep the additives in solution and to prevent varnish or sludge from depositing on the gearbox components.

It is possible for these esters to dissolve and remove mesh check layout dye. When using a Group IV based lubricant, the compatibility of layout dye and the lubricant should be confirmed.

5.1.5 API Group V – all other base oils

API Group V oils are any type of base oil not defined by the other four Groups. Additional descriptions of these fluids follow.

5.1.5.1 Synthetic ester lubricants

Esters are produced from the reaction of an alcohol with an organic acid. There are a wide variety of esters available that can be produced by the numerous combinations of acids and alcohols available. The most common esters for lubricants are dibasic acid esters (diesters) and polyol esters (POE). The principal advantage of many esters is their excellent thermal and oxidative stability. A primary weakness for some esters is poor hydrolytic stability. When in contact with water, esters may deteriorate through a reverse reaction and split back into an alcohol and organic acid. A secondary weakness with some esters is a viscosity index lower than most paraffinic mineral based oils. Some esters do, however, provide a viscosity index higher than mineral or PAO lubricants.

Esters are used to improve additive solvency in base oils, and certain esters may be used in biodegradable lubricants.

5.1.5.2 Alkylated aromatic lubricants

Alkylated aromatic lubricants are hydrocarbon fluids prepared by reaction of an aromatic species, typically benzene or naphthalene, with one or more olefins. They have good thermal and oxidative stability and

better solvency than PAO. Since there are no hydrolysable linkages, they have excellent hydrolytic stability. Viscosity is influenced by the number and structure of alkyl groups attached to the aromatic ring(s).

5.1.5.3 Naphthenic base stocks

Naphthenic base oils are not commonly used as gear lubricants. They are refined from sweet crude distillates which have a low paraffin or wax content. This results in a low VI so their lubricating performance and oxidation stability are relatively poor as compared to paraffinic oil which has a higher VI. However, naphthenic basestocks have benefits in low temperature fluidity and solvency.

5.1.5.4 Polyalkyleneglycol (PAG) lubricants

PAG based oils have a chemical structure that is distinctly different from both PAO and ester-based oils. It is an oxygen rich structure called a polyether. PAG based gear oils can have excellent thermal and oxidative stability and most have very high viscosity indices. They exhibit a lower traction coefficient (increasing efficiency in high sliding applications), additional heat transfer (cooler running), and thicker EHL film for a given kinematic viscosity (higher micropitting resistance), compared to other lubricants. Furthermore, PAG oils do not form sludge or varnish yielding cleaner operation. PAG fluids solubilize sludge and varnish precursors which can reduce sludge and varnish build-up on components.

PAG lubricants are characterized as being either water miscible or oil miscible. Do not combine water miscible PAG with mineral oil, PAO, or oil miscible PAG. Special flushing procedures are required when switching between PAG and mineral or PAO lubricant.

A consideration with PAG lubricants is that they may require different specification for seals, sealants, and paints. Operational experience has shown that under conditions where water ingress is possible, corrosion issues have been documented with PAG based gear oils.

5.1.5.5 Natural products

Natural products such as vegetable-based oils can be used as base stocks where biodegradability is a requirement. The characteristics of natural products should be reviewed to determine if the base stocks under consideration meet the performance requirements. Plant derived esters can have weaknesses, for example, oxidation stability, and low temperature performance might not be adequate.

NOTE: Not all naturally derived oils are biodegradable.

5.2 Lubricant additives

Lubricants contain additives that impart desirable properties or prevent undesirable properties. There are two primary types of additives: surface active and bulk oil. Examples of surface active additives are antiwear and corrosion preventive additives. The term corrosion inhibitor usually applies to additives that protect copper and other yellow metals. Rust preventive additives protect iron and steel-based metals. Typical bulk oil additives are antioxidants and demulsifiers.

Additives are polar, reactive chemicals dissolved in a non-polar liquid. A notable exception is defoamant, or antifoam additives, that should be insoluble in the base stock to be effective. Lubricant additives often interact and interfere with each other. For example, antiwear additives, antiscuff additives, and rust preventatives compete for the metal surface of gears and bearings. A lubricant can have excellent rust prevention, but the application will fail due to scuffing if the additives are not properly balanced. A skilled lubricant formulator balances performance so that one property doesn't succeed at the expense of another property.

Table 5 lists the types of additives that are typically used to impart desired properties to industrial gear oils, along with the standardized tests used to measure these properties. There are also tests that have not been standardized but are required by OEMs. Examples are FVA 54 Micropitting Test [9], and the seal, sealant and paint compatibility tests developed and run by the manufacturers of such ancillary gearbox equipment.