Synthetic base stocks

Lubricant formulation guide

ExxonMobil

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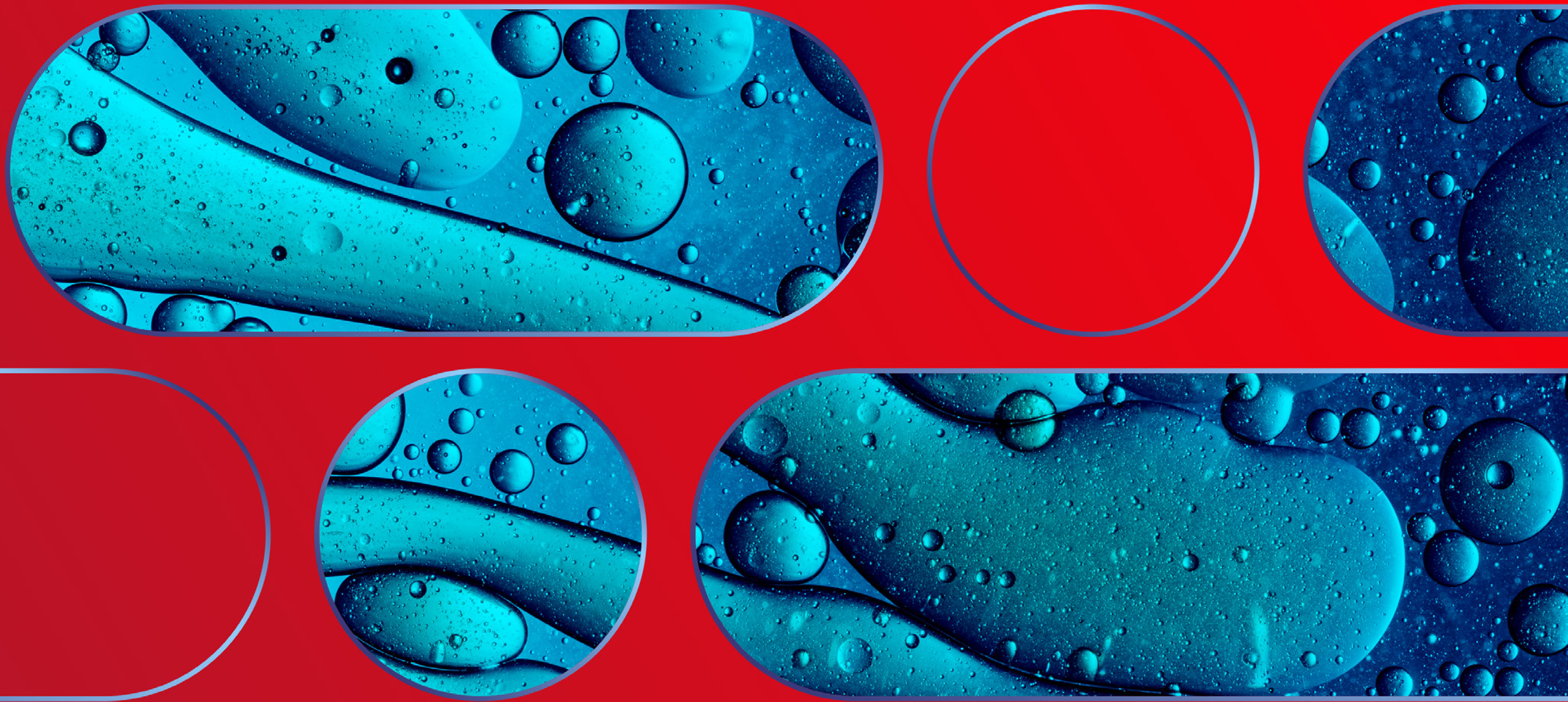

1.0 Introduction

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1.0 Introduction

As technology continues to progress, the high-performance lubricant space is constantly growing to support the evolving needs of various applications. Formulators using synthetic base stocks are being asked to create more sophisticated and advanced lubricants.

This "Synthetic base stocks lubricant formulation guide" can provide a starting point for developing high performance synthetic lubricant formulations and supports optimizing base stock selection for many common lubricant applications.

The guide also serves as a convenient reference source to quickly identify the performance characteristics of the ExxonMobil Product Solutions Company's (ExxonMobil) entire family of synthetic base stocks — SpectraSyn™ polyalphaolefins (PAO), SpectraSyn Plus™ PAO, SpectraSyn™ MaX PAO and SpectraSyn Elite™ metallocene polyalphaolefins (mPAO), Synesstic™ alkylated naphthalene (AN) and Esterex™ esters.

This guide also takes the evaluation of synthetic base stocks a step further by providing, in some cases, recommended combinations of base stocks for a given lubricant viscosity grade. These base stock blends represent many of the core industrial and automotive synthetic lubricant formulations, from internal combustion / electric vehicle engines to industrial gear oils and greases.

The data provides a starting point from which to advance your formulation efforts. As you evaluate the information, you can count on the support of your ExxonMobil sales representative or technology support team to provide samples and answer additional questions. Please visit our web site at www.exxonmobilchemical.com/synthetics for a complete listing of our products and global sales offices.

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2.0 Lubricant formulators FAQs

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Q: Why should I choose ExxonMobil and its synthetic lubricant base stocks?

A: ExxonMobil is the premier producer of both Group IV and Group V synthetic base stocks, including a complete viscosity range of polyalphaolefins (2–300 cSt @ 100°C), a full line of esters and novel alkylated naphthalene products. This broad portfolio gives us a comprehensive understanding of synthetic lubricant formulations that are necessary to help our customers develop innovative solutions to meet their needs.

Q: How can this formulation guide help me?

A: This guide is intended to provide the formulator with a starting point for developing synthetic lubricant products. It reduces the need for extensive base stock screening by recommending a base stock combination for a given viscosity grade in a lubricant application. This guide can help you increase your speed to market by reducing your product development time.

Q: What type of lubricant applications does this guide include?

A: This guide includes synthetic base stock recommendations for automotive lubricants including internal combustion engines, electric drive concepts, and industrial lubricant applications. These recommendations are designed to meet the standard viscosity grades for each lubricant application.

Q: How much variability is there in the formulation recommendations?

A: The base stock combinations listed in the guide should generally achieve a specified viscosity grade and performance level. The formulations can be adjusted as required to meet other viscosity grades or performance properties.

Q: Have the formulations listed in this guide been validated through testing?

A: All base stock formulations are designed to meet the viscometrics listed and have been validated in laboratory testing, unless otherwise noted. This guide contains performance testing on some formulations with specific additive packages. For additional questions about the specific additive packages or any other formulation / data sets, please contact your ExxonMobil sales representative or technical contact.

As with all formulations, adjustments may be required to meet specific formulation requirements.

Q: Are the formulations in this guide representative of a finished lubricant?

A: They are intended to be starting point formulations based on ExxonMobil synthetic base stocks. In some cases, we've also tested specific additive packages so that when properly formulated, the result could be a finished lubricant. In other cases, we are recommending a base stock combination to achieve a specific viscosity grade, with the additive choice left to the preference of the formulator. For additional questions about the specific additive packages, or any other formulation / data sets, please contact your ExxonMobil commercial or technical representative.

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Q: Can I obtain a product sample?

A: Product samples are available for all of our synthetic base stocks. Contact an ExxonMobil sales representative to arrange for sampling. Please visit our website at www.exxonmobilchemical.com/synthetics to contact us.

Q: Are there any limitations to product availability?

A: ExxonMobil has manufacturing, distribution, and sales support facilities around the world. All products listed in this guide are commercially available for global supply.

Q: Can I use these base stocks in applications not listed here?

A: Our synthetic base stocks can be used in a wide variety of applications, from engine oils to data center cooling to textile lubricants. Our technical support staff is available to help with formulation recommendations beyond those covered in this guide. Please contact an ExxonMobil representative for assistance.

Q: What other services are available to me as a potential customer?

A: ExxonMobil offers numerous value-added services to our customers, including formulation assistance, performance testing, product development assistance as well as global product specification and registration.

Q: Where can I get information on the health and safety characteristics of these products?

A: Safety Data Sheets (SDS) for each synthetic base stock product can be obtained through an ExxonMobil sales representative or from our website at www.exxonmobilchemical.com/synthetics.

Q: Do you have any formulations based on mineral oil?

A: Many of our synthetic base stock products can be used with mineral oils to enhance their overall effectiveness. Our technical support staff can help design a semi-synthetic base stock recommendation should you have a specific interest.

Q: My application may require just a single drum of your synthetic base stocks. Can you supply me at that level?

A: We have a global distribution network. We would be pleased to forward your requirement to one of our distributors.

Q: Will this guide be updated to reflect new information and technology?

A: Since we are continually updating our product data and technology, we will update this guide periodically as needed.

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3.0 Synthetic base stock grade slate summary

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3.0 Synthetic base stock grade slate summary

PAO

Polyalphaolefins are hydrogenated olefin oligomers manufactured by the polymerization of linear alpha-olefins. They have well-defined wax-free iso-paraffinic structures, which offer good low-temperature properties, high viscosity index (VI), low volatility, and improved thermal stability. These API Group IV fluids are well-suited for all lubricant applications requiring good stability under extreme operating conditions.

LVLV PAO

Low-viscosity/low-volatility (LVLV) Polyalphaolefins are specialty Group IV fluids with exceptional low volatility at a given viscosity. This chemistry provides excellent low and high temperature properties, as well as enhanced thermal properties compared to conventional PAO. LVLV PAOs have primarily been developed for automotive applications, including driveline fluids, electric vehicle (EV) greases, and low-viscosity engine oils.

mPAO

Metallocene polyalphaolefins are products that leverage metallocene catalyst technology to provide PAOs with a more uniform, comb-like structure and narrow molecular weight distribution to provide high viscosity index (VI), low temperature and shear stability properties versus conventional base stocks.

AN

Alkylated naphthalene products are manufactured through the alkylation of naphthalene with linear alpha-olefins. These resulting API Group V fluids offer very good thermal, oxidative, and hydrolytic stability. In addition, they provide solvency and are useful base stocks to improve the performance of most lubricants.

Esters

Synthetic esters are produced through a reaction of alcohols and acids. Such products provide various features, such as high thermal and oxidative stability, low volatility, good lubricity, solvency, and biodegradability depending on the specific ester (see Section 4.5.1). These API Group V fluids can be used in all types of lubricants as a standalone base stock or as a blend component.

Table 3.0.A Synthetic base stock products, key properties

Product type	Product name	Product description	SG @ 15.6/15.6°C	KV @100°C cSt	KV@ 40°C cSt	KV @-40°C cSt	VI	Pour point, °C	Flash point, COC, °C
Polyalphaolefin (PAO)	SpectraSyn™ 2 PAO	Low viscosity PAO	0.798	1.7	5	252	n/a	-66	157
	SpectraSyn™ 2B PAO		0.799	1.8	5	n/a	n/a	-54	149
	SpectraSyn™ 2C PAO		0.798	2	6.4	n/a	n/a	-57	>150
	SpectraSyn™ 4 PAO		0.820	4.1	19	2,900	126	-66	220
	SpectraSyn™ 5 PAO		0.824	5.1	25	4,920	138	-57	240
	SpectraSyn™ 6 PAO		0.827	5.8	31	7,800	138	-57	246
	SpectraSyn™ 8 PAO		0.833	8	48	19,000	139	-48	260
	SpectraSyn™ 10 PAO		0.835	10	66	39,000	137	-48	266
	SpectraSyn™ MaX 3.5 PAO	Low viscosity / low volatility PAO	0.817	3.5	14.3	1,670	129	<-78	234
	SpectraSyn Plus™ 3.6 PAO	Low viscosity PAO with improved volatility and CCS	0.816	3.6	15.4	2,000	120	<-65	224
	SpectraSyn Plus™ 4 PAO		0.820	3.9	17.2	2,430	126	<-60	228
	SpectraSyn Plus™ 6 PAO		0.827	5.9	30.3	7,400	143	<-54	246
	SpectraSyn™ 40 PAO	High viscosity PAO	0.850	39	396	n/a	147	-36	281
	SpectraSyn™ 100 PAO		0.853	100	1,240	n/a	170	-30	283
Metallocene PAO	SpectraSyn Elite™ 65 mPAO	High viscosity, high VI, mPAO	0.846	65	614	n/a	179	-42	277
	SpectraSyn Elite™ 150 mPAO		0.849	156	1649	n/a	210	-33	277
	SpectraSyn Elite™ 300 mPAO		0.849	303	3358	n/a	241	-33	286
Alkylated naphthalene	Synesstic™ 5 AN	Alkylated naphthalene	0.908	4.7	29	43,600	74	-39	222
	Synesstic™ 12 AN		0.887	12.4	109	392,500	105	-36	258
Esters	Esterex™ A32 ester	Adipate esters	0.928	2.8	9.5	985	149	-65	207
	Esterex™ A34 ester		0.922	3.2	12	1,970	137	-60	199
	Esterex™ A41 ester		0.921	3.6	14	3,286	144	-57	231
	Esterex™ A51 ester		0.915	5.4	27	16,970	136	-57	247
	Esterex™ P61 ester	Phthalate esters	0.967	5.4	38	n/a	62	-42	224
	Esterex™ P62 ester		0.967	5.4	39	n/a	59	-51	243
	Esterex™ P81 ester		0.955	8.3	84	n/a	52	-33	265
	Esterex™ P101 ester		0.965	10.1	100	n/a	76	-33	250
	Esterex™ TM111 ester	Trimellitate esters	0.978	11.9	124	n/a	81	-33	274
	Esterex™ NP343 ester	Polyol esters	0.945	4.3	19	2,540	136	-48	257
	Esterex™ NP451 ester		0.993	5	25	7,610	130	-60	255

Source: ExxonMobil data

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Table 3.0.B Typical applications

Product names	Gasoline and diesel engines	Automatic transmissions	Industrial / automotive gears and transmissions	Hydraulic systems	Industrial bearings	Rotary air and gas compressor	Hydrocarbon refrigeration compressor	Grease	Turbines	Heat transfer fluid	Automotive hydraulic fluids	EV drive unit (Gearbox and E-motor)	Electric vehicle / Battery thermal management
SpectraSyn™ 2/2B/2C PAO		●	•	●			•	•		●	●	●	●
SpectraSyn™ 4 PAO	●	●	●	●		•	•	•	●	•		●	
SpectraSyn™ 5 PAO	●		●	●	●	●	•	●	●				
SpectraSyn™ 6 PAO	●		●	●	●	●	•	●	●				
SpectraSyn™ 8 PAO	●		•	•	•	●	•	•	•				
SpectraSyn™ 10 PAO			•	•	•	●	•	•	•				
SpectraSyn™ MaX 3.5 PAO	●	●	•		●	•	•	●		●		●	●
SpectraSyn Plus™ 3.6 PAO	●	●	●	●		•	•	•	●	•		●	
SpectraSyn Plus™ 4 PAO	●	●	●	●		•	•	•	●	•		●	
SpectraSyn Plus™ 6 PAO	●	●	●	●		•	•	•	●	•		●	
SpectraSyn™ 40 PAO	•	•	●	●	●	●	•	●	•				
SpectraSyn™ 100 PAO	•	•	●	●	●	●		●	•				
SpectraSyn Elite™ 65 mPAO	•	•	●	●	●	●	•	●	•			•	
SpectraSyn Elite™ 150 mPAO	•	•	●	●	●	●	•	●	•			•	
SpectraSyn Elite™ 300 mPAO	•	•	●	●	●	●	•	●	•			•	
Synesstic™ 5 AN	●	•	●	•	●	●	•	●	●	•	•	●	•
Synesstic™ 12 AN			•	•	●	●		●	•				
Esterex™ A32 ester	●	●	●	●	●	●		•		●	●	●	●
Esterex™ A34 ester	•	●	●	●	●	●		•		•	•	●	•
Esterex™ A41 ester	•	•	●	●	●	●		●	•			•	
Esterex™ A51 ester	●	●	●	●	●	●		●	●			•	
Esterex™ NP343 ester	●	●	●	●	●	●	●	●	●	•	•	●	●
Esterex™ NP451 ester	•	•	•	●	●	●	●	●	●			•	•
Esterex™ P61 ester	•	•	●	●	●	●		●	•				
Esterex™ P62 ester	•	•	●	●	●	●		●	•				
Esterex™ P81 ester	•		●	●	●	●		●	•				
Esterex™ P101 ester			●	●	●	●		●	•				
Esterex™ TM111 ester			●	●	●	●		●	•				

● Most common application uses • Less common application uses

Source: ExxonMobil data

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4.0 Industry trends

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4.0 Industry trends

Updated each year, The ExxonMobil Global Outlook is ExxonMobil's long-term view of our shared energy future. We develop the "Outlook" annually to assess future trends in energy supply, demand and technology to help guide the long-term investments that underpin our business strategy.

4.1 Global Outlook

The Global Outlook is ExxonMobil's view of energy demand and supply through 2050. A foundation of our business plan, the analysis is based on a long-term assessment of:

- Economic trends
- Advances in technology
- Consumer behavior
- Climate-related public policy

To access the latest report please visit: https://corporate.exxonmobil.com/sustainability-and-reports/global-outlook#Keytakeaways

4.2 Lubricant industry trends

Advancement in equipment technology is designed to improve production cost and efficiency. This has generally resulted in higher operating speeds, with increased operating temperatures and pressures, that will place greater demands on the lubricants.

These demands are coupled with objectives around reduced-maintenance or maintenance-free operations, increased level of environmental awareness, tighter safety regulations and a strong focus on energy efficiency. These trends will continue to challenge lubricant technology and drive the demand for synthetic lubricants based on API Group IV and V base stocks. This, in turn, will drive research and development activities to further improve the technology and synergies available between these high-performance base stocks.

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Energy savings and efficiency also contribute to overall cost performance. Limiting emissions through improved efficiency and managing waste generation are both important contributions of synthetic-based lubricants to support both cost savings and environmental performance.

Demand for API Group I – III base stocks, overall, is stable, as demand for higher-quality, synthetic-based lubricants continue to rise. API Group IV and V oils will continue to grow in use to meet the more stringent specifications for extended drain intervals, improvements in energy efficiency, and, in some cases, bio-degradable or bio-based lubricant requirements and improved equipment durability.

4.3 Automotive trends

Engine and transmission technologies continue to evolve, mainly driven by the need to improve fuel economy and reduce emissions. Many countries have implemented fuel economy and emission targets for new car production. Engine manufacturers favor smaller-displacement engines that utilize forced induction, whether it be turbocharging or supercharging, to increase both the power density and the fuel efficiency of the vehicles. There is also an increased use of after-treatment devices to reduce exhaust emissions. Automatic transmissions are becoming more common, with an increasing number of gears (6-, 7- and 8-speed transmissions).

Manual transmissions are declining and are being replaced by automated manual transmissions (AMT) or fully automatic transmissions. Dual clutch transmission (DCT) technology is growing, mainly in European vehicles, where they help improve fuel economy and facilitate the hybridization of vehicles. For smaller vehicles, continuously variable transmissions (CVT) are growing in popularity.

The number of hybrid cars using both conventional engines and electric drives is beginning to increase due to the need to meet stringent CO2 emissions requirements. On commercial vehicles, as with passenger cars, fuel economy is driving developments, as is the need to reduce emissions. Lower-viscosity oils with lower high-temperature, high-shear (HTHS) requirements are becoming more common for commercial vehicles. However, the need for reliability and durability of the engines means a conservative approach is being taken to lower the HTHS requirements.

Emission control continues to improve through the increasing application of exhaust gas after-treatment, using devices such as diesel particulate filters (DPF), selective catalytic reduction (SCR) and exhaust gas recirculation. However, many vehicles in developing countries are still not fitted with exhaust-treatment systems.

For commercial vehicles, electronic transmission control has almost completely replaced hydraulic control, offering better gear shifting, integration of power takeoffs and other advantages. Automatic transmissions are also increasing in prevalence, providing improved gear-changing, particularly in stop-and-go applications.

Battery electric vehicles (BEVs) are becoming more and more prevalent globally. These vehicles do not use an internal combustion engine with a traditional transmission for power. Instead, a battery pack supplies an electric current to an inverter and an electric motor. The electric motor converts the current to a mechanical drive system. Electric motors operate at much higher speeds versus the final driveshaft and wheels. Therefore, a gearbox is connected to the electric motor, which reduces the speed. It has become more and more common for the inverter, electric motor and gearbox to be combined into one physical unit (to conserve space on the vehicle), which is often referred to as an electric drive unit (EDU), or e-axle unit.

Development of hybrid and electric vehicles for local use in city driving is ongoing but is a niche market. These types of power units will grow as governments and municipalities encourage their use through taxation, subsidies or limits on the use of conventional diesel vehicles.

In many countries, governments mandate the use of biofuels for transportation to support local agriculture and meet emission targets. However, corrosion, deposits and filtration problems have all been reported by engine manufacturers and users for fuels containing high levels of bio-derived components.

4.3.1 Implications for lubricants and base oils

The need for better fuel economy and lower greenhouse gas (GHG) emissions is driving technology changes in both vehicle hardware and lubricants. Base stocks with lower viscosity and improved volatility characteristics are desired to help achieve the more stringent fuel economy and emission targets. The other challenge of the base oil is to deliver fuel economy at lower viscosity, without compromising on hardware durability. This combination of requirements limits the use of conventional mineral oil, and drives increasing demand for higher quality base stocks such as PAO and API Group V.

In addition, with the continued trend of engine downsizing and increasing use of turbocharging, direct injection, and exhaust gas recirculation, smaller volumes of oil will be needed to maintain thermal and oxidative stability at equal or longer drain intervals. This requires an oil that has an improved viscosity index and thermal and oxidative stability while maintaining oil viscometrics, with an increasing reliance on additives for particulate handling.

For BEVs, within the electric motor and gearbox, there are a number of bearings and gears that require lubrication. For first-generation electric vehicles (EVs), many manufacturers relied on traditional automatic transmission fluids (ATFs) or manual transmission fluids (MTFs) to provide this lubrication. However, as the bearings and gears are operated under significantly different conditions than the traditional transmission (lower temperatures, higher speeds), new fluid technology is being developed to provide optimized protection for EDUs, particularly as next-generation hardware designs evolve.

Formulations for these new EDU fluids will not only need to provide durability and protection under these tribological conditions but also deliver better air release to avoid problems tied to air entrainment (e.g., gear/bearing wear, electro-performance degradation, increased NVH, etc.). And, in integrated EDU designs, lubricants will need to maximize heat transfer as they will also be used as a coolant to directly cool the e-motor.

Also, as new materials are being used or developed to reduce vehicle weight, continued material compatibility with the lubricant will be essential to maintaining durability and engine protection.

4.4 Industrial segment trends

According to the ExxonMobil Energy Outlook[1], energy demand in the industrial segment is projected to grow significantly in non-OECD countries through 2050. However, the rate of energy demand growth is much lower than the rate of economic growth. Energy efficiency is playing a growing role in sustaining the world's energy supplies even as expanding economies are increasing energy demand. Energy efficiency also helps in reducing GHG emissions.

A general trend in the industrial segment is equipment downsizing while also achieving equal or higher production per unit energy consumption. Stresses on the lubricants are subsequently higher, whether through smaller oil quantities, higher temperatures, higher speeds and/or higher loads.

The oil is expected to last for longer periods before replacement. Not only do these factors reduce equipment downtime and improve productivity, but they also reduce the amount of waste oil and the associated disposal costs.

Although currently a small part of the overall energy mix, the renewable energy sector continues to grow, with significant installation of wind turbines globally.

Wind turbine sizes are increasing, and new installations are moving to more remote locations where wind patterns are more reliable and load factors can be increased. Many wind turbines are being installed offshore, where reliability is paramount to control the maintenance costs. Gearbox and bearing failures continue to be a problem due to the extreme load conditions that can exist. As gearbox and bearing design improves, these designs should be coupled with advanced lubricant technology to increase the overall reliability of the wind turbine system. In addition, cold temperature performance for wind lubricants is extremely critical to avoid freezing and other inefficiencies, as well as expensive, unplanned downtime for the operating turbines.

In summary, for wind applications, after the asset has been financed, designed and installed, the primary variable that can be controlled to manage profitability is the Operations & Maintenance of the asset. This underscores the criticality of a high-performance suite of lubricants designed to not only minimize downtime but also optimize tower "up-time" and, therefore, output.

1 For more details, please visit www.exxonmobil.com.

4.5 Sustainability

ExxonMobil is striving to create sustainable solutions that improve quality of life and meet society's evolving needs. We intend to do this in ways that help protect people, the environment, and the communities where we operate. Our focus on innovation and technology, combined with supportive government policies, can further accelerate large-scale deployment of solutions essential to enabling modern life and lowering greenhouse gas emissions, including those for low-carbon initiatives already underway. We strive to play a leading role in the energy transition and plan to accomplish this by applying the company's core strengths, which include scale, integration, technology, functional excellence, and our people.

How can we help?

By supplying base stocks and formulating finished lubricants that can help to improve fuel economy and offer the potential for enhanced energy efficiency. Our products can help lubricate renewable energy assets and support mobility electrification. This means potential enhanced efficiency and potential reduced GHG emission benefits that can be incorporated into your product solutions, such as extending vehicle range, increasing energy efficiency, and improving oxidative stability for long drain intervals.

Performance

We can collaborate with you to provide insights on how Synthetic base stocks performance characteristics enable the formulation of more efficient and more durable finished Lubricants in a wide range of applications.

Industrial gear oil
Up to **3.4%**[1] improved efficiency

Engine oil
+ 0.5%[2] on VW PV1811 fuel economy test

Grease
~13%[3] coefficient of friction reduction comparing synthetic vs. mineral-based greases

Electric vehicle fluids
Enhanced lubrication up to **0.8%**[4] energy savings and lowers system temperature

Wind turbine lubricants
Better **energy efficiency**, improved oil drain intervals

Readily or inherently biodegradable options
76.4%[5] biodegradability in 28 days (OECD301B) for Esterex NP 343

Automotive gear oil
1%[6] fuel efficiency benefit

[1] Efficiency determined using a proprietary worm gear test rig, comparing this synthetic gear oil to a commercially available mineral oil of the same viscosity. Efficiency improvements will vary based on operating conditions and application.

[2] 0.5% fuel economy improvement reported comparing PV1811 results obtained on 0W-20 candidates blended with Grp III + base stock vs. a candidate containing 25% LVLV novel PAO and the balance being the same Grp III+ used in the comparative candidate.

[3] CoF measurements based on ASTM D5707 method running ISO VG 460 NLGI #1 grease candidates prepared with either mineral based stock or with PAO.

[4] Based on WLTC (Worldwide Harmonized Light Vehicles Test Cycle) efficiency gains vs. GR III referenced @ -7°C.

[5] Single sample or two sample average determination.

[6] Fuel efficiency of 75W-85 grade synthetic-based gear fluid measured in field test compared to 80W-90 grade commercially available reference fluid.

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4.5.1 Biodegradability

Beyond the biodegradability data presented in Table 4.5.1, we are continuously working to ensure our products are recognized for their potential benefits in formulations. Please contact your designated ExxonMobil commercial or technical representative to receive additional information on product listing on the Lubricant Substance Classification list (LuSC-list), validity date and maximum treat rate details.

Table 4.5.1 Biodegradability

Product type	Product	Biodegradability[a]
Esterex™ ester	Esterex™ A32 ester	Readily biodegradable
	Esterex™ A34 ester	
	Esterex™ A41 ester[b]	
	Esterex™ A51ester	
	Esterex™ NP343 ester	
	Esterex™ NP451 ester	
	Esterex™ P61 ester	
	Esterex™ P62 ester	
SpectraSyn™ PAO	SpectraSyn™ 2 PAO	
	SpectraSyn™ 2C PAO	
Synesstic™ alkylated naphthalene	Synesstic™ 5 AN	
Esterex™ ester	Esterex™ P101 ester	Inherently biodegradable
	Esterex™ P81 ester	
Synesstic™ alkylated naphthalene	Synesstic™ 12 AN	
SpectraSyn™ PAO	SpectraSyn™ 2B PAO	
	SpectraSyn™ 4 PAO	
	SpectraSyn™ 5 PAO	
	SpectraSyn™ 6 PAO	
SpectraSyn™ MaX PAO	SpectraSyn™ MaX 3.5 PAO	
SpectraSyn Plus™ PAO	SpectraSyn Plus™ 3.6 PAO	
	SpectraSyn Plus™ 4 PAO	
	SpectraSyn Plus™ 6 PAO	

[a]Biodegradability using OECD 301F/301B testing guidelines. (OECD, 1992)

Readily biodegradable: A substance is considered “readily biodegradable” when the test material achieves greater than 60% biodegradation in 28 days. Single substances with one isomer (a monomer, e.g. ethanol) must pass the 10-day window criterion, which means that once the 10% biodegradation mark has been attained, test material must then reach the 60% biodegradation mark within 10 days and before day 28 of the test. The 10-day window criterion does not apply to complex mixtures (isomeric mixtures).

Inherently biodegradable: A substance is considered "inherently biodegradable” when the test material achieves greater than 20% biodegradation in 28 days, or greater than 60% biodegradation within 60 days.

Source: ExxonMobil data

[b]Available in selected regions. Please contact your ExxonMobil sales representative for complete country availability.

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4.6 Advancing climate solutions

For more than 140 years, we have been a leader in innovation, supplying the energy and products people need to live healthy, prosperous lives in the modern world. We are continuing this legacy of innovation by doing our part to provide energy security and evolving our operations in ongoing support of a net-zero future – all while creating long term shareholder value. ExxonMobil's Advancing Climate Solutions Report describes our resolve to drive meaningful change, the results we're already delivering, and the resiliency of our plans.

To find out more please visit: https://corporate.exxonmobil.com/sustainability-and-reports/advancing-climate-solutions#Abouttthereport

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5.0 Automotive applications

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5.0 Automotive applications

5.1 Passenger vehicle engine oils

Application and equipment

Most internal combustion passenger cars are powered by a four-stroke engine, typically fueled by gasoline or diesel. However, they can also run on alternative fuels such as liquefied petroleum gas (LPG), compressed natural gas (CNG), methanol, ethanol, or hydrogen. Regardless of the fuel used, the basic engine design remains the same, with power generated by pistons driven by expanding combustion gases in the engine cylinders. The motion of the pistons propels the car wheels through a gearbox, which translates the engine power/rotation to the wheels.

Engine oils play a crucial role in protecting all the working parts of internal combustion engines, especially as engines become more sophisticated with higher power densities and improved efficiency.

The primary function of engine oil is to create a continuous film of molecules that prevents metal-to-metal contact and reduces friction inside the engine. Lubrication is achieved through a combination of oil being supplied to the top of the engine by the oil pump and splash-lubrication provided by the crankshaft for the lower half of the engine.

Turbochargers and superchargers are commonly used to enhance the power and efficiency of small internal combustion engines. Engine oil also serves to lubricate and cool these components, placing additional stress on the oil due to the high temperatures produced by superchargers and turbochargers.

Lubricant requirements

The engine oil is expected to provide the following key benefits:

- Reduce friction and prevent metal-to-metal contact
- Remove heat and wear particles
- Reduce corrosion by neutralizing combustion products
- Keep the engine components clean
- Provide effective sealing of the cylinders to minimize exhaust gas blow-by
- Help improve fuel economy

Engine oils are categorized in two different ways:

1) Viscosity classification: Multigrade oils are usually specified according to SAE J300 standards.

2) Performance specifications: These are defined by organizations such as the American Petroleum Institute (API), International Lubricant Standardization and Approval Committee (ILSAC), European Automobile Manufacturers Association (ACEA), and various original equipment manufacturers (OEM) like Mercedes Benz, BMW, GM, Ford, VW, etc.

Due to the need for improved fuel economy, the traditional high-viscosity multigrade oil is being replaced by lower-viscosity grades. The most common grade of oil for cars today is 5W-30. However, there is a growing trend toward even lower viscosity lubricants, including 0W-16 and 0W-20 grades, to achieve better fuel efficiency.

As engine technology advances and emissions legislation evolves, the performance specification levels for engine oils continue to become more demanding. This has led to the development of specific lubricants to meet the needs of modern engine hardware. The performance requirements of crankcase lubricants are defined by the API, ILSAC, ACEA, JAMA, and global lubricant specifications.

With the presence of exhaust gas after-treatment systems, metallic additive treat rates are limited, and low-sulfated ash, phosphorous, and sulfur (SAPS) oils are becoming more common. It's a delicate balance to provide the necessary performance and protection while meeting the limitations of each specification.

Advantages of synthetic oils

Compared to mineral oils, the use of synthetic base stocks in automotive lubricants offers improved wear protection, lower volatility, higher viscosity index, and better thermal and oxidative stability. These benefits result in extended drain intervals compared to mineral oil, as well as potential fuel economy benefits.

The highest performance standards for engine oils can be achieved by using PAO base stocks, such as SpectraSyn™ PAO, SpectraSyn Plus™ PAO or SpectraSyn™ MaX PAO. These synthetic base stocks have several advantages over mineral oil base stocks, including:

- Better oxidative and thermal stability for long service life
- Lower volatility for stable viscometrics
- Higher viscosity index for improved protection and low-temperature fluidity
- No inherent contaminants to accelerate corrosion or acid formation
- Lower pour points for improved operational performance at low temperatures

Furthermore, the use of Synesstic™ alkylated naphthalene (AN) base stocks or Esterex™ esters as co-base stocks can offer the following benefits:

- Additive solubility
- Improved lubricity
- Improved cleanliness
- Improved thermal and oxidative stability
- Reduced seal swelling

Formulation data

The suggested engine oil formulations described on the following pages provide a basic guideline for developing various engine oil grades using ExxonMobil's SpectraSyn™ PAO and Group II/II+ EHC™. The engine oil license performances (e.g., API SN/ILSAC GF-7, ACEA A3/B4, A5/ B5, C2, C3, C4, GB (China), D1 (China) and JASO GLV1 & GLV2) are shown in the tables in this chapter, but they are dependent on the specific additive package used and should be verified with the additive supplier. The key physical properties, as defined by SAE J300, are met and should serve as a good starting point for lubricant formulators.

The highest performance standards, industry and OEM specifications for engine oils can be met using PAO base stocks such as SpectraSyn™, SpectraSyn Plus™ or SpectraSyn™ MaX PAO.

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Table 5.1.A Passenger car engine oil blends with SpectraSyn™ PAO, Esterex™ esters and Synesstic™ alkylated naphthalene

Component, wt.%	0W-8	0W-8	0W-16	0W-16	0W-16	0W-20	0W-20	0W-20	0W-20	0W-30	5W-20	5W-30	5W-30
SpectraSyn™ 4 PAO	50.35	40		20	10		35	13			15		
SpectraSyn™ 6 PAO										53			10
SpectraSyn™ MaX 3.5 PAO	35		10			20			10			10	
Group II+ EHC™ 45/EHC™ 50			71.35	61.35		57.95	45.35		48.1	26.85	63.6	32.35	22.35
Group II+ EHC™ 65												35	25
Gr III/III+, 4 cSt or 6 cSt		45.35			71.35			65.1	20				20
Esterex™ NP343 ester*	3	3	3	3	3	3	3	3	3	3	3	3	3
Synesstic™ 5 AN*	3	3	3	3	3	3	3	3	3	3	3	3	3
Additive package	8.65	8.65	8.65	8.65	8.65	8.65	8.65	8.65	8.65	8.65	8.65	8.65	8.65
Viscosity modifier			4	4	4	7.4	5	7.25	7.25	5.5	6.75	8	8

Property	Test method	0W-8	0W-8	0W-16	0W-16	0W-16	0W-20	0W-20	0W-20	0W-20	0W-30	5W-20	5W-30	5W-30
KV @100°C, cSt	ASTM D445	5.2	5.2	7.6	7.3	9.5	9	8.4	8.2	8.6	9.5	10.1	10.6	10.1
KV @40°C, cSt	ASTM D445	22.5	23.5	40.3	38.2	52.8	48.5	45.8	40.7	45.6	52.8	58.3	65.1	58.3
VI	ASTM D2270	172	162	161	158	161	168	163	181	171	164	161	153	161
HTHS @150°C, mPa·s	ASTM D4683	1.8	1.9	2.4	2.3	2.9	2.6	2.6	2.6	2.6	2.9	2.9	2.9	2.9
CCS, @-30°C, cP	ASTM D5293	1,200	1,495	3,008	2,866	2,020	2,716	2,909	2,228	2,894	3,282	4,817	5,257	4,817
CCS, @-35°C, cP	ASTM D5293	2,050	2,488	5,991	5,507	3,485	5,310	5,246	3,870	5,564	5,948	9,318	10,623	9,318
NOACK volatility, wt.%	ASTM D5800	11.8	10.6	12.1	11.6	22.9	12	11.5	11.9	11.8	7.8	10.2	10.5	10.2

*Recommended starting treat rate range of 3-5 wt.% depending on performance requirements.

Source: ExxonMobil data

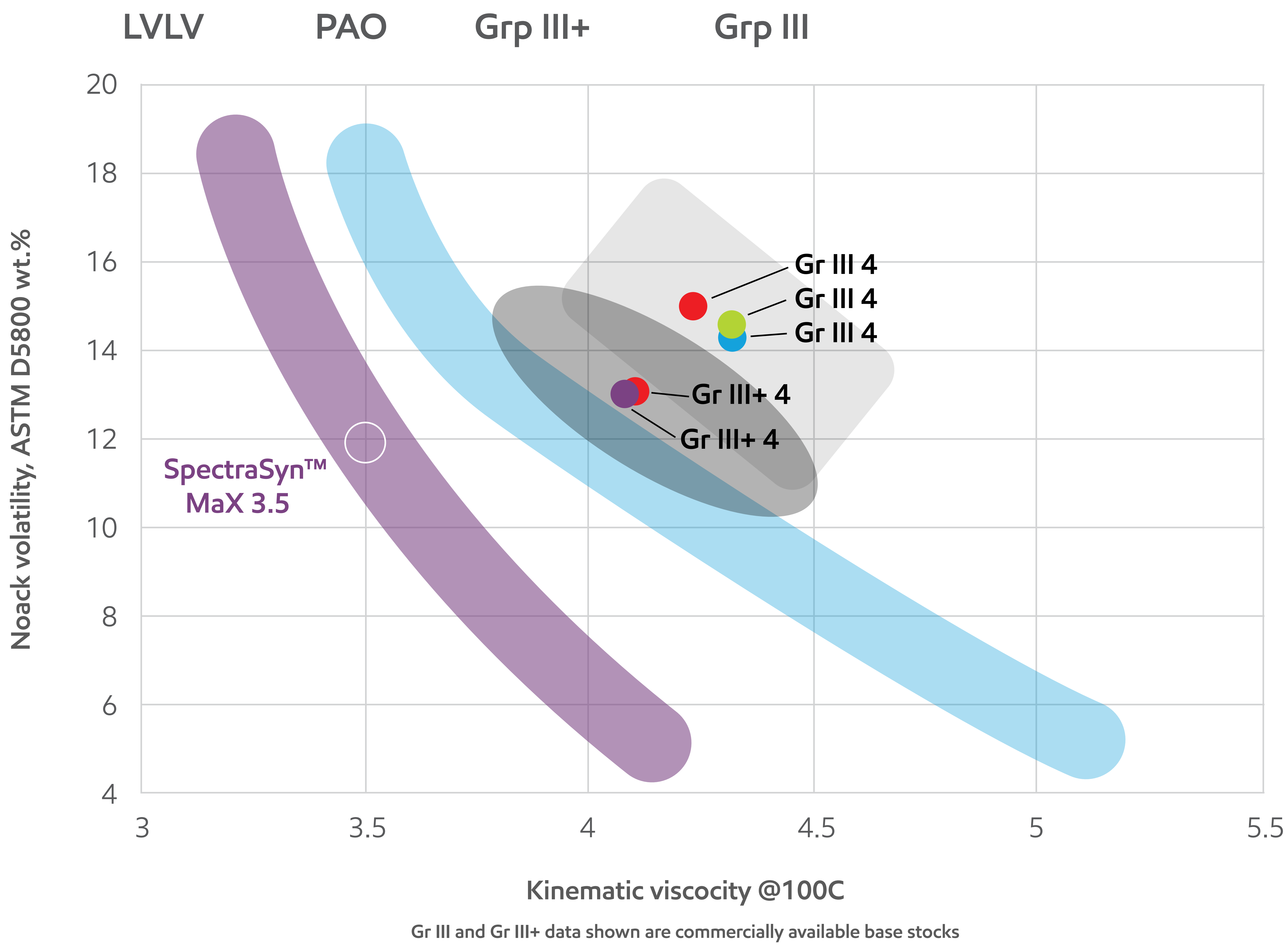
SpectraSyn™ MaX 3.5 PAO

SpectraSyn™ MaX PAO is a new generation polyalphaolefin manufactured using novel process technology. It leverages a unique PAO molecular structure, distinct from conventional or metallocene-derived PAO, to bring about exceptional low viscosity, low volatility (LVLV) balance and excellent low-temperature properties. SpectraSyn™ MaX also provides improved oxidative stability, enhanced lubricity and traction, and improved flashpoint versus conventional PAO. It delivers step-out performance in terms of fuel economy improvements for engine oil and driveline, energy efficiency for EV driveline and enhanced durability for extended oil drain intervals.

Specifically, SpectraSyn™ MaX 3.5 PAO can deliver low-temperature and volatility benefits to compensate for Group III/III+ and Group II/II+ base stocks in high-quality engine oil applications. It can also be used in formulating other high-performing automotive, aviation, and military products that demand excellent volatility and low-temperature performance.

Figure 5.1.A shows the Noack volatility against the KV 100 for various base stocks. The Group II/III/III+ base stocks have significantly higher volatility than the conventional PAOs. Yet, as the KV100 moves below 4 cSt, the volatility increases exponentially. The new generation PAO provides step out performance in Noack volatility. For example, a 3.5 cSt conventional PAO should have a Noack volatility of 18 wt.%. On the other hand, the new generation LVLV (Low Volatility / Low Viscosity) PAO at 3.5 cSt has a Noack volatility of 11.6 wt.%.

Figure 5.1.A Viscosity and volatility relationships for low viscosity base stocks



Source: ExxonMobil data

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Table 5.1.B SpectraSyn™ MaX 3.5 PAO – key properties

Property	Test method	SpectraSyn™ MaX 3.5 PAO	SpectraSyn Plus™ 3.6 PAO	SpectraSyn™ 4 PAO	Gr III+ (A)	Gr III+ (B)	Gr II
KV @100°C, cSt	ASTM D445	**3.51**	**3.60**	**4.10**	**4.16***	**4.11**	**2.74**
KV @40°C, cSt	ASTM D445	14.26	15.40	18.40	17.90*	18.30	10.10
Viscosity index	ASTM D2270	128	120	126	134*	129	114
Noack volatility, wt.%	ASTM D5800	**11.6**	**17.0**	**12.4**	**13.0***	**11.9**	**40.6**
Pour point, °C	ASTM D5950**	-78	-65	-66	-18*	-33	-36
CCS @-35°C, cP	ASTM D5293	**790**	**1,050**	**1,430**	**2,045**	**1,780**	**513**
RPVOT (oxidation test), min	ASTM D2272B	**102**	**47**	**41**	**40**	**35**	**28**
Flash point COC (EV), °C	ASTM D92	**234**	**224**	**220**	**224**	**232**	**201**

*Publicly available data.
**ASTM method D5950 only covers up to -66 °C.
Source: ExxonMobil data

As shown in Table 5.1.B, the new generation LVLV PAO (SpectraSyn™ MaX PAO) offers substantial improvement in high- and low-temperature properties over conventional base stocks and conventional PAO. This technology also offers excellent oxidative stability and higher flash point. These properties enable consistent lubricant performance at low and high temperatures and can improve durability.

Due to its unique molecular structure, SpectraSyn™ MaX exhibits lower traction versus conventional PAO and mineral base stocks. Figure 5.1.B shows a comparison of 0W-12 engine oils formulated using Gr III+ base stocks against SpectraSyn™ MaX PAO. In this test, the SpectraSyn™ MaX technology enabled a ~20% reduction in traction versus fully formulated Grp III+. Extending this to a real-world engine test, the SpectraSyn™ MaX PAO enables a fuel economy advantage. As shown in Figure 5.1.C, the SpectraSyn™ MaX PAO resulted in a 0.6% improvement over the Gr III+ baseline.

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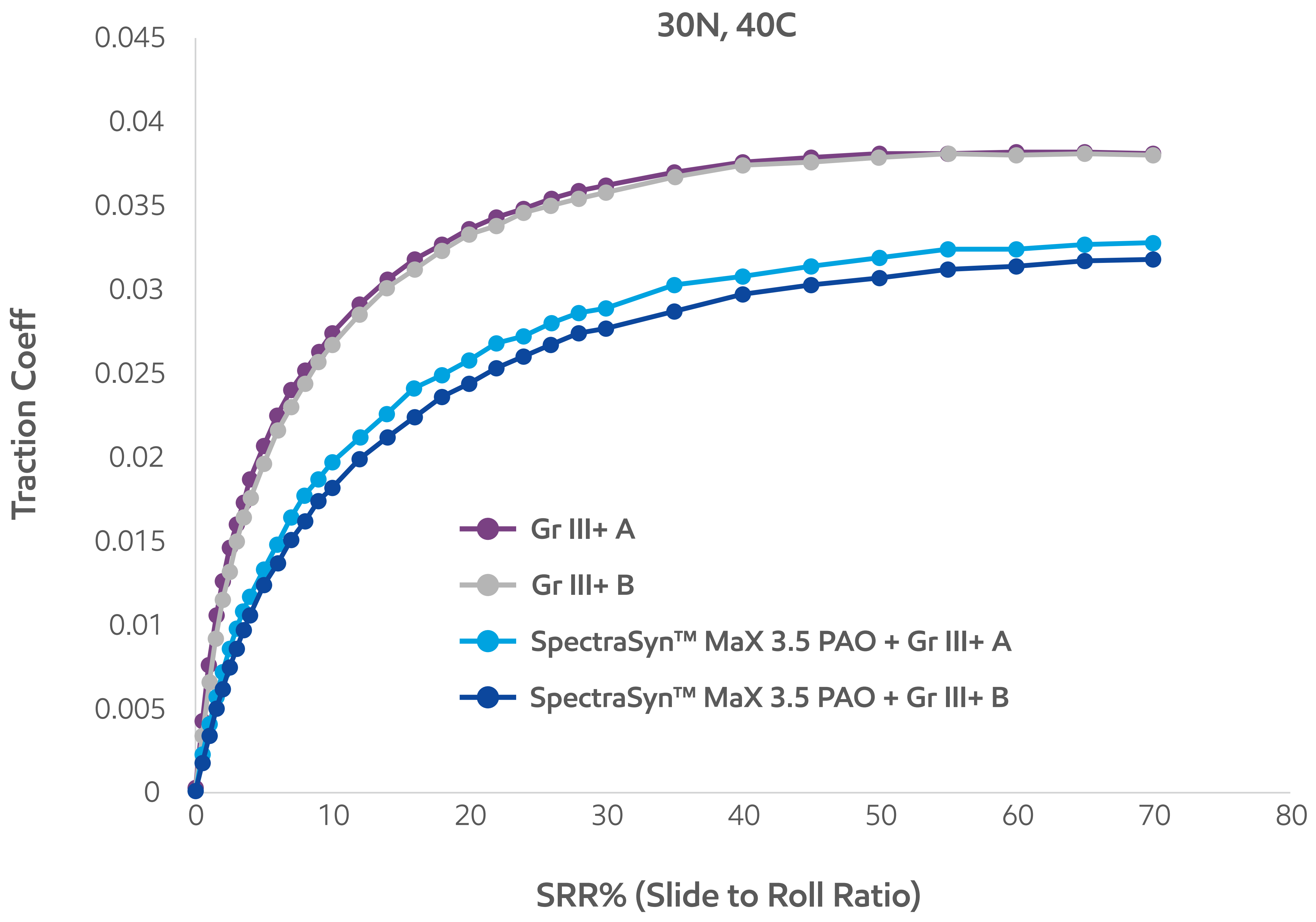
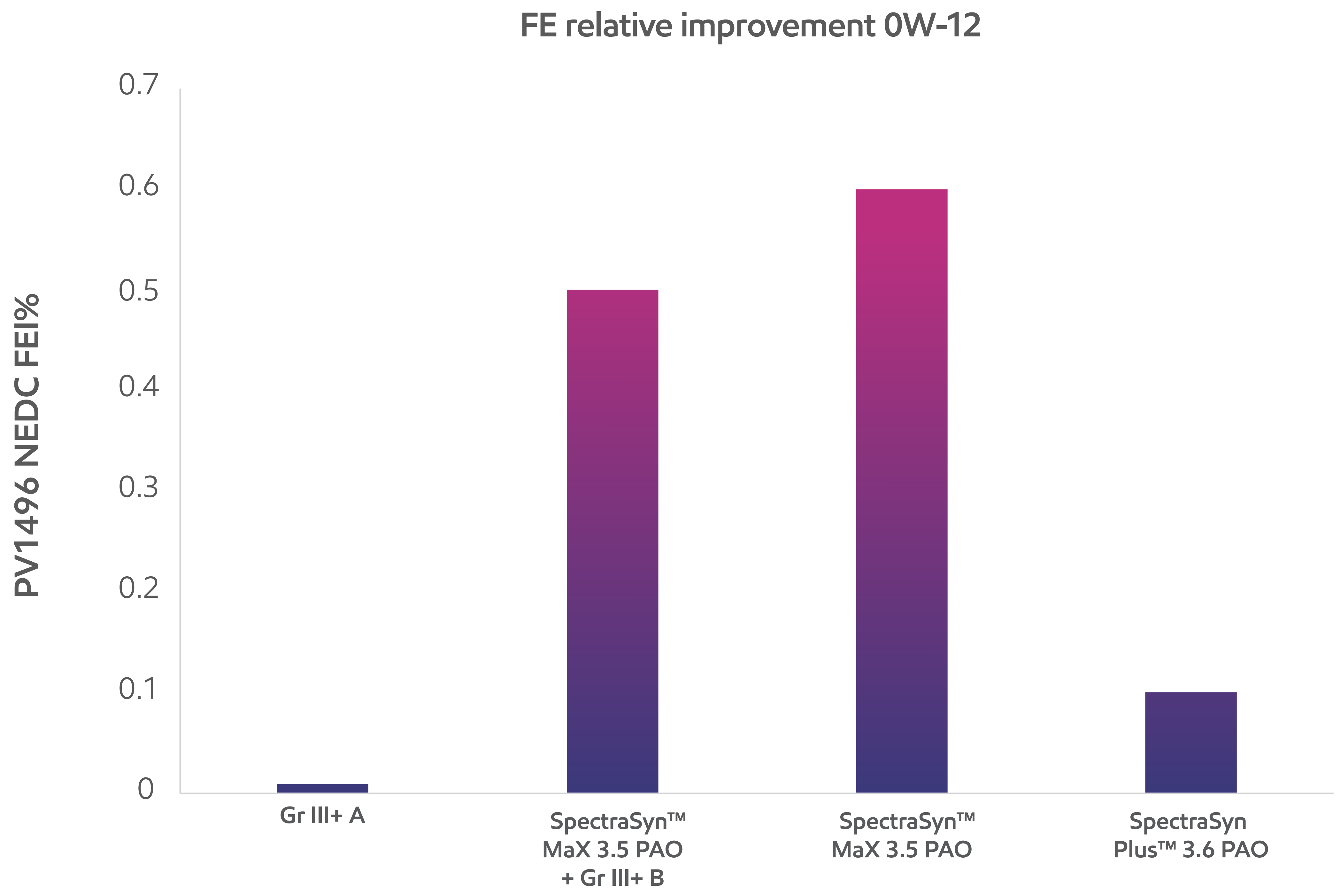
Figure 5.1.B Traction improvement using SpectraSyn™ MaX 3.5 PAO formulation in MTM test



Source: ExxonMobil data

Figure 5.1.C Fuel economy (FE) improvement using SpectraSyn™ MaX 3.5 PAO formulation in VW engine test



Source: ExxonMobil data

SpectraSyn™ MaX 3.5 PAO can provide low temperature and volatility benefits to compensate for Group II/II+ and Group III/III+ base stocks in top-tier engine-oil applications. It can help very low-temperature applications, such as freezer chain fluids, to achieve the required pour point and at the same time maintain energy efficiency.

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Synesstic™ alkylated naphthalene (AN)

Synesstic™ AN base stocks are API Group V fluids that can be used instead of esters in fully synthetic engine oils. By using Synesstic™ AN, engine oil performance can be improved by increasing oxidative stability while limiting seal swell and providing the necessary solvency for deposit control. Engine oils formulated with Synesstic™ AN and a fully synthetic PAO-based product showed significant improvements in oxidative stability during screening tests and demonstrated reduced cam wear in engine tests.

Table 5.1.C Synesstic™ 5 AN improves oxidative stability of blends with Gr II/III/IV*

Sample description	Synesstic™ 5 AN	Group II	Group II/AN	Group III	Group III/AN	Group IV	Group IV/AN
Evaporation loss, wt.%	1.9	3.6	3.0	2.5	2.2	3.3	1.7
Total acid number change, mg KOH/g	0.5	6.3	4.4	7.4	6.4	5.0	0.9
Kinematic viscosity @100°C change, %	3.8	35.8	18.5	99.7	25.8	23.7	4.2
Sludge content, mg/100 ml oil	0	427	< 5	< 5	< 5	< 5	< 5

*Bulk oxidative stability test using modified ASTM D4636.
Blends are 50:50 wt. % with 0.5 wt. % antioxidant.
Test: 175°C (347°F), 4 days, 5 liter/hrs dried air in the presence of Al, Ag, Cu, Steel, & Mg coupons.
Source: ExxonMobil data

Table 5.1.D Passenger car engine oil blends with SpectraSyn™ PAO and Synesstic™ AN base stocks

Component, wt.%		0W-20		5W-30	
SpectraSyn™ 4 PAO		10			
SpectraSyn™ 6 PAO		62.35		42.35	
SpectraSyn™ 8 PAO				30	
Synesstic™ 5 AN		10		10	
Additive package*		8.65		8.65	
Viscosity modifier		9		9	
Property	**Test method**	**Result**	**Specification**	**Result**	**Specification**
KV @100°C, cSt	ASTM D445	11.5	9.3 - < 12.55	13	12.5 – <16.3
KV @40°C, cSt	ASTM D445	68.9		81.5	
Viscosity index	ASTM 2270	161		160	
CCS @-30°C max, cP	ASTM D5293	3,371		4816	6,600 max
CCS @-35°C max, cP	ASTM D5293	5,871	6,200 max	8,566	6,200 min
HTHS @150°C min, cP	ASTM D4683	3.2	2.6 min	3.6	2.9 min

*Additive package designed to meet the latest API, ILSAC and Dexos specifications.
Source: ExxonMobil data

SpectraSyn Elite™ mPAO

In specific situations where enhanced wear protection is desired, SpectraSyn Elite™ metallocene PAO (mPAO) technology can be used to increase the High Temperature, High Shear (HTHS) viscosity. For instance, leveraging SpectraSyn Elite™ mPAO as a booster in fully formulated engine oils (at 2%, 5%, and 8% of SpectraSyn Elite™ 150 mPAO), across both 5W-30 and 10W-30 grades, improved the HTHS viscosity while maintaining the SAE J300 viscosity requirements. Implementing this concept during formulation could enable a reduction in the use of traditional viscosity modifiers, therefore improving durability/shear stability and possibly reducing overall formulation costs.

Table 5.1.E HTHS boost using SpectraSyn Elite™ 150 mPAO

Property	Test method	5W-30	5W-30 + 2% SpectraSyn Elite™ 150 mPAO	5W-30 + 5% SpectraSyn Elite™ 150 mPAO	Specification	
CCS @-30°C, cP	ASTM D5293	4,145	4,418	4,935	< 6,600	
MRV @-35°C, cP	ASTM D4684	13,205	14,049	15,252	< 60,000	
KV @100°C, cSt	ASTM D445	10.55	10.93	11.54	> 9.3 < 12.5	
HTHS @150°C, cP	ASTM D5481	3.053	3.163 (+3.6%)*	3.322 (+8.8%)*	>2.9	
Property	**Test method**	**10W-30**	**10W-30 + 2% SpectraSyn Elite™ 150 mPAO**	**10W-30 + 5% SpectraSyn Elite™ 150 mPAO**	**10W-30 + 8% SpectraSyn Elite™ 150 mPAO**	**Specification**
CCS @-25°C, cP	ASTM D5293	4,294	4,554	5,060	5,612	< 7,000
MRV @-30°C, cP	ASTM D4684	10,866	11,857	12,411	13,815	< 60,000
KV @100°C, cSt	ASTM D445	10.37	10.8	11.52	12.29	> 9.3 < 12.5
HTHS @150°C, cP	ASTM D5481	3.06	3.209 (+4.9%)*	3.398 (+11.0%)*	3.606 (+17.8%)*	>2.9

*The number in parenthesis represents % improvement in HTHS obtained using SpectraSyn Elite™ mPAO.

Source: ExxonMobil data

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Additive requirements

Additive packages for engine oil formulations are carefully balanced combinations of individual components. The treat rates are determined by the requirements of the lube specification. Viscosity modifiers are typically needed, and the treat rates are decided based on the viscosity targets and base stock properties.

The typical additive types used in engine oil formulations include:

- Detergent and dispersants
- Oxidation inhibitors
- Corrosion inhibitors
- Metal passivators
- Defoamants
- Pour point depressants
- Anti-wear additives
- Rust inhibitors
- Viscosity modifiers
- Friction modifiers

5.2 Commercial vehicle engine oils

Application and equipment

Commercial vehicles, such as trucks and buses, typically use a four-stroke internal combustion engine powered by diesel. However, some also use alternative fuels such as LPG, CNG, and ethanol. Moreover, there are hybrid-engine technologies available that combine internal combustion engines with electric motors.

The basic design of the engine is similar in all cases, with power being provided by pistons driven by expanding combustion gases in the engine cylinders. The motion of the pistons drives the vehicle wheels through a gearbox, which matches the engine speed to the wheel speed.

Engine oils play a crucial role in protecting the working parts of internal combustion engines, which are becoming more sophisticated with greater power densities and improved efficiency. A well-designed engine oil provides an unbroken film of molecules that prevents metal-to-metal contact and reduces friction. This is accomplished by a combination of oil fed to the top of the engine by the oil pump and by splash lubrication supplied by the crankshaft for the lower half of the engine. Turbochargers are common components that enhance the power and efficiency of engines. It's important for the engine oil to also lubricate and cool these components, which places additional strain on the oil due to the high temperatures generated by the turbochargers.

In addition to these engine design considerations, commercial vehicle oils require higher performance in some cases versus passenger vehicle lubricants to achieve key requirements for this application, such as longer drain intervals between oil changes and improved cleanliness and wear protection to extend overhaul periods. For example, commercial drain intervals typically range from 13,000 to 19,000 miles (20,000 to 30,000 km) or even higher. Strong oxidation performance is crucial due to the longer drain intervals. Additionally, wear protection and cleanliness are also critical for ensuring engine durability.

Lubricant requirements

The engine oil is designed to provide the following essential benefits:

- Reduce friction and prevent metal-to-metal contact
- Remove heat and wear particles
- Reduce corrosion by neutralizing combustion products
- Keep engine components clean
- Provide effective sealing of the cylinders to minimize exhaust gas blow-by
- Help improve fuel economy

Vehicle engine oils are categorized in two different ways:

1) Viscosity classification - typically, multigrade oils are specified according to SAE J300.

2) Performance specifications - defined by API, ACEA or various Original Equipment Manufacturers (OEMs) such as Mercedes Benz, Volvo, Scania, Mack, Cummins, MAN, etc.

In this industry, there is a focus on improving fuel efficiency to address fuel costs. Therefore, when it comes to engine oils, traditional multigrade oils are being replaced by lower viscosity grades, which induce less friction loss and, therefore, increase efficiency. Most modern commercial vehicles now use 10W grades, and 5W and 0W grades are being considered for further improvements in fuel efficiency. One of the main concerns with switching to low-viscosity oils is compromising engine durability, but choosing the proper engine oil and designing with high-quality base stocks can enable a lower viscosity option while maintaining durability and protection, therefore possibly enabling both improved efficiency and longer engine overhaul timelines of greater than one million operating miles (or 1.6 million km). However, depending on the truck size and driving conditions, especially in severe stop-and-go traffic, an overhaul may be necessary sooner.

As engine technology advances and emissions regulations become more stringent, the performance specifications for crankcase lubricants are also becoming more demanding. API, ACEA, and global OEM lubricant specifications are designed to meet the changing requirements of modern engine hardware and the legislative rules that mandate specific fuel-efficiency targets.

Heavy-duty engine oils can face issues with bio-based diesel fuel accumulation, affecting viscosity and leading to problems with oxidation stability, potentially promoting sludge formation and corrosion in the engine. In addition, the higher detergent/dispersant levels required to handle the higher soot levels in commercial diesel engines can negatively impact the oil's low sulfate ash limit and low-temperature properties. Many vehicles today use exhaust gas after-treatment devices to reduce exhaust gas emissions. These devices include selective catalytic reduction (SCR) systems, exhaust gas recirculation (EGR), and diesel particulate filters (DPF). Each of these devices affects the oil requirements differently. SCR systems lead to fuel sulfur and lube-oil additive restrictions to prevent catalyst poisoning. EGR systems require improved soot handling, while DPF systems result in lube-oil fuel dilution. A potential solution is to incorporate increasing levels of PAOs in semi or fully-synthetic oils based on API Group III base stocks to meet the low-temperature requirements.

Advantages of synthetic oils

Compared to mineral oils, synthetic base stocks in automotive lubricants provide improved wear protection, lower volatility, a higher viscosity index, and better thermal and oxidative stability. These benefits result in extended drain intervals compared to mineral oil and potential fuel economy benefits.

The highest performance standards for engine oils can be achieved with low-viscosity PAO base stocks such as SpectraSyn™ PAO, SpectraSyn Plus™ PAO or SpectraSyn™ MaX PAO. These synthetic base stocks offer numerous advantages over mineral oil base stocks, such as:

- Better oxidative and thermal stability for long service life
- Lower engine oil volatility to reduce the NOACK value
- Higher viscosity index for improved protection and low-temperature fluidity
- No inherent contaminants to accelerate corrosion or acid formation
- Lower pour points for improved operational low temperatures

High-viscosity PAO can also be used to boost viscosity index (VI) and enhance film thickness. SpectraSyn Elite™ mPAO has been shown to boost HTHS viscosity at low treat rates (see Table 5.1.E).

In addition, the use of Synesstic™ AN or Esterex™ esters as co-base stocks can offer the following benefits:

- Seal swell and additive solubility
- Improved lubricity
- Improved cleanliness
- Improved thermal and oxidative stability

Formulation data

The commercial engine oil formulations suggested in the following table provide a basic guideline for creating fully- and semi-synthetic engine oils using ExxonMobil's SpectraSyn™ PAO and Synesstic™ alkylated naphthalene. The properties of the engine oils are listed in the table, but the performance parameters are dependent on the specific additive package used, which should be verified with the additive supplier. The key physical properties, as defined by SAE J300, are met and should serve as a good starting point for lubricant formulators.

Table 5.2.A Fully- and semi-synthetic commercial vehicle engine oil blends with SpectraSyn™ PAO

Component, wt.%		0W-20	0W-30	0W-40	5W-30
SpectraSyn™ 4 PAO		56	52	7	22
SpectraSyn™ 6 PAO				55	
Group II+ EHC™ 50		13.8	10		21
Group II+ EHC™ 65					
Group II EHC™ 110					
Group III cSt 8					23
Synesstic™ 5 AN		9	8	5	9
Additive package		18	18	18	18
Viscosity modifier		3.2	12	15	7
Property	**Test method**	**0W-20**	**0W-30**	**0W-40**	**5W-30**
KV @100°C, cSt	ASTM D 445	8.0	10.9	14.2	11.0
KV @40°C, cSt	ASTM D 445	45.0	63.6	89.3	66.0
Viscosity index	ASTM D2270	153	164	164	158
HTHS @150°C, mPa·s	ASTM D4683	2.6	3.2	4.0	3.5
CCS, @-20°C, cP	ASTM D5293				
CCS, @-25°C, cP	ASTM D5293				
CCS, @-30°C, cP	ASTM D5293				6519
CCS, @-35°C, cP	ASTM D5293	6059	6072	5917	

Source: ExxonMobil data and models

Synesstic™ alkylated naphthalene (AN)

Synesstic™ AN is an API Group V fluid that can be used in place of esters in fully synthetic engine oils. Synesstic™ AN can enhance the performance of engine oil by improving oxidative stability while ensuring the required solvency, seal swell, and deposit control. Fully synthetic PAO-based engine oils, formulated with Synesstic™ 5 AN, showed improved oxidative stability in oxidative screening tests and significantly reduced cam wear in engine tests. The example below is a high performance API engine oil based on Group III base stocks. In this case, the addition of Synesstic™ 5 AN reduces the level of piston deposits and carbon top-groove fill as seen in a Caterpillar 1-K diesel engine test.

Table 5.2.B Benefit of Synesstic™ AN

API high performance engine oil formulation using Group III base stock		
Caterpillar 1-K diesel engine test	**Without AN**	**With AN**
Synesstic™ 5 AN, wt.%	0	20
Weighted deposits demerits (WDK)	500	385
Top groove fill (TGF)	19	12

Source: ExxonMobil data

SpectraSyn Elite™ mPAO

Further enhancement of the performance of synthetic engine oils can be achieved by using the SpectraSyn Elite™ series of mPAOs, which can provide improvement in viscosity index and may improve wear protection through a boost in HTHS viscosity (see Table 5.1.E).

Additive requirements

The additive packages used in engine-oil formulations are precise combinations of individual components, with treat rates determined by the requirements of the lube specification. Typically, viscosity modifiers are also necessary, and the treat rates are determined based on the viscosity targets and base stock properties.

Typical additive types used in engine oil formulations are:

- Detergent and dispersants
- Oxidation inhibitors
- Corrosion inhibitors
- Metal passivators
- Anti-wear additives
- Defoamants
- Rust inhibitors
- Viscosity modifiers
- Friction modifiers

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5.3 Automotive transmission oils

Application and equipment

Automotive vehicles require a power-transmission system to transfer engine power to the driving wheels. In addition to transferring power, the powertrain typically has several other components, including a clutch mechanism, a gear system, and a differential mechanism. The four most common types of automotive transmissions are automatic AT, manual MT, dual-clutch DCT, and continuously variable CVT.

Clutch mechanism. The powertrain leverages a clutch mechanism to disengage the drive train so the vehicle can be stopped while the engine is running. Manual gearboxes typically have a dry-plate clutch that requires no lubrication. "Wet" clutches are typically multi-plate devices found on tractors or off-road vehicles. In these cases, the frictional properties of the lubricants are important to ensure the effective operation of the clutches while still lubricating the rest of the transmission system.

Dual-clutch transmissions (DCT) are two transmission systems working in parallel. One gearbox houses the odd-numbered gears, while the other houses the even-numbered gears. This allows the next gear in sequence to be preselected and ready for engagement, providing a smooth mechanical gearshift transition. Most DCTs have wet clutches, which can handle high torques with good heat dissipation, although smaller versions with dry clutches have also been designed.

Gear system. The powertrain provides a gear system to match the speed and torque requirements of the drive wheels to the engine speed and provides a means to reverse the drive direction. Many different types of gear systems exist, but most can be classified into one of four groups: mechanical, semi-automatic, automatic, or hydrostatic.

Mechanical transmissions have a series of gears that the operator can select to access different speed ratios between the input and output shafts. Most mechanical types have helical gear sets with a synchromesh, which is a type of friction clutch that allows for smooth transitions from one gear mesh to another.

In an automatic transmission, the fluid is typically driven through a torque convertor, which is a simple hydraulic pump. At low engine speeds, the torque generated is insufficient to drive the vehicle, so the vehicle can be stopped without disconnecting the engine from the power train. The gearbox is usually a planetary gearbox that provides additional torque multiplications, as well as reverse direction and neutral. Planetary gears are compact with good load-carrying capability. The gears are always in mesh, and the different ratios or directions are achieved by locking or unlocking different clutches and brakes within the gearbox. Hydraulic servomechanisms operate these clutches and brakes. The driver selects a driving range, and the gears are automatically changed within that range, taking signals from speed sensors on the gearbox's output. More modern transmissions use electric control systems instead of hydraulic. Semi-automatic transmissions combine the benefits of both types of gearboxes, allowing the driver to operate in automatic mode or to change gears manually without having to operate a clutch.

Differential mechanism. The powertrain also provides a drive axle or differential mechanism for allowing one wheel to be driven at a different speed than the other when negotiating a curve. The drive axle is usually fitted on a rear-wheel-drive vehicle and changes the drive from the

engine and gearbox through a 90° transition to the driving wheels. The gears are generally of the hypoid type, which allows for good load-carrying with low noise. They also allow the input drive shaft to be offset from the output shaft, providing a lower installation of the drive shaft under the vehicle.

The differential allows the drive shafts to the wheels to operate at different speeds, as required when the vehicle negotiates a curve. The differential usually consists of a number of bevel gear pinions that rotate around each other to balance out the differences in speed between the wheels. One of the drawbacks of a differential arises when the wheels sit on surfaces with different levels of traction.

Low-traction surfaces allow one wheel to slip and increase in rotational speed. When this happens, the system directs all power to this wheel while the other wheel stops turning. Limited-slip differentials (LSD), or locking differentials, have been developed to overcome this problem. These use special clutches to resist the differential action, depending on the torque applied. This ensures that more torque is supplied to the wheel that has the best traction. This type of differential is popular on sports cars or four-wheel-drive, off-road vehicles.

Hydrostatic drives are typically used on tractors and construction machines. In this type of drive, the engine drives a variable displacement hydraulic pump, and the hydraulic pressure is used to provide power for hydraulic motors, which drive the wheels. The benefits of this system are that the hydraulic motors can be driven in different directions, permitting the vehicles to spin on the spot. The hydraulic system can also be used to provide other functions, such as driving hydraulic arms or tools.

Lubricant requirements

The primary role of lubricants in powertrain systems is to manage friction between moving parts. This involves reducing friction in gears and bearings, while also providing the correct level of friction in clutches and synchromeshes. Transmission oils also need to function as hydraulic fluids, capable of transmitting power or performing control functions.

The lubricant must provide good fluidity at low temperatures and yet still maintain good film thickness at operating temperatures, so a high viscosity index (VI) is desirable.

The fluid used in automatic transmissions serves several purposes, including enabling efficient power and heat transfer. It must have the correct viscosity and frictional characteristics to work with the clutches and brakes that control gear selection. Automatic transmissions operate at high temperatures and are subject to mechanical stress. Therefore, the fluid needs to have good oxidation stability, low foam formation, and good shear stability to provide adequate lubrication.

In automatic transmissions, a common fluid is used for the torque converter, clutches, and gears. Automatic transmission fluids are typically light-viscosity oils designed for efficient power transfer and heat dissipation. It’s important for these fluids to have the right frictional characteristics to match the different clutches and brake materials used for gear control. Automatic transmissions often operate at high temperatures and undergo significant mechanical shearing. Lubrication products for automatic transmissions need to have good oxidation stability, low foam formation, and strong shear stability.

Final drives and differentials often require a high-viscosity product, such as a 75W-140 with high extreme pressure (EP) properties, to handle the loads, particularly on commercial vehicle drives.

In hydrostatic drives, the system functions as a high-pressure hydraulic system, so the fluid needs to meet those specific requirements including: A high VI product with good oxidation stability, low foam formation and good anti-wear properties. In smaller machines, automatic transmission fluid (ATF) is used. On larger off-highway machines, multipurpose tractor fluids are used because the engine oil and hydrostatic drive are part of the same system.

Advantages of synthetic oils

Several advantages may be associated with the use of synthetic lubricating oils in automotive gears, including the following:

- Better low-temperature properties
- Improved viscometrics at high temperature (high VI)
- Improved thermal and oxidative stability
- Lower volatility
- Higher shear resistance
- High efficiency
- Low foaming

Synthetic base stocks can be used to formulate broad multigrade lubricants such as 75W-80/85/90 or 75W-140. Lubricants in these viscosity grades are generally suitable for a wide range of operating temperatures in automotive gears.

Properly formulated SpectraSyn™ PAO gear oils will provide benefits in low-temperature performance, high-temperature bulk viscosity, and thermal- and oxidative stability. The addition of some Esterex™ ester or Synesstic™ AN to the PAO can improve additive solubility and increase the polarity of the entire base stock system, which moderates the normal shrinking and hardening tendencies of the PAO with elastomer seals. SpectraSyn™ PAO and Esterex™ ester base stocks show significantly lower pour points than comparable petroleum oil due to a tailored molecular structure and the absence of wax, which is typically found in mineral oils. The low pour point of the synthetic base stocks allows the formulator to secure improved low-temperature properties in gear oils. In addition, the use of SpectraSyn Elite™ mPAO can further increase the viscosity index and significantly improve the low-temperature performance.

Additive requirements

Finished gear lubricants are typically composed of high-quality base stocks with between 3 and 12% additive, depending on desired performance characteristics. These additives include:

- Rust inhibitor
- Oxidation inhibitor
- Corrosion passivator
- Anti-wear*
- Extreme pressure friction modifier*
- Dispersant*
- Defoamants

*Not always required, application dependent

Formulation data

The following formulations provide a suitable starting point for developing fully synthetic transmission oils.

In Table 5.3.A, we give an example of cost effective and robust formulations which utilize Gr II or III with Gr IV + V combinations. Those formulations can be considered for Premium Tier in the product offer and give all advantages, which are expected from the premium automotive gear oils – durability over an extended time, good fluidity at lower temperatures, and maintaining the viscosity despite high shear stress.

Table 5.3.A Gr II, Gr III formulation options using mPAO for creating premium 75W-90 gear oils

Component, wt.%		SAE 75W-90 Standard ODI	SAE 75W-90 Extended ODI	SAE 75W-85 Super-long ODI
SpectraSyn Elite™ 150 mPAO		30.4	28	27.4
Group II+ EHC™ 50		56.47	55.67	
Group III 4 cSt				53.27
Esterex™ A41 ester		5	5	8
Additive package		8	11.2	11.2
Pour point depressant		0.1	0.1	0.1
Defoamant		0.03	0.03	0.03
Property	**Test method**	**SAE 75W-90**	**SAE 75W-90**	**SAE 75W-85**
KV @100°C, cSt	ASTM D445	14.05	13.9	11.81
KV @40°C, cSt	ASTM D445	92	90.82	67.84
Viscosity index	ASTM D2270	157	157	171
Flash point, °C	ASTM D92	199	211	209
Brookfield viscosity @-40°C, cSt	ASTM D2983	105,800	116,400	82,800
Sheared oil viscosity (20 h) @100°C, cSt	CEC L-45-A-99	13.9	13.76	11.66

Source: ExxonMobil data

Group III, in combination with SpectraSyn Elite™ mPAO, gives exceptional shear stability performance over the long operating life of the fluid, as well as exceptional Brookfield viscosity for maintaining low-temperature fluidity. Together they enable this combination to meet the stringent requirements from OEMs. This option can be considered instead of using, for example, a shear stable PIB, in case those performance attributes are specifically desired.

Table 5.3.B Gr III + mPAO formulation example with exceptional shear stability and low-temperature performance

Component, wt.%		SAE 75W-90
SpectraSyn Elite™ 300 mPAO		30.5
Group III 4 cSt		61
Additive package		7.5
Pour point depressant		1
Property	**Test method**	**SAE 75W-90**
KV @100°C, cSt	ASTM D 445	15.81
KV @40°C, cSt	ASTM D 445	91.99
Viscosity index	ASTM D 2270	183
Brookfield viscosity @-40°C, cSt	ASTM D2983	47,100
Sheared oil viscosity (20 h) @100°C, cSt	CEC L-45-A-99	15.35
Viscosity increase, L-60-1, %	ASTM D5704	10

Source: ExxonMobil data

ExxonMobil

Fully synthetic gear oils leveraging SpectraSyn™ PAO with Esterex™ ester or Synesstic™ AN are also formulated to achieve the longest oil drain intervals (ODIs), and for specialized applications where top tier performance is required; For example, high speed railway gearboxes, or axle fluids with ODI above 500,000 km.

Table 5.3.C 75W-90 fully synthetic gear oils

	Component, wt.%	PAO formulation	SpectraSyn Elite™ 150 mPAO	SpectraSyn Elite™ 65 mPAO	
	SpectraSyn™ 6 PAO	40	41.4	27.5	
	SpectraSyn™ 100 PAO	32.5			
	SpectraSyn Elite™ 150 mPAO		31.1		
	SpectraSyn Elite™ 65 mPAO			45	
	Synesstic™ 5 AN	20	20	20	
	Additive package*	7.5	7.5	7.5	
Property	**Test method**	**PAO formulation**	**SpectraSyn Elite™ 150 mPAO**	**SpectraSyn Elite™ 65 mPAO**	**SAE J2360 specification**
Viscosity @100°C, cSt	ASTM D445	15.8	15.5	15.5	13.5 - 24.0
Viscosity @40°C, cSt	ASTM D445	111.6	102.3	106.7	
Brookfield viscosity @-40°C, cSt	ASTM D2983	83,882	55,288	64,486	150,000 max
Viscosity index	ASTM D2270	150	160	154	
Flash point, °C	ASTM D92	198	198	198	
Pour point, °C	ASTM D97	-48	-51	-54	
Shear stability	CEC L-45-A-99				
kV @100°C @20 hours	ASTM D445	15.4	15.3	15.5	>13.5 cSt @100°C
kV @100°C @100 hours	ASTM D445	15.3	15.3	15.4	
kV @100°C @192 hours	ASTM D445	15.3	14.9	15.5	
Oxidation stability 192 hours @160°C	CEC L-48-A(B)				
kV @100°C increase	ASTM D445	6.3	4.3	2.6	
TAN increase	ASTM D664	1.9	-0.1	-1.3	

*The additive package meets the requirements of API MT-1, API GL-5, MIL PRF-2105E, Mack GO-J.

Source: ExxonMobil data

ExxonMobil

Certain OEMs may require viscosity 75W-140 that maintains lubricating properties in extreme conditions, providing better protection for transmissions, transfer cases, and differentials, especially in extreme load conditions and hot temperatures. Moreover, a formulation based on mPAO will provide significantly better oxidation stability compared to high viscosity conventional PAO.

Table 5.3.D 75W-140 fully synthetic gear oils

Component, wt.%	PAO formulation	mPAO formulation
SpectraSyn™ 6 PAO	19	2.3
SpectraSyn™ 100 PAO	53.5	
SpectraSyn Elite™ 65 mPAO		70.2
Esterex™ A32 ester	20	20
Additive package*	7.5	7.5

Property	Method	PAO formulation	mPAO formulation	SAE J2360 specification
Viscosity @100°C, cSt	ASTM D445	24.5	24.4	24.0 – 41.0
Viscosity @40°C, cSt	ASTM D445	175.7	166.2	
Brookfield viscosity @-40°C, cSt	ASTM D2983	136,000	88,781	150,000 max
Viscosity index	ASTM D2270	171	179	
Flash point, °C	ASTM D92	198	194	
Pour point, °C	ASTM D97	-54	-60	
Shear stability	CEC L45-A-99			
kV @100°C @20 hours	ASTM D445	24.5	24.2	>24.0 cSt @100°C
kV @100°C @100 hours	ASTM D445	24.2	24.4	
kV @100°C @192 hours	ASTM D445	24.4	24.5	
Oxidation stability 192 hours @160°C	CEC L-48-A(B)			
kV @100°C increase	ASTM D445	13.2	4.9	
TAN increase	ASTM D664	3.78	0.19	

*The additive package meets the requirements of API MT-1, API GL-5, MIL PRF-2105E, Mack GO-J.

Source: ExxonMobil data

ExxonMobil

5.4 Electric vehicle fluids

Application and equipment

Electric vehicles (EVs) typically are categorized into four types: hybrid electric vehicle (HEV), fuel cell electric vehicle (FCEV), plug-in hybrid electric vehicle (PHEV), and battery electric vehicle (BEV). It is important to understand the differences between these vehicle types to understand their lubricant requirements.

An HEV uses two or more different sources of power to provide direct or supplemental propulsion to the wheels, the most common power sources being an internal combustion engine (ICE) and an electric motor (e-motor). The ICE runs on traditional automotive fuel. The battery pack (not found on traditional ICE vehicles) provides current to the inverter and e-motor, which converts the electrical current to mechanical power. In many cases, the e-motor only provides supplemental power for the ICE to optimize overall energy efficiency. However, in some hybrids, vehicle power can be achieved directly from the ICE and/or the e-motor. The ICE is also used, similar to a generator, to generate current to recharge the battery.

An FCEV is like an HEV, except that a fuel cell, which converts hydrogen fuel to electric current, replaces the ICE in the above HEV configuration. The fuel cell can then charge the battery and/or directly power the e-motor, and the e-motor is the sole source of mechanical energy (via the transmission) to the final driveshafts and wheels.

A PHEV is an HEV that can also be plugged directly into the power grid to recharge the battery. The battery is typically larger and more powerful than that used for an HEV, meaning the vehicle can go for a longer range with just e-motor/battery power.

A BEV is any vehicle that uses only a battery pack and e-motor(s) to provide direct power for the vehicle (i.e., no ICE or fuel cell on board).

The powertrain for most hybrid vehicles typically utilizes a unique type of transmission, often referred to as a dedicated hybrid transmission (DHT). This type of transmission can adjust how much power comes from the e-motor versus the ICE and simultaneously adjust the output speed to drive the final drive shaft(s) and wheels.

Alternatively, BEVs do not have an internal combustion engine and, thus, do not use a traditional transmission or a DHT. Instead, a battery pack supplies current to an inverter and an electric motor. The electric motor converts the current to mechanical drive. As electric motors operate at much higher speeds than what is required for final driveshafts and wheels, a gearbox is necessary to reduce the speed, typically by about a 9:1 ratio (often referred to as a reduction gearbox). It has become more and more common for engineers to combine the inverter, electric motor and gearbox into one physical unit (to reduce complexity and conserve space on the vehicle). This type of design is often referred to as an electric drive unit (EDU) or e-axle unit.

Lubricant requirements

Similar to ICE vehicles, most HEVs require both engine oil and transmission oil. These lubricants may be standard automotive engine oils and ATFs. However, as hybrid technology advances, new lubricant technology may be required due to the different operation and duty cycles that a hybrid places on the engine and transmission.

BEV EDUs have two primary components that need lubrication: an e-motor(s), and a gearbox(s). The gearbox will require lubrication for the gears and bearings. The e-motor will also require lubrication for its bearings, but also it must be cooled. For first-generation EVs, many manufacturers relied on traditional ATFs or MTFs to provide this lubrication. However, EDU bearings and gears are operated under significantly different conditions (temperatures, speeds, etc.) than those in a traditional ICE transmission, and thus, new fluid technology is being developed to provide the proper and optimum protection for EDUs, particularly as next-generation hardware designs evolve.

New EDU fluid technology will need to deliver performance in three areas. These areas include traditional lubrication, thermal management, and electro-performance. (See Figure 5.4.A.) While traditional lubrication still entails durability and protection of gears and bearings, the requirements are different from those placed on today's ATF/gear lubricants. Significantly higher input gear and bearing speeds will drive an increased focus on not only different tribological conditions but also on other performance areas such as air release. Operating temperatures will also be different than standard transmissions as well.

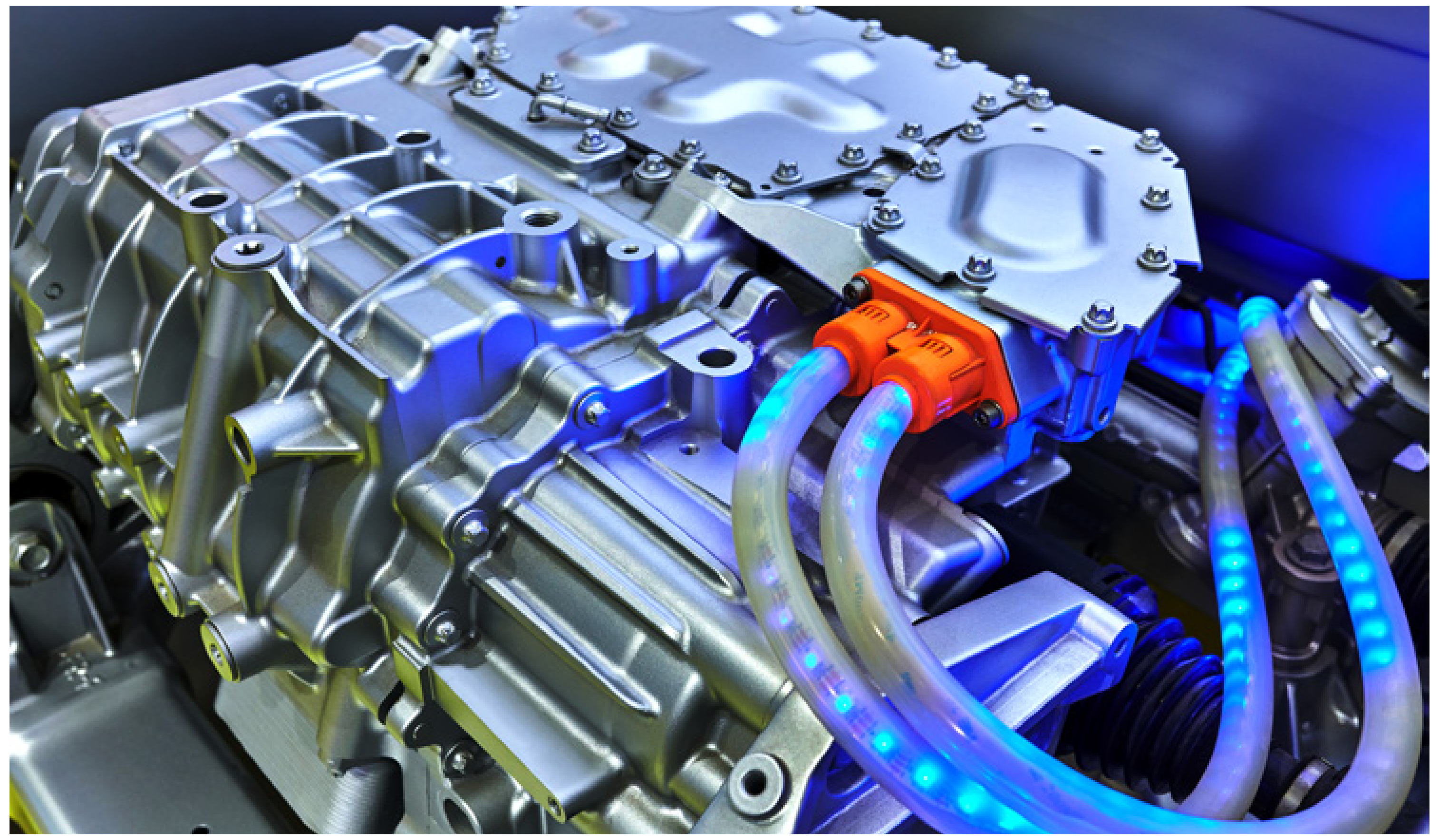
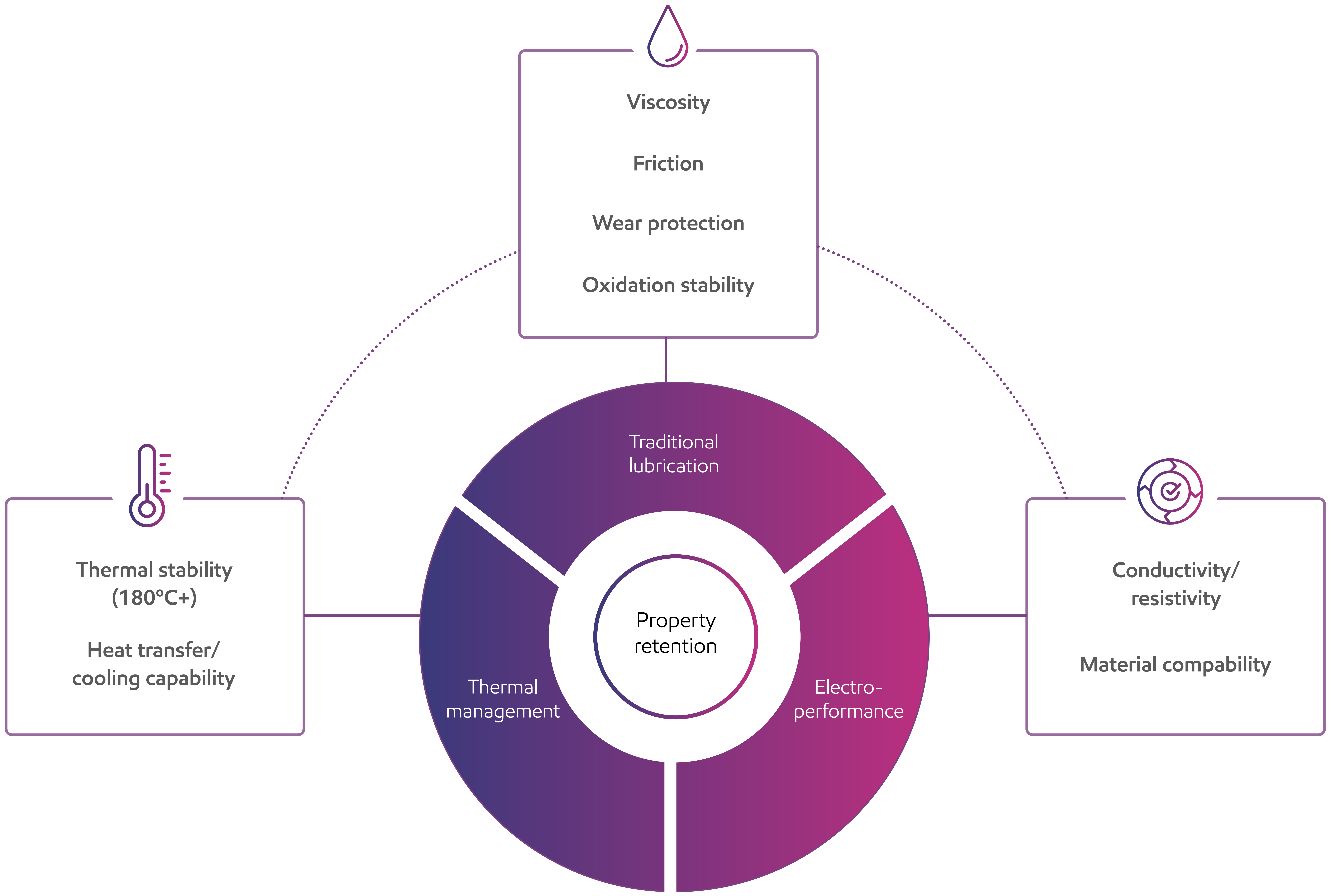


Figure 5.4.A EDU fluid performance area



To achieve cooling for the e-motor, EV engineers have the option of air cooling, indirect water/glycol cooling (e.g., via a cooling jacket), or direct oil cooling via the gearbox oil. The latter, which is becoming more and more prevalent, is sometimes referred to as a wet motor or integrated EDU design. In this design, the oil is circulated from the gearbox directly through the e-motor for both lubrication and cooling purposes. Hence, the area of thermal management is a new area of focus for these automotive lubricants and will be an important driver for EDU fluid technology going forward. Finally, using the gearbox lubricant to directly cool the e-motor means that EDU fluids will now have to deliver the proper level of electro-performance, as the fluid is directly in contact with electrified components such as the stator end windings. Hence, electrical conductivity and general performance of the lubricant in an electrified environment will also now be important areas for EDU fluid technology development.

Advantages of synthetic oils

A number of advantages may be associated with the use of synthetic lubricating oils in EDUs, including performance benefits in the following areas:

- Energy efficiency / can extend driving range or lower costs
- Air release / allows for high-speed EDU operation
- Thermal management / enables increased EDU power density
- Fluid aging / retains performance over life of the fluid (fill-for-life)
- Durability / protects equipment over life of vehicle
- Low temperature / allows operation over broad temperature range

Synthetic base stocks can be used to formulate EDU fluids to an optimum final fluid viscosity that best suits the targeted application. Specifically, PAOs and esters of different viscosities across a very broad range of KV100°C values (e.g., 2 cSt – 300 cSt) can be blended to achieve a net base oil viscosity that delivers the best balance of the above requirements for any specific EDU design. In other words, synthetic fluids offer great flexibility in tailoring the final EDU fluid formulation to the specific hardware design.

Most importantly for EVs, synthetic base stocks, when properly formulated into the final formulation, can reduce the traction coefficient and increase the overall efficiency of the EDU. In the absence of a traditional ICE and transmission, the EDU becomes a significant contributor to energy loss for the overall EV system. Hence, improvements in EDU efficiency are a critical step to improving battery range and/or providing EV engineers with opportunities for vehicle cost savings. Synthetic fluids are a valuable tool that can be used to achieve these vehicle engineering goals.

Additive requirements

Finished EDU lubricants are typically composed of high-quality base stocks blended with 5% to 15% additive system, depending on desired performance characteristics. A typical additive system may include:

- Detergents
- Oxidation inhibitors
- Metal deactivators
- Anti-wear agents
- Viscosity thickener
- Friction modifiers
- Dispersants
- Defoamants

Formulation science

Currently, there are no industry-standardized performance specifications for EV lubricants. For now, in the absence of industry standards, each EV OEM and/or Tier 1 are developing their own specifications to describe the required performance of their EDU lubricant(s). In addition, most of today's lubricant tests for ATFs and gear lubricants were not originally developed with EDUs in mind. Hence, many of these current test methods are now being modified, and new test methods are being considered to more accurately simulate EDU conditions, which will, in turn, provide more accurate tools to assess a fluid's capabilities. The result is that current OEM specifications, which drive formulation development, vary significantly from one OEM to the next, and there is no standardized formulation for an EDU fluid. Having said that, in many cases, the current EDU formulation practice uses existing ATF formulations as a starting point and updates the additive mix to better align with what makes an EDU and its operation different from a traditional automatic transmission. The following are some examples of how an EDU may differ from a standard transmission and, in turn, drive an alternative EDU fluid additive and base stock selection:

- Simpler, higher-speed gearbox design - typically multi-stage, single speed, helical gear operation, and multiple ball bearings, with input gear and bearing speeds of over 20,000 rpm
- Lower gearbox oil sump operating temperatures – typically 40°C – 80°C
- No clutch or synchronizer components (single speed)
- Efficiency is top priority – ultra-low viscosity (3.0 cSt – 3.5 cSt, KV100) EDU lubricants are being evaluated
- Fill-for-life performance is desired by many OEMs
- Gearbox lubricant may also be circulated through the e-motor for cooling purposes

All of these design parameters collectively describe how an EDU and its operation is different than anything else seen before in the automotive arena and explain why new formulations and testing are required for EV fluids going forward.

ExxonMobil

5.5 Small engine lubricants

Small engines are used in a wide range of applications, including outboard boats, motorcycles, scooters, snowmobiles, and a variety of lawn and garden equipment, such as chainsaws, string trimmers and snow blowers.

Small engines are typically fueled by gasoline on a two-stroke cycle, which provides good power density with low weight.

For vehicle applications where weight is less of an issue, engines typically run on a four-stroke cycle. The benefit is that four-stroke engines have lower exhaust emissions, which allows them to meet increasingly stringent emission targets or regulations.

For two-stroke engines, the lubricating oil is added to the engine either premixed with the fuel or via an oil-injection system. The product owner's manual will guide the user to the recommended fuel-to-oil ratio for premixed fuel-oil systems. Depending on the engine speed, this ratio can vary from 16:1 to 50:1. The evaporation of the fuel in the engine cylinder deposits oil on the cylinder walls, providing lubrication. As the oil burns, it is continuously replaced as more fuel enters the cylinder. As a result of this "once-through system," emissions tend to be higher with two-stroke engines. Consequently, conventional two-stroke engines are increasingly being replaced by either direct-injection two-stroke engines or more efficient four-stroke engines.

Four-stroke engines have an oil sump from which the oil is recirculated throughout the engine to provide lubrication. The fuel and the oil are not intentionally mixed, so these engines have lower exhaust emissions than traditional two-stroke engines. Small four-stroke engines are typically used to power motorcycles, generators, outboard boats, personal watercraft, and lawnmowers.

Lubricant requirements

Engines of smaller size, lower oil volume, and higher speed and power density mean that engine lubricants' performance requirements are different compared to those for passenger cars.

Many small engines are air-cooled and tend to run at higher temperatures than water-cooled engines. This means that lubricants with high-temperature stability and good wear protection are required.

In many modern motorbikes, power is transmitted to the wheels through a multi-plate clutch, which is cooled by the engine oil. This highlights the incompatibility of conventional engine oils for motorcycle applications, as the friction modifiers used to enhance fuel economy can disrupt the clutch operation. Additionally, the engine oil also lubricates the motorcycle gearbox, which is exposed to very high speeds and loads, further emphasizing the need for specialized lubricants that can protect against pitting and shearing.

Therefore, a lubricant for a modern four-stroke engine must be meticulously formulated to effectively balance the often-conflicting requirements of fuel economy, clutch friction control, and gearbox protection.

Two-stroke engine oils need the following properties:

- Good fluidity for operation at low temperatures (e.g., snowmobiles)
- Miscibility with gasoline
- High film strength to prevent piston scuffing on air-cooled engines
- Clean burning to reduce deposits, emissions and smoke. This cleanliness is vitally important to prevent carbon buildup, which leads to ring sticking and sparkplug fouling

Two-stroke oils are classified into two types based on different additive chemistries:

Low ash. This type of oil is used in motor scooters, lawn and garden equipment, snowmobiles, and personal watercraft.

Ashless. This type of oil, used in NMMA TC-W3® outboard engine oils, snowmobiles, and personal watercraft, is particularly effective due to its additive package. The additive package is designed to reduce the buildup of combustion-chamber deposits (which can lead to pre-ignition).

Japan is the primary country that produces two-stroke engines, and the specifications are usually determined by the Japanese Automotive Standards Organization (JASO). Most manufacturers are required to meet the JASO FC certification as a minimum standard. In the U.S., the predominant service designation is API TC, while in Europe, the OEMs have adopted an ISO EGD specification with greater detergency compared to JASO FC.

For watercraft in the U.S., the National Marine Manufacturers Association (NMMA) has a modified API TC specification, known as TC-W3®, designed to reduce water pollution.

Four-stroke engines on motorcycles tend to operate under more severe conditions than automobiles:

- Many are air-cooled, leading to higher operating temperatures
- The power density is much higher (e.g., 200 hp per liter versus 100 hp per liter)
- They operate to higher maximum speeds (e.g., 15,000 rpm versus 6,000 rpm)
- They have smaller oil sumps (e.g., 1.0 to 1.25 liters versus 3.5 – 4.0 liters)
- The oil is common to the engine gearbox and clutch, so friction characteristics must be well-managed

While OEMs have their in-house engine tests, there are two main industry specifications for four-stroke engines:

- **JASO 4T motorcycle specification.** Friction performance is the main area of concern, with JASO MA1 and MA2 classifications defining different friction performance levels. The JASO MB classification is used for motorcycles with a continuously variable transmission (CVT)
- **NMMA FC-W® specification** for gasoline-fueled marine applications.

Advantages of synthetic oils

The exceptional quality of synthetic lubricants ensures optimal protection and high performance for small engines. Additionally, the excellent low-temperature characteristics of synthetic base stocks perfectly address the low-temperature requirements of snowmobiles and snowblowers.

PAOs also provide excellent high-temperature stability for reliable performance and superior oil quality.

When combined with the right additive package, synthetic esters and/or AN, along with PAO fluids, can improve lubrication and provide excellent anti-wear performance, especially for high-lift camshafts and other heavily loaded valve-train components. Synthetic fluids have good low-temperature flow characteristics, offering protection to the valve gear even in severe winter conditions and enhancing cold-start performance.

Synthetic two-stroke oils provide the ultimate protection for two-stroke engines operating at higher temperatures. The pistons expand at high temperatures, thus decreasing the piston-to-cylinder wall clearance. This increases engine friction and the possibility of piston scuffing, which could ultimately lead to reduced power and/or engine seizure. The superior lubricity protection of synthetic base stocks in the thin-film boundary layer of oil separating the piston and cylinder wall can improve engine performance. The use of Synesstic™ 12 AN in such applications has been shown to provide good results.

Esters are commonly used for synthetic formulations in two-stroke applications. They offer high viscosity, high viscosity index, good low-temperature flow, biodegradability (see Section 4.5.1), and lubricity.

In some environmentally sensitive locations, biodegradable oils may be required by law or desired by the consumer for use in chainsaws, snowmobiles, or outboard boat engines. The readily biodegradable nature of Esterex™ NP451ester (see Section 4.5.1) can make it an excellent choice for two-stroke oils in these applications.

Synesstic™ AN base stock has also exhibited good lubricity in JASO engine tests and are readily (Synesstic™ 5 AN) / inherently (Synesstic™ 12 AN) biodegradable (see Section 4.5.1).

Synthetic oils for the four-stroke engines are usually based on PAO/ester and, more recently, PAO/AN blends, and offer a variety of advantages over mineral oil-based lubricants. The use of PAO in the oil improves both power and performance through reduction in friction and wear.

Formulation data

Two-stroke engine oils. A typical generic ester-based two-stroke formulation is shown below. The wide range of treat rates is due to the two different types of two-cycle oils (low ash and ashless) and different quality levels.

Additive requirements

Two-stroke additives are a combination of detergent, dispersant, lubricity and flow improver components, and may also contain rust and corrosion inhibitors and fuel stabilizers, depending on the type of oil.

Table 5.5.A Generic synthetic two-stroke engine oil formulation

Component	Treat rate	Function
Additives	3-20%	Anti-wear and detergency
Solvent	10-20%	Oil and fuel miscibility, low-temperature fluidity
Polyisobutylene	0-30%	Reduced smoke and lubricity
Ester	40-85%	General lubrication and delivery of additive system to metal surfaces

Table 5.5.B Synthetic two-stroke JASO FD/API TC oil

Component	Treat rate
Additive package (JASO FC/API TC-W3 oil)*	2.25% (API TC), 2.5% (JASO FD)
Solvent	25%
Polyisobutylene	25%
Esterex™ NP343 or NP451 esters	48.5 - 48.75%

*Additive package meets JASO FC/API TC-W3 oil requirements.
Source: ExxonMobil data

Table 5.5.C Synthetic two-stroke oil with Synesstic™ AN meeting JASO FC/API TC-W3 oil requirements

Component	Weight %			
Additive package*	40	40	40.4	
Pour point depressant	0.3	0.3	0.3	
Exxsol™ D80 dearomatized fluid (solvent)	23	18.7	19	
Synesstic™ 5 AN	--	41	32.1	
Synesstic™ 12 AN	36.7		8.2	
Property	**JASO engine test results**			**JASO FC limits**
Lubricity index	111**	91	96	≥95
Torque index	99	100	100	≥98
Smoke index	106	***	***	≥85

*Additive package meets JASO FD, ISO-L-EGD, API-TC.
**Average of 105 and 116.
***Predicted pass.
Source: ExxonMobil data

ExxonMobil

Formulation data

Four-stroke engine oils. The following oil is a representative four-stroke synthetic small-engine formulation using SpectraSyn™ PAO. It meets the JASO T903 MA2 specification and is designed for use in motorcycles with wet clutches. The viscosity modifier used in such formulations must have high shear stability.

Additive requirements

Small-engine four-stroke additives are a combination of

- Anti-wear additive
- Detergent
- Dispersant
- Oxidation inhibitor
- Rust and corrosion inhibitors

Table 5.5.D Fully synthetic four-stroke small engine oil (meets API SL, JASO T903: 2023 (Appendix A)

	Component, wt.%	5W-40	
	Additive package	8	
	Viscosity modifier	10	
	SpectraSyn™ 6 PAO	82	
Property	**Test method**	**Results**	**Limits**
KV @100°C, cSt	ASTM D445	14.6	12.5min, <16.3
CCS, @-30°C, cP	ASTM D5293	3920	6,600 max
MRV @-30°C, cP	ASTM D4684	23,300	60,000 max
HTHS @150°C, cP	JPI-5S-36	3.7	2.9 min
JASO clutch test friction property	**JASO T 903:2023 (Appendix A)**	**Results**	**Limits**
DFI (Dynamic friction characteristic index)		1.9	≥1.45 and < 2.60
FFI (Static friction characteristic Index)		1.95	≥1.60 and <2.55
STI (Stop time index)		1.82	≥1.50 and <2.65

Source: ExxonMobil data

6.0 Other engine applications

ExxonMobil

6.0 Other engine applications

6.1 Marine and industrial diesel engines

Application and equipment

Marine and industrial engines are mainly diesel engines that come in a range of sizes. The following information primarily pertains to marine engines but also applies to industrial engines, which are often installed onshore as power-generation drives.

Specifically, marine propulsion engines can be categorized as either a two-stroke or four-stroke engine type.

Two-stroke engines. Two-stroke engines are the most common type of main propulsion engine in large vessels, such as container ships. They are typically connected directly to the ship's propeller and run at slow speeds (50–200 rpm). Because of their immense size, they use a crosshead design to reduce the size of the connecting rod. With this design, the piston connecting rod moves vertically in the cylinder and is connected to a crosshead bearing, which is a vertical sliding bearing. A short connecting rod is then used to connect to the crankshaft. One of the benefits of this design is that the cylinder can be sealed from the crankcase to prevent contamination of the crankcase from the residual fuel that is typically used to fuel these engines. Another benefit is that the upper part of the engine can be lubricated with different oil from the crankcase.

Cylinder oil is injected into the cylinders and passes through the system once, with the oil burnt in the cylinder. Due to the high oil volumes used in these engines, fully synthetic oils are not cost-effective and are typically not used as cylinder lubricants.

The rest of the engine—crankcase bearings and crosshead bearings—are lubricated with system oil, which is continuously treated by centrifugal purifiers to remove contaminants. Because of this, system oil tends to have a long life with regular top-ups.

The turbochargers for these engines are very large and typically have their own lubrication system, which, due to the high temperatures, usually is fully synthetic oil (e.g., synthetic compressor oil).

Four-stroke engines. Four-stroke engines are classified as medium-speed or high-speed engines. Medium-speed engines run in the speed range of 200–800 rpm. They are often installed in sets, comprising a multiple-engine system that provides propulsion for ferries, cruise liners, and others. They are also used as generator drives and are found on larger ships that use two-stroke engines as their main engines. They typically run on residual fuel and use SAE 30 or 40 monograde lubricants.

High-speed engines are like commercial-vehicle engines running in the 1,000–5,000 rpm speed range and are often found on harbor craft, ferries, patrol boats, fishing boats, and others. They run on distillate fuel and use multigrade lubricants. Reliability is a crucial issue, particularly in the fast ferry market, which has resulted in the selection of synthetic lubricants.

Lubricant requirements

Two-stroke engines. The cylinder oil is injected into the cylinders to lubricate the piston rings, and the cylinder liner is typically an SAE 50 viscosity oil with high alkalinity: a total base number (TBN) of 40–100, depending on the sulfur level of the residual fuel being used. The system oil is usually an SAE 30 viscosity oil with low alkalinity (5 TBN).

Four-stroke engines. For medium-speed four-stroke engines, the sump oil is usually a SAE 30 or SAE 40 monograde engine oil with a high alkalinity, depending on the type of fuel (i.e., sulfur level) being used. Levels of 30 or 40 TBN were common in the past, but with the introduction of cylinder cutting rings (designed to remove piston-crown carbon) on many engines, oil consumption levels have dropped, reducing the oil top-up process. Consequently, TBN retention in the engine sump oil has fallen, and in an effort to maintain safe levels, the starting TBN of engine oils has risen up to 50 in some cases.

High-speed four-stroke engines run on distillate fuel, and the lubricant requirements closely follow those for commercial vehicles. The only major difference is that monograde engine oils are still regularly used.

Advantages of synthetic oils

No synthetic base stocks are typically used for marine two-stroke cylinder lubricants due to the once-through operation of two-stroke engines. The oil being burned negates the benefits that synthetic oils may offer. However, using Synesstic™ AN may boost oxidation stability for the system oil while providing some solvency for fuel contamination.

For medium-speed engines running on residual fuel, the high volumes and fuel contamination make the use of fully synthetic lubricants uneconomical. Again, the use of Synesstic™ AN may offer a boost in oxidation stability while providing some solvency for fuel contamination.

Fully synthetic engine oils can benefit high-speed engines running on distillate fuel. Compared to mineral oils, these oils can provide improved wear protection, lower volatility, a higher viscosity index, and better thermal and oxidative stability. These improved characteristics translate to extended drain intervals and fuel economy benefits.

PAO base stocks such as SpectraSyn™ PAO or SpectraSyn™ MaX PAO can be used in combination with mineral oils (part-synthetic formulations), Esterex™ esters, or Synesstic™ AN. Esters and AN are useful base stocks for providing solvency, seal swell, and lubricity.

Formulation data

See Section 5.2 for some commercial-engine oil formulations that can be used in high-speed marine oil applications.

6.2 Railroad

Application and equipment

Because of space limitations, railroad diesel engines tend to have very high specific power ratings to realize high power outputs from small engines. Due to small cooling-water systems, the engines tend to run at higher temperatures. This, coupled with long periods of idling and sudden speed/load changes, makes locomotive applications severe.

The U.S. Locomotive Maintenance Officers Association (LMOA) operates a classification system for locomotive diesel-engine lubricants. The current classification is Generation 7 (which must also meet API CF-4) for Tier IV engines, which was intended to provide extended drain intervals, although drain periods are highly dependent on the locomotive's duty cycle.

This classification system is an industry guideline, and engine manufacturers typically approve lubricants after field evaluations and then claim compliance with the LMOA requirements. The two leading manufacturers in the U.S. are Wabtec (GE) and Progress Rail (EMD).

Lubricant requirements

Typical lubricants are SAE 40 monograde engine oils with an alkalinity level of 9 or 12 TBN. One engine manufacturer, EMD, had silver-plated bearings, and the oils used in these engines were free of zinc and chlorine to prevent corrosion. The industry continues to use zinc-free oils. 20W-40 multigrade engine oils have become more prevalent to improve fuel efficiency and fluidity at lower temperatures.

Advantages of synthetic oils

Due to the high-power ratings and difficult operating conditions, synthetic base stock combinations, such as PAO/ester or PAO/AN, offer the following advantages over mineral oils:

- Better oxidation and thermal stability, leading to lower deposit formation
- Lower viscosity and acidity increase, providing extended oil-drain periods
- Lower volatility for reduced oil consumption and oil carryover
- Higher viscosity index for wider temperature performance

6.3 Gas engine oils

Application and equipment

Although many people believe that the gas engine is a recent development, it in fact arose from the steam engine and predates the diesel engine. Today, modern gas engines are used extensively in a wide range of applications. The most common types of gas engines are spark-ignited, in which a sparkplug is used to ignite a compressed mixed charge of air and fuel, similar to a car engine. Less common are dual-fuel and diesel-gas engines.

Gas engines can run on a wide variety of gaseous fuels, which is a critical parameter for gas engines. Liquid fuels have well-defined specifications for fuel types, and fuel quality changes relatively little. With gaseous fuels, the composition can change quickly, especially with biologically derived or chemical process gases. Even with natural gas, "spiking" can occur (the addition of propane or butane to supplement heating values). This can pose a severe risk in the operation of a gas engine, causing pinking and potential detonation.

The most common sources of gas are:

Natural gas. Natural gas is predominantly methane (around 88%) with smaller concentrations of other hydrocarbons and contaminants such as sulfur and nitrogen. Natural gases with low levels of sulfur (<10 ppm H2S) are known as sweet gases, while those with increased levels of sulfur (up to 7% H2S) are known as sour gases.

LPG and CNG. Liquified petroleum gas (LPG) and compressed natural gas (CNG) are the most common fuels for automotive or mobile-engine applications. LPG has a higher thermal value than natural gas, plus the portability of liquid fuels.

Biogases (landfill or sewage digester). When household waste is dumped into landfill sites, it decomposes and generates methane gas. This gas is contained and used to generate electricity. Trace contaminants in the gas can cause severe problems. Those creating the most problems are hydrogen sulfide (H2S), halogenated compounds of chlorine, fluorine, and others, and gaseous silicon compounds known as siloxanes. These contaminants can react in the combustion process to form corrosive acids or abrasive deposits in the gas engine.

Sewage gas is formed from the bacterial decomposition of sewage sludge and agricultural or vegetable waste. The methane produced is used to drive an engine, invariably in a co-generation mode, with the heat being fed back into the decomposition process to encourage bacterial activity.

Process gas. Chemical processes also produce waste gases, which can be used in gas engines. As with landfill and sewage gases, these fuels will have widely differing characteristics and contaminants that will affect overall engine performance and usually have an adverse effect on the life of the lubricant.

Coal gas. Coal gas is primarily methane and is released from coal deposits. It can also be manufactured from the distillation or carbonization of coal in closed vessels, such as a coke oven.

Producer gas. This is the term used for a gas thermally manufactured through the conversion of solid wastes. Using the process of pyrolysis, a gasifier can produce a good quality gas with minimal residue. Most organic products can be used as feedstock, but typical wastes suitable for conversion are plastics, car tires, animal waste, packaging and wood.

Most gas engines are used in co-generation plants, in which the gas engine drives a generator, and the electrical power produced is supplemented by the recovery of heat from the engine and exhaust gases. These systems can realize efficiencies of 80% or more.

Conventional power generation is another popular application for gas engines, typically on landfill gas sites located in remote areas where there is no demand for heat. Gas engines can also be used for mechanical drive applications, such as pump or compressor drives. For gas-transmission purposes, large two-stroke gas engines are used to drive compressors, which, in some designs, are integral with the engine.

Due to environmental concerns with traditional internal combustion engines, gas engines in vehicles are also becoming more popular. The requirements of modern vehicles, as well as differences in load and speed, add another dimension to the lubricant performance. Applications of gas engines vary considerably by country and depend significantly on government legislation and incentives.

Lubricant requirements

As with most other internal combustion engine lubricants, gas-engine lubricants must carry out a number of tasks, the main one being separating moving surfaces and reducing friction. This is primarily a function of viscosity, although anti-wear additives are used to provide protection in areas of marginal lubrication, such as cams and piston rings. The oil then must keep the engine clean, preventing deposit formation that leads to ring sticking, bore polishing, and other problems. It must also protect against corrosion through the application of protective films or the neutralization of acidic components. Finally, it must help remove heat from the engine.

With no international standards, such as API or ACEA, to define gas-engine lubricants, the main criteria for their selection are provided by the individual engine builders and are generally based on viscosity, total base number (TBN), and sulfated ash level.

Because of higher operating temperatures and ever-increasing cylinder pressures, SAE 40 oils are preferred to maintain sufficient oil films between bearing surfaces. A recent trend has been to examine SAE 30- and SAE 20-grade oils to enhance energy efficiency.

Finished-product approvals are typically based on the results of an engine field trial.

Advantages of synthetic oils

Gas engines tend to run at higher temperatures and higher loads than passenger car engines. Synthetic base stocks for lubricant oils offer the following advantages over mineral oils:

- Better oxidation and thermal stability, leading to less deposit formation
- Lower viscosity and acidity increase, providing extended oil-drain periods
- Lower volatility for reduced oil consumption and oil carryover
- Higher viscosity index for wider temperature performance

Formulation data

The formulations in Table 6.3.A are examples of fully synthetic gas engine oils that are suitable for different engine and gas applications with low, medium, and high ash configurations.

Table 6.3.A Fully synthetic SAE 40 gas engine oils

Component, wt.%		Low ash product	Medium ash product	Medium ash product	High ash product
SpectraSyn™ 6 PAO		60.2	59.5	24.8	58.4
SpectraSyn™ 40 PAO		30.0	30.0	25.5	30.0
EHC™ 110				34.0	
Additive package*		9.8	9.7	9.7	9.7
Overbased detergent			0.8		1.9
Esterex™ NP343 ester				6.0	
Property	**Test method**	**Low ash product**	**Medium ash product**	**Medium ash product**	**High ash product**
KV @100°C, cSt	ASTM D445	12.7	13	13.42	13.4
KV @40°C, cSt	ASTM D445	93	95.1	110.87	98.8
Viscosity index	ASTM D2270	133	134	118	135
Total base number TBN, mg KOH/g	ASTM D2896	5.72	8.38	5.0	12.44
Sulphated ash	ASTM D874	0.46	0.78	0.75	1.27

Finished lubricant properties are calculated from the typical values of the base oils and standard additive packages.

*Standard additive package is designed for use in lubricating oils for gas engines running on natural gas, landfill gas, and biogas. This package also meets API CF performance requirements.

Source: ExxonMobil data and models

Synesstic™ AN

Synesstic™ AN base stocks are API Group V fluids that can be used to help improve the performance of PAO-based engine oils. Synesstic™ AN provides a boost in oxidative stability while providing the necessary solvency for seal swell and deposit control.

Fully synthetic PAO-based passenger car and heavy-duty engine oils formulated with Synesstic™ 5 AN, instead of ester, showed substantially improved oxidative stability in oxidative screening tests and significantly reduced cam wear in engine tests.

SpectraSyn Elite™ mPAO

Further enhancement of the performance of synthetic engine oils may be achieved using the SpectraSyn Elite™ mPAO series of high-viscosity mPAOs. SpectraSyn Elite™ mPAO provides improvement in viscosity index and may improve wear protection through a boost in HTHS viscosity (see Table 5.1.E).

Additive requirements

Additive packages for engine oil formulations are carefully balanced combinations of individual components, with the treat rates determined by the demands of the lubricant specifications.

Typical additive types used in gas engine oil formulations are:

- Detergent and dispersants
- Oxidation inhibitors
- Corrosion passivators
- Defoamants
- Rust inhibitors

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7.0 Industrial applications

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7.0 Industrial applications

7.1 Compressor oils

Application and equipment

Compressors are used to pressurize many different types of gases throughout many industrial sectors. The type of gas being compressed should be considered when selecting lubricants for compressors, because reactions between the gas and the lubricant can occur and adversely affect the lubrication.

Air compressors are by far the most common of all gas compressors. They provide compressed air to pneumatic tools and control systems. Hydrocarbon gases are routinely compressed in the process industries while natural gas is compressed as part of extensive gas transmission systems. Compression of refrigerant gas is also another important application.

Compressors can be classified into two major types: positive displacement and dynamic.

Positive-displacement compressors. Positive-displacement compressors are further subdivided into rotary and reciprocating types. Both types move a fixed volume of gas. For example, as a rotary screw turns, it moves a set volume of gas, and as a piston moves, it displaces a set volume with each stroke. Rotary compressors may be of a screw, vane or lobe type, while reciprocating compressors are generally of the piston type. Different types of compressors have different lubrication requirements.

Rotary compressors can be dry or wet (oil-flooded). In the dry type, the rotors run inside the stator without a lubricant and, due to the limited cooling and sealing, are limited to single-stage compression. The lubricant for these machines is not exposed to the gas, and so general circulating lubricants can typically be used. Oil-flooded machines have oil injected into the stator to provide cooling, sealing and lubrication. In these types, the oil is separated from the gas discharge at the exit and continuously recycled.

In reciprocating compressors, the cylinder and crankcase may be lubricated from a common system, or the cylinders may be lubricated from a separate system. Apart from some small compressors where splash lubrication is used, the cylinders are lubricated by means of oil injection to the cylinders or suction valves. The oil will pass out of the compressor with the gas and collect in the discharge pipework. With splash lubrication, the oil thrown onto the cylinders is scraped off the cylinder liner by scraper rings fitted to the piston. The scraper ring controls the amount of oil feed to the upper cylinder and valves.

The bearings are lubricated by oil contained in a reservoir in the base of the compressor. Although splash lubrication can be used in smaller machines, a forced lubrication system is typically used, where a pump delivers oil under pressure to the various lubricated parts.

Dynamic compressors. Dynamic compressors generate pressure by increasing the kinetic energy of a gas with an impeller, much like a fan blows air. These compressors are either centrifugal- or axial-flow types.

Like the dry compressors above, the lubricant for these machines is generally not exposed to the gas, so circulation-type lubricants can be used. Screw compressors are reliable machines and are increasingly replacing the traditional workhorse of industry — the reciprocating compressor. As with other industrial equipment, more compact units with higher power-to-size ratios are being designed and built.

Due to the severe conditions and demand for longer oil-drain intervals, the use of synthetic lubricants is common in air compressors. To handle the various quality levels found in the industry, compressor OEMs are increasingly requiring the use of their own oils during the warranty period.

Lubricant requirements

The lubricant requirements for gas compressors can be summarized as follows:

- Good compatibility with the gas being compressed
- Correct viscosity for compressor type
- Good resistance to oxidation and carbon formation
- Elevated flash/fire point and auto-ignition temperature
- Good water separation (demulsibility)
- Good anti-wear and corrosion protection
- Good low-temperature performance and detergency (portable equipment)

By far, most lubrication problems are related to the severe operating conditions experienced by reciprocating (piston) compressors and rotary screw or vane compressors. In fact, oil-flooded screw compressors probably provide the most difficult set of conditions that any lubricant is likely to face: high oil temperatures, intimate mixing of hot oil with high-temperature air, high-pressure surface contact and water condensation. This means that the quality of the base oil is very important for air compressor lubricants, and narrow-cut base oils with low volatility and low carbon-forming tendencies are recommended where possible.

The high temperatures of operation (120°C to 260°C) require drain intervals with mineral oil to be in the range of 500 to 1,000 hours. The use of synthetic fluids can increase drain intervals up to 10,000 hours for rotary compressors and provide good discharge-valve cleanliness in reciprocating compressors. The higher cost of the synthetic lubricant can be readily justified by the increased drain interval, reduced maintenance and reduced equipment downtime.

In general, both PAO- and ester-based lubricants are recommended for use in rotary and reciprocating compressors. AN can be used as a co-base stock with mineral or PAO-based formulations to provide enhanced performance.

ISO VG 32, 46 and 68 are the recommended viscosity grades for rotary compressors, with ISO VG 100 and 150 recommended for reciprocating compressors.

Large dynamic compressors used in process industries often operate at relatively low pressure but very high flow rates. The lubricants used in these machines are typically rust and oxidation-inhibited (R&O) bearing-circulation or turbine oils with an ISO viscosity grade of 32-68. The oil is normally not in contact with the gas. Occasionally, the seals are lubricated from the main oil system, and the oil is directed to a degassing tank before being returned to the main oil system. This can be a source of contamination.

Fires and explosions are a risk with compressed-air systems fed from oil-lubricated compressors. In service, oil from the compressor may pass into the air-discharge system, where it coats the pipework and collects around the system. The lighter fractions will evaporate and pass through the system until they condense back into oil, usually at the air receiver. The heavier components, subject to high air temperature and oxidizing conditions from the iron oxide in the pipework, create carbonaceous deposits. Under the combined influence of oxygen and temperature, these deposits can become thermally unstable and may auto-ignite. If the surrounding atmosphere has the correct combination of oil vapor and oxygen, an explosion may occur.

A serious explosion in Belecke, West Germany in 1963 led to the death of 19 men, and since that time, the requirements for air-compressor lubricating oils have become more stringent.[2]

The German Safety and Technical Inspection organization TÜV defined the requirements for "safety oil," and this was incorporated into DIN specification 51506. The specification allows for three oil groups depending on the air-discharge temperatures.

2 "Safety aspects for selection and testing of air compressor lubricants," Hans W. Thoenes, Rheinisch-Westfalischer Technischer Uberwachungs-Verien e.V, Essen Germany.

Table 7.1.A DIN classification of air-compressor lubricants

DIN 51506 category	Air discharge temperature
VB or VB-L	<140°C
VC or VC-L	140°C to 160°C
VD-L	160°C to 220°C

L = oils with additives

Other specifications which may be applied are:

- DIN 51524 HLP
- GM LJ
- SAE MS-1003-2

Advantages of synthetic oils

The higher thermal, oxidation and chemical stability of synthetic base fluids allow lubricants to be formulated to resist breakdown under the severe conditions found in compressors. This helps to improve productivity through longer oil-drain intervals and longer filter/separator life. Their physical properties allow safer operations through higher flash, fire and auto-ignition points, while low volatility helps to reduce oil consumption, oil carryover and deposit formation.

PAOs are commonly used in rotary compressor lubricants. Their compatibility with mineral oils makes them an easy choice for upgrading lubricants. Fully formulated PAO-based lubricants offer very good oxidation stability, excellent low-temperature fluidity and improved film thickness at high temperatures.

For lubricants where incidental food contact may occur, all ExxonMobil SpectraSyn™ PAO, SpectraSyn Plus™ PAO and SpectraSyn Elite™ mPAO base stocks meet the FDA specifications for a technical white mineral oil (21 CFR 178.3620(b)) and are listed in the National Sanitation Foundation (NSF) "White Book™" (category code H1), lubricants for incidental food contact. Therefore, these can be used to make NSF H1 compressor oils.

The highly polar characteristics of Esterex™ esters lead to good cleanliness in air-compressor lubrication. They are often used in reciprocating compressors where the low carbon-forming tendencies and increased solvency may reduce or eliminate deposit formation on the discharge valves. This leads to safer operation because it removes the ignition source for fires and extends ring, cylinder and valve life. In rotary applications, ester-based lubricants provide natural detergency and do not form insoluble varnishes or heavy polymers. They have very good oxidative and thermal stability and also provide good lubricity and wear protection.

Ester-based formulations can suffer from hydrolysis, particularly on rotary equipment where intimate mixing of the oil and air occurs, and PAO/AN may offer a better solution for difficult applications.

ANs are highly stable and, when blended with other base stocks, may provide a synergistic boost to the overall oxidation stability. Like esters, they offer good solvency for deposit and sludge control, but unlike most esters, they do not suffer from hydrolysis.

ExxonMobil Synesstic™ AN base stocks and Esterex™ NP343 esters are also listed in the NSF "White Book™," with category codes H1 and HX-1 (lubricants or components for lubricants for incidental food contact).

The improved lubricity or lower traction properties of synthetic base stocks help to reduce friction and save energy. Dynamic compressors are typically large, and they commonly use gear drives and operate at high speeds. In these cases, the low traction coefficient of PAOs can help reduce internal energy losses and lower oil temperatures.

Formulation data

Ester-based compressor lubricants

The following base stock ratios are recommended for the formulation of the various viscosity grades of ester-based compressor lubricants. These ratios were blended with appropriate additive components, and the physical properties of the blends are shown below. These blends can serve as a guideline for ester-based compressor oil formulation.

Table 7.1.B Ester-based compressor oils

Component, wt.%		ISO VG 32	ISO VG 46	ISO VG 68	ISO VG 100
Esterex™ A51 ester		83.5	53.1	19.7	–
Esterex™ P81 ester		14.7	45.2	78.6	80.6
Esterex™ TM111 ester		–	–	–	17.7
Additive package*		1.8	1.8	1.8	1.8
Property	**Test method**	**ISO VG 32**	**ISO VG 46**	**ISO VG 68**	**ISO VG 100**
Kinematic viscosity @40°C	ASTM D445	32.7	47.5	70.7	103.2
Kinematic viscosity @100°C	ASTM D445	5.7	6.6	7.8	9.8
Viscosity index	ASTM D2270	105	76	48	62
Flash point COC, °C	ASTM D92	252	254	272	274
Pour point, °C	ASTM D97	-45	-42	-39	-33

*Combination of antioxidants and corrosion inhibitor.
Source: ExxonMobil data

Additive requirements

Other typical ester compressor oil formulations could contain a total of 1 to 6% of the following additives, with the remainder, depending on the viscosity grade, being the base stocks in the ratios shown in Table 7.1.B:

- Anti-wear
- Defoamant
- Rust and/or corrosion inhibitor
- Oxidation inhibitor
- Metal passivator
- Demulsifier
- Dispersant**

**Not always required, application dependent

PAO-based compressor lubricants

All PAO-based synthetic air compressor lubricants must contain appropriate additives to provide premium performance, and generally require a more polar base stock component (ester or alkylated naphthalene) to improve additive solubility and seal compatibility.

In rotary applications, PAO-based lubricants provide very good thermal and oxidative stability over a wide range of temperatures, as well as improved water tolerance and protection against corrosion. They are particularly effective in rotary compressors that have oil-injection cooling with higher final-compression temperatures, and in compressors that tend to form varnish and other system deposits. PAO-based lubricants have drain intervals that are significantly increased over mineral oils. The good hydrolytic stability of the PAO-based lubricants is especially important in humid environments.

In reciprocating compressor applications, PAO-based lubricants are used where there are high discharge temperatures. With the proper selection of PAO, the lubricant can have low volatility and low carbon-forming tendencies, which result in clean compressor operating conditions. Another benefit of PAO-based lubricants is their compatibility with the elastomers and paints found in older machines that were designed for use with mineral oils. The use of Synesstic™ AN, in combination with the PAO, should result in greater oxidative and thermal stability. In all applications, these lubricants have a broad operating temperature range with good low-temperature properties.

Additive requirements

A typical PAO-based compressor-oil formulation could contain a total of 0.5% to 6% of the following additives, with the remainder, depending on the viscosity grade, being the base stocks in the ratios shown in Table 7.1.C:

- Anti-wear
- Rust inhibitor
- Oxidation inhibitor
- Defoamant
- Rust and/or corrosion inhibitor
- Metal passivator
- Demulsifier
- Dispersant*

*Not always required, application dependent

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Table 7.1.C PAO-/ester-based compressor oils (base oils only)

Component, wt.%		ISO VG 32	ISO VG 46	ISO VG 68	ISO VG 100	ISO VG 150
SpectraSyn™ 6 PAO		84	74	63	53	42
SpectraSyn™ 100 PAO		1	11	22	32	43
Esterex™ A51 ester		15	15	15	15	15
Property	**Test method**	**ISO VG 32**	**ISO VG 46**	**ISO VG 68**	**ISO VG 100**	**ISO VG 150**
KV @100°C, cSt	ASTM D445	5.9	7.9	11.1	15	21
KV @40°C, cSt	ASTM D445	30.5	44.1	67.3	99	151.2
Viscosity index	ASTM D2270	140	153	158	159	163
SG @ 15.6/15.6°C	ASTM D4052	0.833	0.841	0.844	0.847	0.850
Flash point, °C	ASTM D92	236	241	243	253	253
Fire point, °C	ASTM D92	269	273	277	277	281
Pour point, °C	ASTM D97	-58	-56	-54	-51	-48

Source: ExxonMobil data

Compressor lubricants with AN

In air compressor lubricants, Synesstic™ AN can replace ester to improve hydrolytic stability. In formulations using API Group II and III mineral oils, Synesstic™ AN can also be used to enhance their performance by boosting oxidation resistance and helping to reintroduce a degree of solvency.

Table 7.1.D shows how API Group III oils, blended with Synesstic™ AN, can meet specifications for modern high-performance compressor oils.

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Table 7.1.D Compressor oil blends with Synesstic™ AN and API Group III oils

Component, wt.%			ISO VG 32	ISO VG 46	
Gr III 4 cSt			41.1	7.3	
Gr III 8 cSt			41.5	74.8	
Viscosity index improver			0.5	1.0	
Additive package* (contains 15% Synesstic™ 5 AN)			16.9	16.9	
Property		**Test method**	**ISO VG 32**	**ISO VG 46**	**Limits**
KV @40°C, cSt		ASTM D445	32.7	43.9	ISO VG +/- 10%
KV @100°C, cSt		ASTM D445	6.0	7.3	
Viscosity index		IP226	133	130	
Pour point, °C		ASTM D97	-42	-39	<-20
Flash point COC, °C		ASTM D92	232 (>210)	241 (>230)	Shown in brackets
TAN, mg KOH/g		ASTM D974	0.4	0.4	<0.6
Ash content, %		ASTM D874	<0.05	<0.05	
Conradson carbon, %		ASTM D189	0.03	0.05	
Air release, minutes		IP313	1.5	2.5	
TOST, hours		ASTM D943	7,269	6,250	>4,000
Demulsification, time to 40-40-0, minutes		ASTM D1401	4.5	4.8	<30
Demulsification	Water in oil, %	ASTM D2711	0.1	0.15	<1
	Total free oil, ml		88.2	87	>60
	Emulsion, ml		0.1	0.1	<2
Foam	Sequence 1, ml	ASTM D 892	0/0	0/0	<50/0
	Sequence 2, ml		20/0	0/0	<50/0
	Sequence 3 ml		10/0	0/0	<50/0
Copper corrosion, 3h @100°C		ASTM D130	1b	1b	1b
Rust test		ASTM D665 B	Pass	Pass	Pass
RPVOT, minutes		IP229	1,885	1,956	
CCMA modified	Change in TAN, mg KOH/g		-0.15	-0.15	<0.15
	Change in viscosity, %		1.5	1.7	<5
	Sludge, mg/100 ml		16.2	19.9	<25
	Copper rod rating		5	5	≤5
	Copper weight loss, mg		3.5	4	≤10
	Steel rod rating		1	1	1 max
FZG visual (A/8.3ms-1/90°C)		ASTM D5182	12 Fail	11 Fail	≥11 Fail
4 ball wear, ASTM D4172, mm (40kg/1,200 rpm/60 mins/75°C)		ASTM D4172	0.34	0.39	≤0.4

*Additive package meets the requirements of: DIN 51506 VDL; DIN51524 HLP; GM LJ; SAE MS1003.

The test results are typical values and are not intended to be specifications.

Source: ExxonMobil data and models

Refrigeration oils

Refrigeration and air conditioning systems work through the principle of evaporation. They take advantage of fluids that boil at low temperatures, such as ammonia, which boils at −33°C @ atmospheric pressure. In order to evaporate the refrigerant, heat energy is taken from the surrounding area, thus lowering its temperature. One of the key characteristics when choosing a refrigerant gas is its boiling point relative to the desired colder temperature.

The refrigerant compressor is an integral part of the system, drawing in the hot refrigerant gas coming from the evaporator (i.e., the refrigerator compartment or chiller room). The gas is then compressed, raising its temperature and its boiling point. The high-temperature gas is then passed through a condenser (cooler), which removes heat, dropping the temperature of the gas below its boiling point and returning it to a high-pressure liquid. This liquid is then passed through an expansion valve, which drops the pressure to match the suction pressure of the compressor.

Because the temperature of the liquid is now above its boiling point (at the lower pressure), this immediately causes some flash evaporation of the refrigerant. The heat required for the evaporation comes from the liquid itself, so the bulk temperature of the refrigerant liquid drops. From the expansion valve, the mixture of gas and cold liquid flows through a heat exchanger (the evaporator). During this time, the remainder of the liquid refrigerant is evaporated, removing heat from the surroundings. The gas then re-enters the compressor to start the cycle again.

Like air compressors, refrigeration compressors can be reciprocating, rotary screw or dynamic centrifugal types. Similar to air compressor lubricants, those for refrigerant compressors must act to lubricate internal parts, serve as a coolant to remove heat and act as a sealant in rotary-type compressors.

Because the refrigeration cycle is closed, the lubricant must have good compatibility with the refrigerant gas. Usually, some oil will pass from the compressor into the gas stream. This oil needs to be separated from the gas and returned to the compressor. If not, the oil level in the compressor can decrease, possibly leading to failure.

There is no "oil consumption" and "topping up," as you would find in a conventional compressor. The oil level relies completely on oil being returned from the refrigeration circuit to the compressor. Therefore, the oil has to separate completely from the gas or be miscible with the gas, such that it is carried through the system without coating out and blocking the expansion valve or coating the inside of the heat exchangers and decreasing their heat-transfer efficiency.

Water in a refrigeration system causes severe problems, such as freezing and reacting chemically with the refrigerant gas, which can cause deposits or corrosion. Care needs to be taken when using polyalkylglycols (PAG) and polyol esters, as they are hygroscopic.

With the extensive use of refrigeration and air conditioning systems, the industry is coming under pressure to improve energy efficiency. It is estimated that, in the U.S., 15% of the total energy consumption in a modern building is due to the refrigeration and air conditioning system.[3] As with many other types of equipment, the lubricant in a refrigerant system can play a key role in reducing friction and energy consumption.

Lubricant requirements

Lubricants for refrigeration compressors need to have the following characteristics:

- Good chemical compatibility with the refrigerant gas in use
- Low pour points to maintain fluidity on the low-temperature side of the system
- Low floc points (the temperature at which wax-like materials will separate from a Freon 12/oil mixture, the floc point defines the lowest temperature that can be achieved with that oil)
- Good viscosity retention to maintain film thickness when mixed with refrigerant gas
- High viscosity index to provide good fluidity at the low-temperature suction side of the compressor while maintaining good film protection at the compressor discharge
- Low volatility to reduce oil vaporization at the compressor discharge
- Low foaming potential to help release dissolved refrigerant gases
- Good thermal stability to avoid deposit formation at compressor discharge

Typical oil viscosities range from ISO VG 10 for reciprocating machines up to ISO VG 220 for screw compressors. The trend is toward lower viscosity grades to save energy.

3 "Lubricants for Sustainable Cooling," Peter Gibb, Steven Randles, Michael Millington, and Andrew Whittaker, Uniqema Lubricants.

Most mineral compressor oils are based on naphthenic base stocks, which have naturally low pour points and low floc points. Paraffinic oils may be used but need to be deeply dewaxed.

Care needs to be taken when using hydrocarbon gases. PAGs are the preferred base stock for this application because the hydrocarbon gases are not miscible. With mineral, PAO or alkyl benzene (AB) lubricants, gas miscibility can cause viscosity dilution, foaming and high oil carryover. Higher-than-normal viscosity grades may need to be used.

Table 7.1.E Base stock choice for refrigerant

Base stock type	Compatible with refrigerant gas type	Comments
Mineral naphthenic	▪ Hydrochlorofluorocarbon (HCFC)* ▪ Ammonia ▪ Hydrocarbon (HC)	▪ Natural low pour points ▪ Low floc point ▪ Not miscible with ammonia or CO_2
Mineral paraffinic	▪ HCFC* ▪ Ammonia ▪ HC	▪ Needs to be deeply dewaxed ▪ Not miscible with ammonia or CO_2
PAO	▪ HCFC* ▪ Ammonia ▪ Carbon dioxide (CO_2) ▪ HC	▪ Natural low pour points ▪ Low floc point ▪ Not miscible with ammonia or CO_2
Polyol ester (POE)	▪ Fluorinated hydrocarbons (HFC) ▪ CO_2	▪ Default product for HFC gases ▪ Good miscibility with CO_2
Alkyl benzene (AB)	▪ HCFC* ▪ Ammonia ▪ HC	▪ Not miscible with ammonia or CO_2
PAG	▪ HCFC* ▪ HFC ▪ HC	▪ Often used in air conditioning systems ▪ Miscible with ammonia ▪ Limited miscibility with CO_2 ▪ Preferred option for HC gases

*HCFC gases are being phased out due to their global warming potential.

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Advantages of synthetic oils

Synthetic base stocks such as alkyl benzene (AB), PAO, esters and polyglycols have all been used in refrigerant applications. In comparison to mineral base stocks, these fluids offer better thermal stability, lower pour points, lower foaming and lower floc points. The choice of different chemistries allows the selection of optimum solubility to enhance efficiency and reliability.

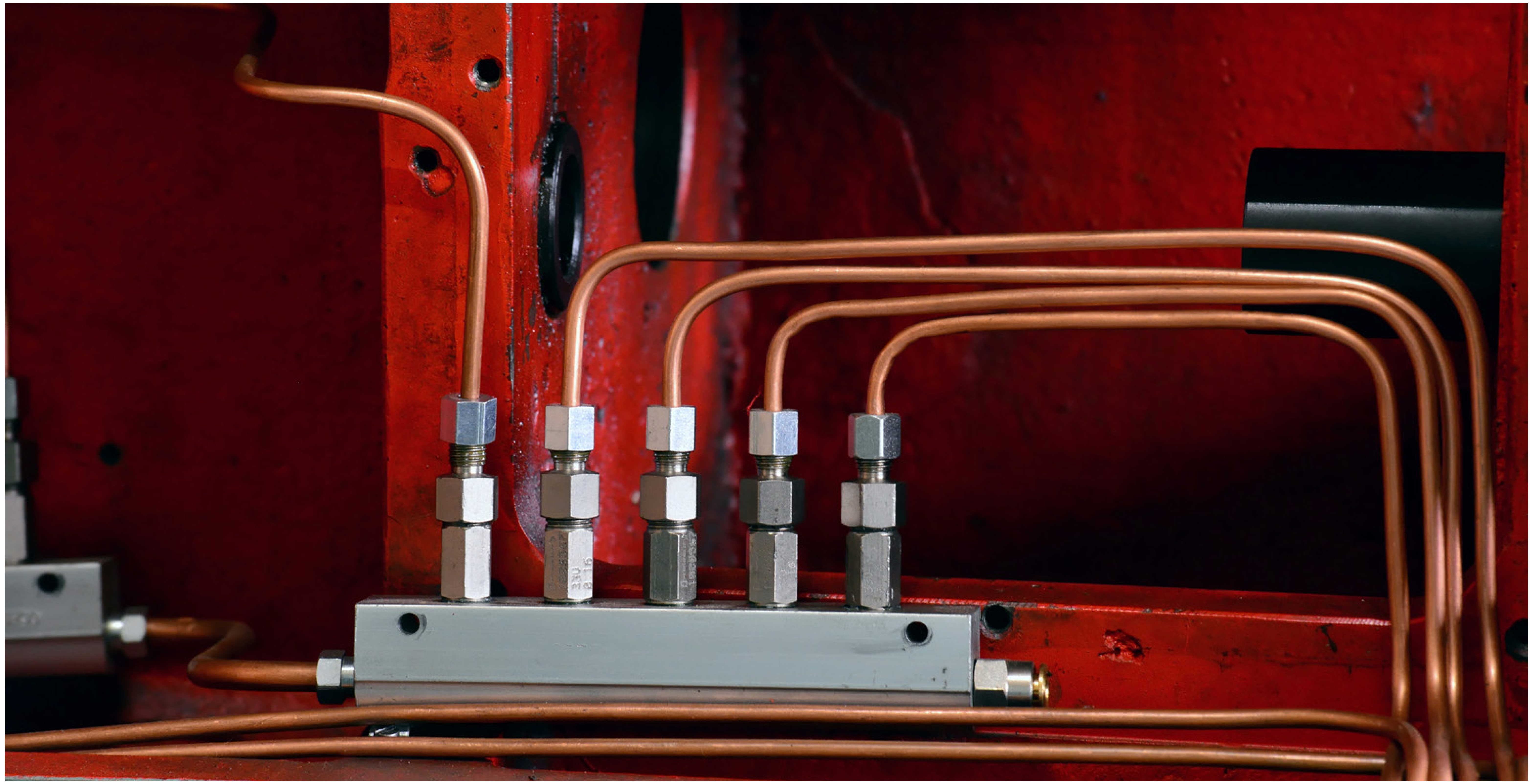
PAO-based lubricants, containing no wax, offer significant advantages. Their low pour points allow them to remain fluid at low temperatures. They also have a very high viscosity index, providing enhanced wear protection at high temperatures. Because of these properties, PAO-based lubricants offer good protection against wear of bearings, cylinders and piston rings. Since they are chemically similar to mineral oils, PAO-based lubricants are usually compatible with the same type of seals and coatings as are mineral oils.

In screw compressors, the lower traction coefficient of PAOs also offers the potential for energy savings. PAOs operate well in ammonia systems when blended with AB, and the same performance would be expected if Synesstic™ AN base stocks are used. Synesstic™ AN base stocks are members of the alkylated aromatic family and, being similar to AB, should be able to be used in similar refrigerant applications. There are, however, currently no data to support its use in this type of application.

Polyol esters are the default choice for lubricant base stock for compressors using most modern hydrofluorocarbon (HFC) refrigerant gases. They can chemically react with ammonia, so they are avoided in those systems.

Table 7.1.F PAO-based formulations for refrigerant lubricants (base oil blends only, weight %)

Component, wt.%	ISO VG 15	ISO VG 22	ISO VG 32	ISO VG 46	ISO VG 68	ISO VG 100	ISO VG 150	ISO VG 220
SpectraSyn™ 2 PAO	18							
SpectraSyn™ 4 PAO	82	70						
SpectraSyn™ 6 PAO		30	100		69	54	38	23
SpectraSyn™ 8 PAO				100				
SpectraSyn™ 40 PAO					31	46	62	77



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Additive requirements

Typical PAO-based refrigeration lubricants may contain 0.1% to 2.0% of the following additives, with the remainder, depending on the viscosity grade, being the base stocks in Table 7.1.F:

- Anti-wear
- Oxidation inhibitor
- Defoamants

7.2 Hydraulic oils

Application and equipment

Hydraulic systems transform and control mechanical work and are utilized to transmit and apply large forces in a flexible and controlled manner. A typical hydraulic system, besides the fluid, includes:

- A pump that converts mechanical energy into hydraulic energy
- Piping for transmitting fluid under pressure
- A unit that converts the hydraulic energy of the fluid into mechanical work, such as an actuator or motor
- A control circuit with valves that regulate flow, pressure, direction of movement and applied forces
- A fluid reservoir that allows for separation of any water or debris before the fluid is returned to the system through a filter

The pump can be considered the heart of the system, and the hydraulic fluid, the lifeblood of the equipment. Good wear control by the fluid is essential for pump efficiency. Wear causes internal slippage or leakage, which reduces the pump output, resulting in power loss and increased operating temperatures.

Hydraulic systems can range from a simple actuator system to a complex control system providing rapid and precise control of equipment.

In some cases, fire resistance is a major requirement that has been pushing large segments of industry and commerce toward the adoption of special, non-mineral-oil hydraulic fluids made of synthetic base stocks. Fires have been caused by the accidental leakage of hydraulic fluid onto hot areas. Rupture or puncture of a high-pressure hydraulic hose has been known to squirt fluid up to 12 meters away in the form of a fine mist that is highly combustible if made from mineral oil.

Biodegradable hydraulic fluids are also becoming more important globally. The trend originated in Europe; however, legislation on both sides of the Atlantic is driving the formulation of these types of hydraulic fluids. At the same time, the need for high performance levels remains.

Hydraulic pumps are becoming smaller and operating at higher pressures and temperatures, while systems are getting more compact, with less oil in circulation. Both trends place increased stress on the lubricant. The use of complex control valves with extremely fine clearances means that cleanliness requirements are critical. Good filterability, especially in the presence of water, is therefore important. Servo-control valves with fine clearances are also subject to sticking due to the build-up of lacquers, so oxidation stability and good solubility are important. This is particularly relevant for oil formulations that use higher-quality base stocks to improve oxidation stability. These base stocks typically have lower aromatic content, so the use of AN or esters with these base oils is very effective in providing solvency. Energy efficiency is of growing importance, and so high-VI fluids are increasingly required.

There are many different specifications for hydraulic oils, but the DIN and ISO specifications provide a benchmark for the minimum properties of hydraulic oil, depending on its application (see also "Hydraulic oil classifications").

The DIN and ISO specifications are based on classic laboratory tests, plus, for certain types of fluids, a mechanical test is required (e.g., the FZG or Vickers V104 C vane pump test). This reflects the level of performance required by the industry but does not guarantee the oil performance in service in the long term.

Various equipment builders also have oil-approval specifications that are typically based around DIN specifications but include testing on their specific equipment (i.e., Vickers, Bosch Rexroth, Sauer-Danfoss, Poclain Hydraulics). Among the commonly met principal builder specifications are those from Denison (HF1, HF2 or HFO).

Lubricant requirements

Excellent wear control is essential in a hydraulic fluid. The formulated lubricant must also resist compression and flow readily at all operating temperatures. It must also provide adequate seal compatibility, provide corrosion resistance, and separate readily from water and debris while in the sump before being re-circulated.

Maintaining fluid cleanliness through efficient filtration is key to reliable operation — contamination and poor filtration are the causes of most hydraulic-system failures (figures up to 90% have been quoted). Filtration testing is therefore an essential part of a fluid's performance requirement, particularly in the presence of water.[4]

4 "Contamination: hydraulic system enemy #1," www.machinedesign.com, September 13, 2001.

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Long-term seal compatibility is important to prevent damage to the many seals that can be found in a hydraulic system, and OEM specifications are featuring increasingly tighter requirements. On multi-grade or high-VI fluids, shear stability is required to prevent the lubricant from shearing down in service. The subsequent viscosity reduction can cause excessive leakage and failure of the hydraulic pump to maintain pressure.

Concerns over the extreme temperature performance of vegetable oils have increased interest in synthetic esters. Higher performance fluids are required, and equipment builders are developing their own specifications.

Hydraulic oil classifications

ISO 11158 defines the key requirements for conventional hydraulic oils, such as ISO L-HH, HL, HM, HR, HV and HG types.

Conventional:

- ISO-HH: Non-inhibited refined mineral oils are suitable for non-critical applications
- ISO-HL: HH-type oils with rust and oxidation inhibition properties are used for non-critical applications that do not require anti-wear additives (e.g., low-load vane pumps)
- ISO-HM: HL-type oils with anti-wear additives are generally the most widely used category of hydraulic oils and can usually be used with all types of equipment and for most applications
- ISO-HV: High VI, HM-type oils are for use in applications where cold start-up conditions prevail (e.g., mobile construction, marine, outdoor requirements, cold climate regions, and others)
- NB: HM and HV types constitute the most important and widely used categories. Other categories, aside from those listed, also exist (e.g., HR, HS, HG)
- ISO 12922 defines the key requirements for fire-resistant hydraulic oils, such as ISO L-HFAE, HFAS, HFB, HFC, HFDR and HFDU types

Fire resistant:

- ISO-HFAE: oil-in-water emulsions
- ISO-HFAS: chemical aqueous solutions
- ISO-HFB: water-in-oil emulsions
- ISO-HFC: water/glycols/polyglycols solutions
- ISO-HFDR: synthetic phosphate ester
- ISO-HFDS: synthetic chlorinated synthetics
- ISO-HFDT: mixture of HFDR and HFDS fluids
- ISO-HFDU: synthetic fluids other than HFDR/ST type

ISO 15380 defines the key requirements for environmentally acceptable hydraulic oils, such as ISO L-HETG, HEPG, HEES and HEPR types.

Parker (formerly Denison) HF 1:

- Used for R&O non-antiwear hydraulic oils

Parker HF 2:

- For anti-wear hydraulic oils
- Approval for vane pump tests (only)
- Standard laboratory tests (e.g., foaming, rust test, TOST, hydrolytic stability, filterability, aniline point)
- Parker T6 Vane pump

Parker HFO:

- Anti-wear hydraulic oils
- Approval for vane and piston pumps
- Standard laboratory tests
- Parker Hybrid T6H20C vane and piston pump tests
- Formal approval procedure defined
- Denison HFO requirements are stricter than DIN 51524

Advantages of synthetics

In general, PAO, AN- and ester-based fluids can be utilized to formulate synthetic or semi-synthetic hydraulic fluids. All synthetic hydraulic fluids need appropriate additives to provide premium performance. PAO-based products typically require AN or ester to improve additive solubility and seal compatibility.

Synthetic hydraulic fluids, based, on PAO and AN/esters, may be more durable under thermal and oxidative stress, are cleaner in operation, and are able to span wider operating regimes in more applications. Synthetic fluids may be justified, despite their higher initial cost, when used to extend the lubricant life under severe oxidative or high-temperature environments or where their low-temperature benefits maintain reliable operation.

When properly formulated with anti-wear containing hydraulic fluid additive packages, PAO and AN/ester combinations are recommended for systems using gear, piston, or vane pumps operating at either high or low pressures. The high-VI and wax-free composition of such lubricants support a wide range of operating temperatures.

Formulation data

The base stock formulations in Table 7.2 demonstrate the flexibility to blend various viscosity grades of hydraulic fluids. The use of SpectraSyn Elite™ mPAO should provide some additional wear protection. Both the PAO/AN and PAO/ester formulations provide high-performance products that benefit from the higher oxidative and thermal stability of AN or ester base stocks. However, the use of Synesstic™ AN is recommended over the use of ester to avoid any hydrolysis problems.

Table 7.2 Recommended base stocks for PAO-/ester- and PAO-/AN-based hydraulic oil formulations (weight %)

ISO viscosity grade		ISO VG 32		ISO VG 46		ISO VG 68	
Component, wt.%		PAO/ester	PAO/AN	PAO/ester	PAO/AN	PAO/ester	PAO/AN
SpectraSyn™ 6 PAO		74.2	77.2				
SpectraSyn™ 8 PAO				72.2	76.2	54.2	58.2
SpectraSyn™ 40 PAO		5	2	7	3	25	21
Esterex™ NP343 ester		20		20		20	
Synesstic™ 5 AN			20		20		20
Additive package*		0.8	0.8	0.8	0.8	0.8	0.8
Property	**Test method**	**PAO/ester**	**PAO/AN**	**PAO/ester**	**PAO/AN**	**PAO/ester**	**PAO/AN**
KV @100°C, cSt	ASTM D445	6.2	6.0	8.0	7.6	10.7	10.2
KV @40°C, cSt	ASTM D445	32.0	32.0	45.8	45.3	67.3	67.1
Viscosity index	ASTM D2270	146	134	145	134	148	138
Density @ 15.6°C, g/m3		0.851	0.844	0.855	0.848	0.859	0.851
Flash point, °C	ASTM D92	250	238	260	242	254	242
Pour point, °C	ASTM D5950	-54	-48	-51	-48	-51	-48
Color	ASTM D1500	0.6	0.6	0.5	0.6	0.5	0.6

*Multifunctional additive package which meets DIN 51524, Part 2 and 3 (HLP, HVLP) and many other specifications.

Source: ExxonMobil data

Table 7.2 (continued) Recommended base stocks for PAO-/ester- and PAO-/AN-based hydraulic oil formulations

Additional data for ISO VG 46 only			
Property	**Test method**	**PAO/ester**	**PAO/AN**
RPVOT, mins	**ASTM D2272**	352	396
Air release @50°C, mins	**ASTM D3427**	1.9	2.6
Demulsibility, ml (mins)	**ASTM D1401**	40/40/0 (15)	40/40/40 (15)
Foaming characteristics, ml (Seq I, II, II)*	**ASTM D892**	0/0, 0/0, 0/0	0/0, 0/0, 0/0
Copper corrosion, 3 hrs @100°C	**ASTM D130**	1a	1a
Steel corrosion, 24 hrs	**ASTM D665**	Pass	Pass
Hydrolytic stability	**ASTM D2619**		
Acid number change, mg KOH/g		0.15	-0.14
Total acidity of water, mg KOH/g		4.4	3.6
Weight change of copper strip, mg/cm2		0.0	0.0
Appearance of strip		3B	3B
4 ball wear scar, mm	**ASTM D4172**	0.35	0.33
Seal compatibility, SRE-NBR @100°C for 168 hrs	**ASTM D471 modified**		
Volume change, %		7.7	6.2
Hardness change, points		-5	-3
Tensile strength change, %		-7.7	-9.2
Elongation change, %		-11.1	-9.8

*With 0.01% defoamant.

Source: ExxonMobil data

Additive requirements

A typical hydraulic fluid formulation would contain a total of 0.5 to 6% of the following additives, with the remainder, depending on the viscosity grade, being the base stocks in the ratios shown in Table 7.2:

- Anti-wear
- Defoamant
- Rust and/or corrosion inhibitor
- Oxidation inhibitor
- Demulsifier
- Extreme pressure, friction modifier*

*Optional; application dependent

7.3 Turbine oils

Application and equipment

A turbine is a device that converts the force of a gas or liquid moving across a set of rotor and fixed blades into rotary power. There are three basic types of turbines: steam, gas and hydraulic.

Steam turbines. By powering large electric generators, steam turbines produce most of the world's electricity. They employ steam that enters the turbine at high temperature and pressure and expands across both rotating and fixed blades (the latter serving to direct the steam). Only high-quality lubricants can withstand the wet conditions and moderate temperatures associated with steam-turbine operation. The term "turbine oil" has thus become synonymous with quality. Traditional steam-turbine power plants have very large oil systems (>100,000L), and with careful monitoring and treatment, the oil life can be on the order of 20 years or more. These systems typically use a well-refined mineral oil-based lubricant and regular top-ups of fresh oil to maintain the oil's properties. Synthetic oils have traditionally not been used in these applications, except possibly in small-scale plants, due to high cost.

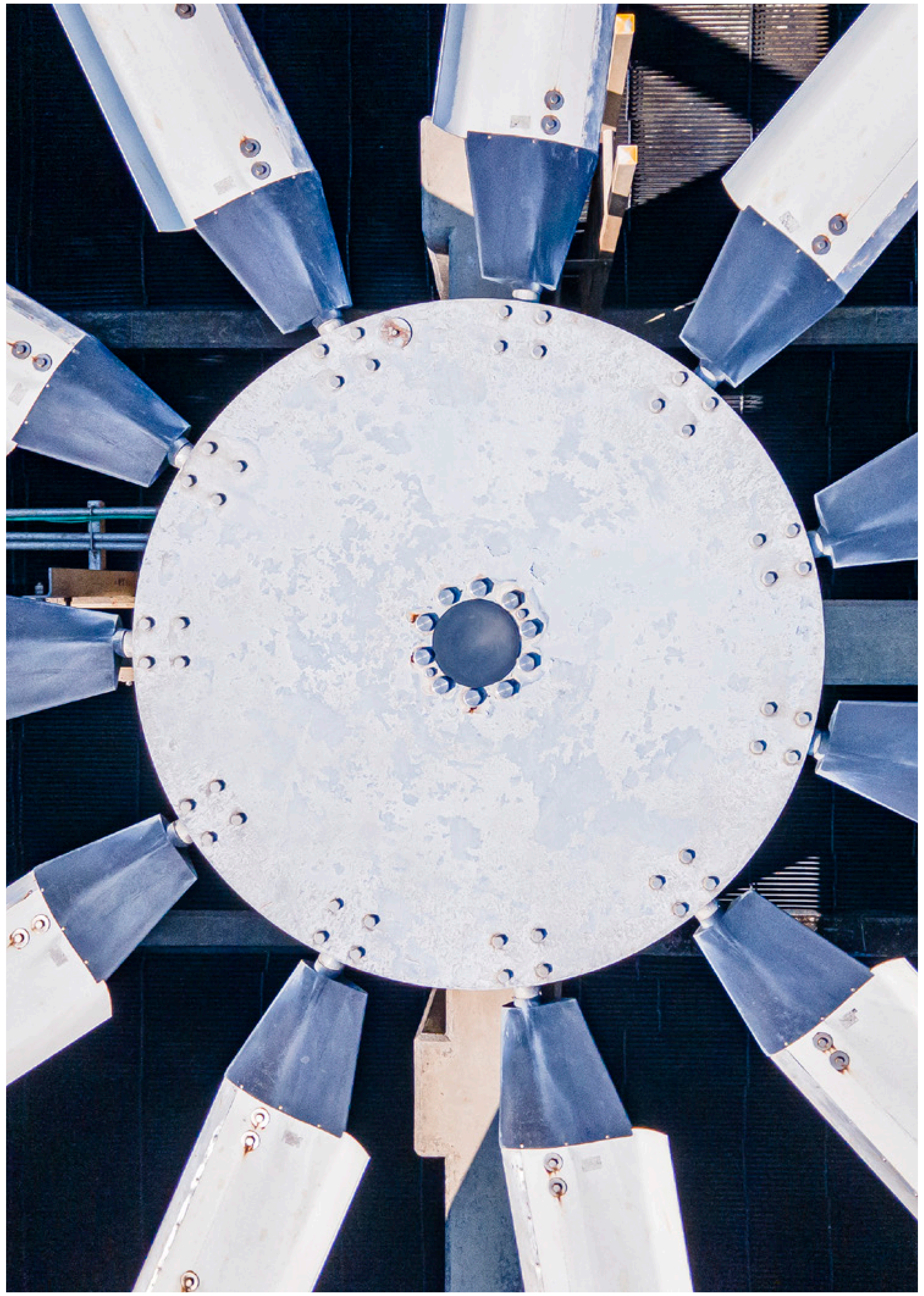
Gas turbines. Gas turbines are powered by the expansion of compressed gases generated by the combustion of a fuel. Some of the power thus produced is used to drive an air compressor, which provides the air necessary for the combustion of the fuel. In a turbo-jet aircraft engine, the turbine's only function is to drive the compressor; the plane is propelled by the force of the expanding gases escaping from the rear of the engine. In other applications, however, the rotor shaft provides the driving thrust to some other mechanism, such as a propeller or generator. Thus, gas turbines power not only turbo-jet aircraft but also turbo-prop aircraft, locomotives, ships, compressors and small to medium-sized electric utility generators. Aero-derived gas turbines present severe lubrication demands that are best met with synthetic turbo oil, which is usually ester-based. Industrial gas turbines do not have the weight and size issues associated with aero-derivative gas turbines. Consequently, they have larger oil systems, better cooling and lower bearing oil temperatures, so PAO-based oils provide excellent performance, as do high-quality mineral oils.

Combined-cycle gas turbines (CCGT). This design, typical of many modern power plants, uses a gas turbine to drive a generator and the high-temperature exhaust gas from the gas turbine to generate steam that can drive another turbine and generator.

In some of the newer designs, the turbines are on the same shaft, sometimes driving the same generator. Consequently, oil systems can be combined so that the oil has to work in the high temperatures experienced by the gas turbine and the water contamination experienced by the steam turbine.

Hydro turbines. Water turbines (or hydro turbines) are either impulse type, in which moving water hits blades or buckets on the periphery of a wheel that turns a shaft, or reaction type, where water under pressure emerges from nozzles on the wheel, causing it to turn.

Hydraulic turbines can be found where there is a flow of water either in a river or tidal system or where there is a head of water such as a mountain or dam. Most machines have a vertical design, which avoids the use of a gearbox as required on a horizontal type. The oil for a hydro



turbine typically must fulfill several roles — lubricating main bearings, as hydraulic fluid for control systems and as gearbox oil (if fitted). The typical oil life expectation is 15 years for large machines.

Again, due to high levels of water contamination, mineral oils are typically used, and general-purpose R&O circulating oils compete with high-quality turbine oils. However, the use of PAO-based formulations in this type of application has been shown to provide energy savings of about 12% through reduced mechanical losses at the bearing pads.[5] This results in reduced bearing temperatures (with a subsequent reduction in cooling required) and reduced oxidation conditions, which would lead to longer oil life.

Electric power generation. Today, the trend is for smaller power stations that are fueled by natural gas to help reduce emissions. Typically, these employ CCGTs, as previously described. They can be built in a modular fashion offsite, require a smaller land area, and, with reduced emissions, can be sited closer to where the demand is, thereby reducing power transmission losses. Due to the improved efficiency of combined heat and power (CHP) systems, small-scale systems are also popular, although they tend to be driven by reciprocating gas engines rather than by turbines. Due to large demands for power in developing countries, small-scale turbine packages (<50MW) have been developed based on aero-derivative gas turbines. These can be modularized and moved easily between sites as power is required.

Smaller oil volumes and increased bearing temperatures have increased the thermal stress on lubricants. At the same time, the end-user expects extended life. As a result, more turbine oils are manufactured based on API Group II and III base stocks. While this brings improved oxidation resistance, base-oil solvency is reduced, which can lead to problems with lacquering because oxidation products are no longer held in solution by the oil. This problem has been aggravated by the operating modes commonly experienced by gas turbines. Due to the need to keep large inflexible plants, such as nuclear or coal-fired power stations, running all the time, many gas turbines are used during peak-demand periods and are regularly shut down or put on standby in between demand peaks. The heating and cooling cycles encourage the dropout of deposits and lacquer formation in the lubricant.

To meet the requirements of various applications, different turbine setups have been developed, including those with a gearbox. The oil must function in severe environments, which can include high temperatures and water ingress. Reducing complexity, the turbine and gearbox typically share the same lubricant supply. To protect the gear drive from typical damage mechanisms, such as scuffing, the lubricant may contain mild Extreme Pressure (EP) additives, while the resistance to scuff is typically evaluated by a test commonly known as the FZG scuffing test. Due to some turbine failures in the 1980s, reportedly caused by deposit problems from hydrolytic breakdown when using zinc dialkyldithiophosphate (ZDDP), most turbine oils are zinc-free today.

5 "A Comparative Study of Mineral and Synthetic Based Hydro Turbine Oils," W. Dmochowski, K Brockwell & B. Liko, National Research Council Canada.

Due to sparking from static electricity, interest in oil conductivity is increasing. Sparking is reported to cause localized oxidation of oils. The Solar turbine oil specification (ES9-224) now includes the ASTM D4308 electrical conductivity test with a recommended limit of 50ps/m at 0°C.

DIN 51515 and ISO 8068 are the principal industry specifications affecting turbine oils. In general, it is the builder requirements that drive lubricant oil development. The main specifications come from the following companies:

- Siemens
- General Electric
- Alstom
- Mitsubishi Heavy Industries (MHI)
- MAN Turbo
- Solar Turbines

Note: There may be several different OEM specifications depending on the turbine type and whether EP or non-EP oil is required.

Due to the increasing severity of operating conditions, builder-specification requirements are becoming more stringent in the form of higher rotary pressure vessel oxidation test (RPVOT), modified RPVOT and turbine oil stability test (TOST) values. As traditional tests become less relevant in terms of performance, turbine manufacturers have been developing their own tests, which have become part of their specifications (e.g., the MHI dry TOST acceleration degradation test). Other specifications include the British Standard BS489, Chinese National Standard GB11120-89, Japanese JIS K-2213 and Russian TP-22S.

Lubricant requirements

All turbine lubricants must:

- Lubricate
- Remove heat
- Remove contamination
- Control sludge and varnish formation
- Seal
- Prevent rust and corrosion

Long service life for lubricants is expected. Traditional coal-fired power stations using large steam turbines could expect to have a life of over 20 years with a mineral-oil lubricant (made possible through large volume, low circulation rates and high make-up rates). Along with greater prevalence of CCGT plants, smaller lubricant volumes and increasing loads and temperatures means that expected oil life on large machines is now between two and five years, with a high-quality mineral oil, depending on the turbine design.

Oxidation stability is, therefore, a key property for turbine oil to ensure good viscosity control and resistance to the formation of sludge, deposits and acidic oxidation products.

For steam, CCGT and hydro turbines, effective demulsibility is required to handle water contamination from steam leaks, oil-cooler water leaks and condensation in the oil tank and large bearing housings. At the same time, rust and corrosion protection are also key properties.

The oil also has to perform hydraulic control (particularly speed control), and therefore, air release properties are critical to prevent erratic response of any control functions. Critical systems sometimes use a separate control-oil system. These may utilize a fire-resistant hydraulic fluid to reduce the risks of fire where the control oil could spray onto hot surfaces in the event of a leak.

Sludge and varnish control is also extremely important to prevent the blocking of turbine control systems. The increasing use of higher quality mineral-based oils to provide improved oxidation stability has, however, contributed to increasing varnish issues as the oil solubility is reduced.

Most turbine shafts are supported on plain journal bearings with one thrust bearing using hydrodynamic lubrication. High shaft speeds and light loads mean that anti-wear requirements can be low. However, some applications utilize gear drives that require anti-wear or extreme-pressure properties.

Advantages of synthetics

PAOs, when formulated with appropriate additives, can meet the requirements of all types of turbine lubrication. Esters have typically been used as a co-base stock to provide solubility and seal swell capability but AN offers a better option for avoiding hydrolysis.

In industrial gas turbines, properly formulated PAO and AN/ester lubricants can provide superior rust protection, low-temperature fluidity, and high-temperature oxidation stability.

In steam turbines, properly formulated PAO and AN/ester lubricants can provide exceptional chemical stability, outstanding resistance to oxidation, superior demulsibility, and protection against rust and deposits. These lubricants can also survive hydrolytic attack under the wet conditions in a steam turbine, particularly where AN is used over ester. Ester selection is critical to hydrolytic stability.

Where Group II and III oils are being used to formulate turbine oils, the use of AN will bring improved solvency (additives and oxidation products) while improving oxidation resistance.

Formulation data

The following tables show the combination of base stocks that could be used to produce turbine oils. Note that these are base stock combinations only, and additives would be required. The additives could be in the form of a prepared package or from individual components, as suggested below.

The Synesstic™ AN based formulations should provide better hydrolytic stability than the ester-based formulations. The use of SpectraSyn Elite™ mPAO would help to improve viscosity index and film thicknesses, especially where extreme-pressure gear performance is required.

Additive requirements

A typical turbine oil formulation would contain a total of 0.3 to 2% of the following additives, with the remainder, depending on the viscosity grade, being the base stocks in the ratios shown in Tables 7.3.A and 7.3.B.

- Anti-wear
- Rust and/or corrosion inhibitor
- Oxidation inhibitor
- Defoamant
- Metal passivators
- Demulsifier
- Extreme-pressure dispersant and friction modifier*

*Optional, application dependent

Table 7.3.A PAO-/AN-based formulations

Component, wt.%	ISO VG 32	ISO VG 46	ISO VG 68
SpectraSyn™ 6 PAO	85	71	55
SpectraSyn™ 40 PAO	-	14	30
Synesstic™ 5 AN	15	15	15

Table 7.3.B PAO-/ester-based formulations

Component, wt.%	ISO VG 32	ISO VG 46	ISO VG 68
SpectraSyn™ 6 PAO	83	69	53
SpectraSyn™ 40 PAO	2	16	32
Esterex™ A51 ester	15	15	15

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7.4 Industrial gear oils

Application and equipment

Early machines used gearing systems built from wooden pegs. When gears started being manufactured from metal, lubrication became more important in reducing wear and prolonging the life of the gear. Loads and speeds were relatively light at first, and vegetable or animal fats were used as lubricants.

Gear systems have become increasingly complex with highly accurate, cut teeth and finely finished surfaces. Modern gear systems can now be found in every field where power must be transmitted or where mechanical motion needs to be controlled.

The recent increase in wind turbine applications, with new gearbox designs, high loads, vibration and shock loading, has given rise to more occurrences of gear pitting, particularly micropitting (also known as gray staining) in surface-hardened gears. New materials are being used to reduce gearbox sizes, which places higher loads on the gear teeth and bearings. Because the oil temperatures are rising, higher-quality lubricants are required.

Viscosity classifications are covered by the ISO viscosity classification (DIN 51519) and the American Gear Manufacturers Association (AGMA) specifications 250.02 (Standard Specification for Lubrication for Industrial Enclosed Gearing) and AGMA 252.01 (Standard Specification for Mild Extreme-Pressure Lubricants for Industrial Enclosed Gearing). Gear oil performance has traditionally been defined by manufacturers. The following are the most commonly used:

- DIN specification 51517 (part 3)
- AGMA 900-5-E02
- ISO 12925-1 type CKD
- AIST 224 (Formerly US Steel 224)
- David Brown
- Cincinnati Milacron
- Flender
- ZF
- SEW Eurodrive

Typical tests

Apart from the usual physical property tests, such as viscosity, pour point and others, most gear oils require the following tests:

- Wear protection
  - ZG DIN 51534 parts 1 and 2
  - Timken OK load
  - 4 ball weld - ASTM D2783 or DIN 51350 part 1
  - 4 ball wear - ASTM D4127 or DIN 51350 part 2
- Elastomer and paint compatibility
- Shear stability
- Foam test

Lubricant requirements

Unlike plain bearings, where there is good surface conformity and a continuous oil film created, gear teeth require an oil film to be created with each tooth engagement. In high-speed gear sets, the lubricant film is established in a very short time. In the gear-tooth engagement, significant sliding occurs between the two gear surfaces, and rolling only occurs at the pitch point. Gear applications are essentially governed by elasto-hydrodynamic lubrication.

Optimized lubrication is required to ensure minimum wear, quiet operation, and long service life. Also, the lubricants are required to transfer forces, reduce friction, dissipate heat and remove abrasive particles. They need to be carefully selected to meet the service requirements and have the proper characteristics. These include the following:

- **Correct viscosity** is required to ensure sufficient film thickness across all the rubbing surfaces at all temperatures and speeds.
- **Good thermal and oxidation stability** enables the lubricant to resist breakdown because of heat and oxygen. The continuous agitation of the oil found in gearboxes can give rise to severe oxidation conditions, so oils with high chemical stability are required.
- **High film strength and lubricity** are required under conditions of boundary lubrication because the oil needs to reduce friction and prevent oil film rupture.
- **Good demulsibility** is required because many gearboxes work in severe environments where water contamination is always present. The ability to quickly separate from water and reduce the risk of emulsion formation is important.
- **Good air release** is important because air is easily entrained into gear systems and the ability of the oil to release air quickly helps prevent foaming and loss of oil film, and reduces oxidation conditions.

Advantages of synthetics

While modern gear-oil lubricants based on mineral oils provide good performance, synthetic gear oils offer several significant advantages, including the following:

- Improved thermal and oxidation resistance
  - Allows significantly longer oil life (typically 3-5 times longer than mineral oils at the same temperature)
  - Allows operation at higher temperatures where mineral oils may not be able to perform
- Improved viscosity-temperature behavior through high viscosity indices
  - Reduces oil viscosity at low temperature for easier pumping and more rapid circulation at startup
  - Maintains a higher viscosity and, hence, thicker oil film at higher temperatures, preventing wear
- Improved low-temperature properties
  - Very low pour points and Brookfield viscosity allow operation at conditions where mineral oils would be solid
  - More rapid oil circulation at startup, improving wear protection and reducing churning energy losses
- Increased gear efficiency
  - Lower traction forces translate into a number of benefits, such as reduced power requirements, reduced oil temperature and extended component life
- Lower volatility and evaporation losses
  - The low volatility of synthetics reduces evaporation losses and reduces oil top-up requirements
- Reduced flammability
  - Compared to mineral oils, the higher flash points and reduced volatility provide increased safety conditions
- Improved cleanliness
  - Improved thermal and oxidation resistance of synthetic base stocks reduces the tendency to form lacquers and deposits

Synthetic industrial gear oils are typically PAO-based, although polyglycol lubricants are widely used in worm-gear applications. Esters and AN can be formulated with PAO to provide additive solubility, improved seal compatibility, and sludge control. For additional potential performance benefits, such as improved wear protection and energy savings through reduced traction, conventional PAO in conjunction with metallocene high viscosity index PAO can be used. The severity of application will usually drive the selection of PAO grade and finished oil viscosity.

Formulation data

The synthetic base stock combinations in Table 7.4.A can be used to make heavy-duty industrial-gear lubricants operating under severe temperature ranges and loads. These base stock combinations, when formulated with an appropriate additive package, are recommended for steel-on-steel enclosed gear drives.

Table 7.4.A Recommended base stocks combinations (weight %)

ISO viscosity grade	100	150	220	320	460	680
SpectraSyn™ 6 PAO	53	42	31	21	11	1
SpectraSyn™ 100 PAO	32	43	54	64	74	84
Esterex™ A51 ester	15	15	15	15	15	15

Additive requirements

A synthetic gear-oil formulation can contain a total of 1 to 5% of the following additives, with the remainder, depending on the viscosity grade, being the base stocks in the ratios shown in Table 7.4.A:

- Anti-wear*
- Dispersant*
- Defoamant
- Extreme pressure
- Corrosion passivator
- Friction modifier*
- Demulsifier
- Oxidation inhibitor
- Detergent*
- Rust inhibitor

*Not always required, application dependent

SpectraSyn Elite™ mPAO

The use of SpectraSyn Elite™ mPAO, with exceptional VI, may provide improved wear performance because of thicker film formation. The improved low-temperature properties also help to reduce the pour point and provide significant reductions in Brookfield viscosities (see Table 7.4.B).

Synesstic™ AN

The use of Synesstic™ AN base stocks with PAO can provide a synergistic boost to improve oxidation stability. By replacing ester as the co-base stock for solvency and seal swell, AN can diminish hydrolytic issues and, due to its low polarity, may allow increased effectiveness of surface-active additives.

Esterex™ polyol ester

The use of Esterex™ NP343 and Esterex™ NP451 polyol ester with PAO can provide a synergistic boost to improve the oxidation stability. By replacing other types of ester as the co-base stock for solvency and seal swell, polyol ester can diminish hydrolytic issues due to its structure stability.

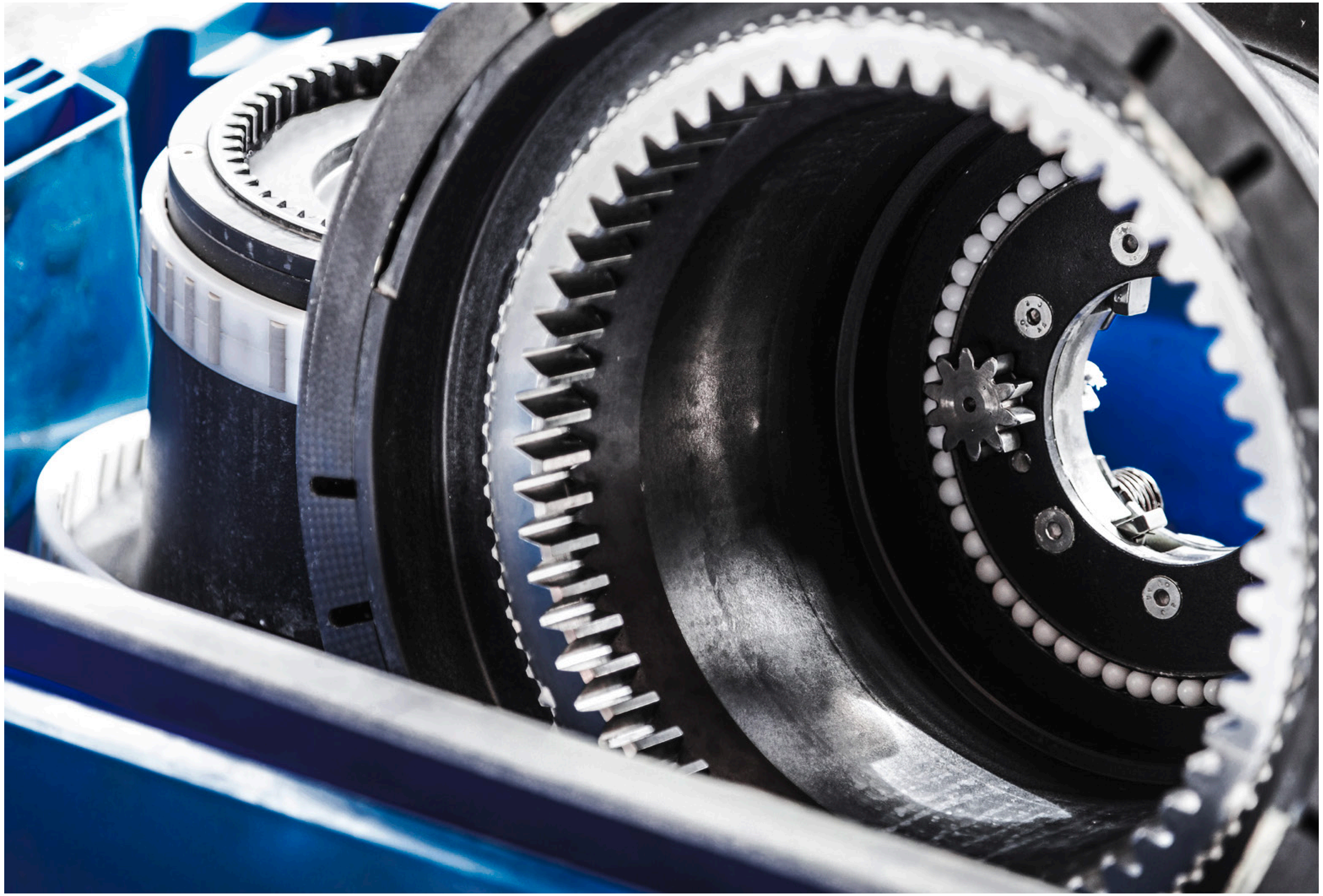

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Table 7.4.B Typical gear oil formulations (weight % treat rates)

		Conventional PAO		SpectraSyn Elite™ 65 mPAO		SpectraSyn Elite™ 150 mPAO		SpectraSyn Elite™ 300 mPAO
Component, wt.%		ISO VG 220	ISO VG 320	ISO VG 220	ISO VG 320	ISO VG 220	ISO VG 320	ISO VG 320
SpectraSyn™ 6 PAO		8.5		17.5		35.4		36.7
SpectraSyn™ 8 PAO			28.2		7.2		29.4	
SpectraSyn™ 40 PAO		80						
SpectraSyn Elite™ 65 mPAO				71	81.3			
SpectraSyn™ 100 PAO			60.3					
SpectraSyn Elite™ 150 mPAO						53.1	59.1	
SpectraSyn Elite™ 300 mPAO								51.8
Synesstic™ 5 AN		10	10	10	10	10	10	10
Additive package*		1.5	1.5	1.5	1.5	1.5	1.5	1.5
Property	Test method	ISO VG 220	ISO VG 320	ISO VG 220	ISO VG 320	ISO VG 220	ISO VG 320	ISO VG 320
KV @40°C, cSt	ASTM D445	222.8	332.6	220.3	324.9	221.6	326.6	319.6
KV @100°C, cSt	ASTM D445	25.7	36.8	29.8	40.0	29.0	39.4	42.72
Viscosity index	ASTM D2270	147	159	176	176	170	173	190
Pour point, °C	ASTM D97/D5950	-48	-45	-54	-51	-54	-51	-54
Flash point, °C	ASTM D92	234	232	230	236	230	236	
Brookfield @-40°C, cP	ASTM D2983	325,000	536,000	147,000	285,000	143,000	281,000	197,000
RPVOT, minutes	ASTM D2272	353	279	383	330	461	437	353
Air release @75°C, min	ASTM D3427	10.4	16.4	5.0	5.7	4.8	5.8	
4 ball wear scar, mm	ASTM D4172	0.48	0.50	0.50	0.48	0.48	0.47	0.52
4 ball EP weld point, kg	ASTM D2783	315	315	315	250	250	250	
4 ball wear, LWI	ASTM D2783	58.0	61.0	58.0	49.0	49.0	49.0	

*The additive package meets or exceeds the requirements of:
US Steel 224
AGMA 9005
GM LS-2 Specification for EP gear oils
Source: ExxonMobil data

Modern gearboxes, which are designed with lower capacity sumps and are subject to higher operating temperatures, often favor the use of fully synthetic gear oils. These oils not only extend the time between oil changes due to superior resistance to oxidation but can also withstand unusually high temperatures during operational cycles and extremely low temperatures.

Metallocene PAOs are well known for their ability to keep lower formation of foam compared to conventional PAOs even in the case of defoamant depletion. Usage of polyol esters is giving optimal solubility of the additive package and extra cleanliness benefits in terms of deposits formation.

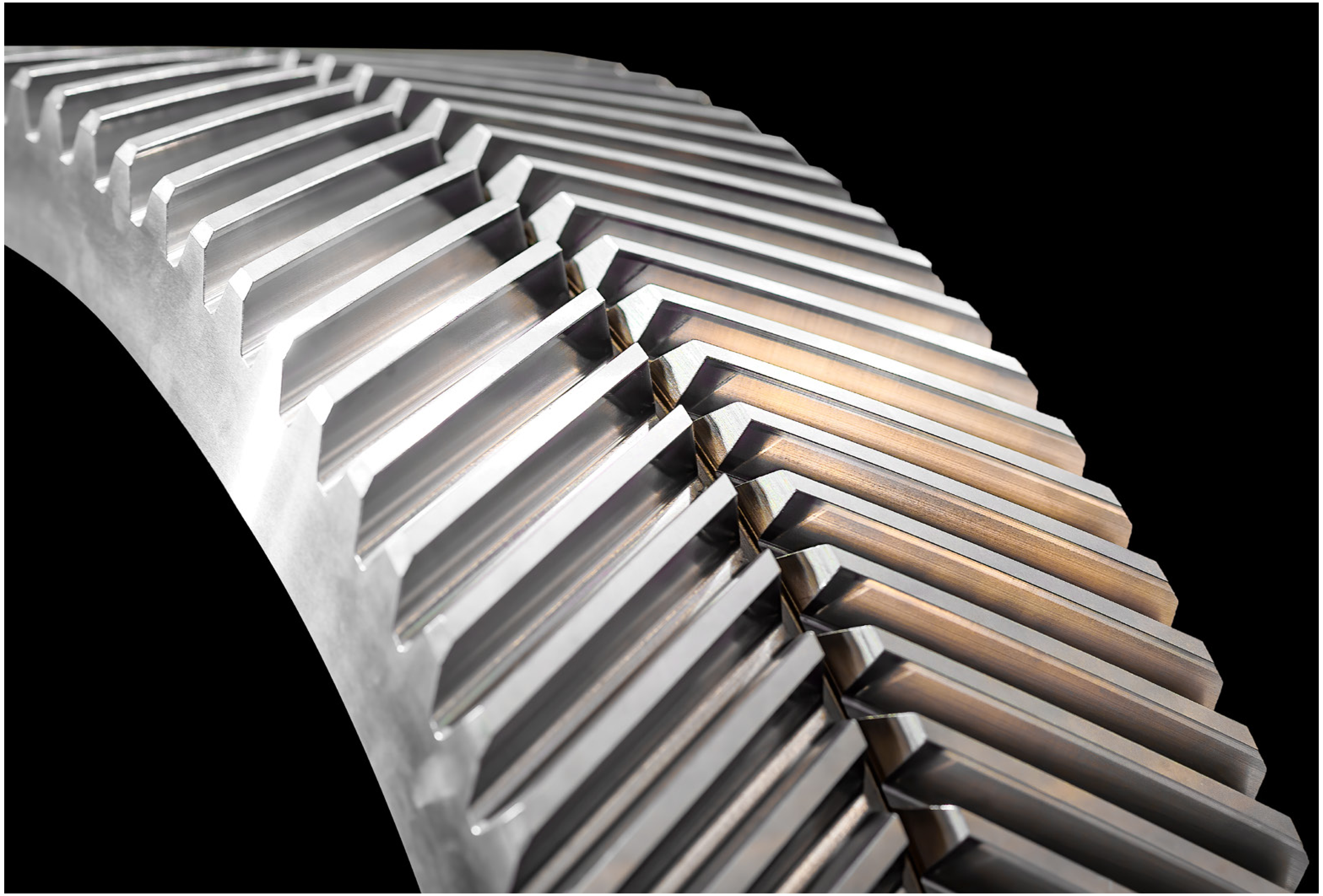

Table 7.4.C Fully synthetic gear oil formulations with key industrial claims

Component, wt.%		ISO VG 150	ISO VG 220	ISO VG 320	ISO VG 460	ISO VG 680
SpectraSyn™ 6 PAO		36.57	26.67	17.77	8.67	0
SpectraSyn™ Elite 150 mPAO		46.1	56	64.9	74	82.67
Esterex™ NP343 ester		15	15	15	15	15
Additive package*		2.33	2.33	2.33	2.33	2.33

Property	Test method	ISO VG 150	ISO VG 220	ISO VG 320	ISO VG 460	ISO VG 680	DIN 51517-3 limit	Flender AS 7300 rev. 16 limit	ISO 12925-1 CKD limit
KV @40°C, cSt	ASTM D445	152.37	224.36	324.35	474.29	694.5			
KV @100°C, cSt	ASTM D445	22.64	31.26	42.13	57.66	79.01			
Viscosity index	ASTM D2270	177	182	186	191	197	90 min		
Flash point, °C	ASTM D92	245	257	251	245	261	200 min		200 min
Pour point, °C	ASTM D97	-48	-48	-45	-45	-36	9 max		9 max
Foam tendency/stability, ml/ml	ASTM D892	0/0	0/0	0/0	0/0	0/0			100/0
Air release @75°C, min	ASTM D3427	<0.5	1.4	<0.5	3.2	3.2			
Flender foam, volume increase after 1min (total volume), ml	ISO 12152	2	4	5	6	7	15 max	15 max	15 max
Flender foam, volume increase after 5 min (oil-air dispersion), ml	ISO 12152	0	1	1	2	2	10 max	10 max	10 max
Demulsibility @82°C, min	ASTM D1401	15	20	25	40	60	30/45/60 max		
Copper corrosion, 3h @100°C	ASTM D130	1b	1b	1b	1b	1b	1 max		1 max
Rust test, procedure A	ASTM D665	Pass	Pass	Pass	Pass	Pass	Pass		Pass
Rust test, procedure B	ASTM D665	Pass	Pass	Pass	Pass	Pass	Pass		Pass
S-200 oxidation, 312h @95°C, viscosity increase @100°C, %	ASTM D2893	0.83	3.23	1.42	2.37	-1.23	6 max		6 max
S-200 oxidation, 312h @95°C, precipitation number, ml	ASTM D2893	<0.05	<0.05	<0.05	<0.05	<0.05	0.1 max		0.1 max
FZG scuffing load, A/8/3/90	ISO 14635-1	>12	Read across from ISO 150	Read across from ISO 150	Read across from ISO 150	Read across from ISO 150	12 min	12 min	12 min
FAG FE8, 7.5 rpm, 80kN axial load, 80°C, 80 hours, weight loss rollers, mg	DIN 51819-3	6.6	6.7	4.3	3	2.2	30 max		30 max

*Additive package is defined in the solution to endure the industrial claim approval, please contact ExxonMobil representative to understand more.

Source: ExxonMobil data

7.5 Paper machine oils

Application and equipment

Modern paper machines are generally split into two main sections — the "wet end" and the "dry end." Pulp preparation, paper forming, and initial pressing are carried out in the wet end. As the paper moves through this section of the process, the moisture content decreases from about 99% to approximately 50% after pressing. A wet-end oil system may contain up to 25,000 L of oil. Significant contamination of the oil can occur in this area.

The paper then travels through the dryer section, where the remaining moisture is removed using steam-heated rollers. Roller temperatures typically reach 130 to 190°C, but the final drying section, called the "calendar," can reach up to 280°C and may use a heat-transfer oil system to heat the rollers. The dryer section may hold up to 40,000 L of oil. These machines are expected to operate for about 10 to 15 years, with only a few days per year of planned shutdowns. Typical oil life is about four to five years for the dry end, with a longer period expected for the wet end.

Although there are efforts to use a single oil grade, at least between wet and dry sections, several grades are typically required for one paper machine. Lubrication of plain bearings, roller bearings, and gearboxes is maintained using ISO VG 220 oil; roller hydraulics may require an ISO VG 100, while the hydraulic control system actuators may require ISO VG 46 oil.

At the dry end, the higher temperatures usually dictate the use of synthetic oil, generally with higher viscosities. The main lubrication system, therefore, may use ISO VG 220 or ISO VG 320 oil, while the hydraulic systems may require ISO VG 68 oil. In super calendar sections, ISO VG 1000 oils may also be required.

Oil cleanliness is especially important on paper machines, and avoiding deposit formation is critical. On a typical machine, there may be over 500 individual lubrication points where the oil flow is controlled through flowmeters. Dark oxidized oil and deposit formation can prevent the flowmeters from being read and adjusted correctly, which may result in a bearing failure.

Thus, synthetic lubricants are particularly effective in the circulating systems of paper machines, where they perform well at the high operating temperatures normally found in the dryer sections of paper machines. In the wet section of the paper machine, the lubricant must be particularly resistant to contamination by water, acidic solutions, and to process chemicals used in the paper-making process.

As with most other industrial applications, increasing production rates and efficiency improvements increase the stress on the lubricant.

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Common trends include the following:

- Higher bearing loads and operating temperatures
- Reduced oil volumes
- Reduced top-up from leaks
- Increased use of Group II and III base stocks over Group I
- Move to zinc-free oils
- Increased process water recycling, leading to higher compatibility issues
- Conflicting requirement for increasing EP capability, but at reduced EP additive levels
- More advanced hydraulic control systems with fine filtration

Paper machine oil must meet the minimum performance levels of the specifications provided by the principal paper machine builders. Air release, foaming, and demulsibility are key parameters, as is anti-wear (or mild EP) protection. Typically, the anti-wear performance is dictated by tests developed by the principal bearing manufacturers (SKF and FAG).

The two main builder specifications come from Voith and Metso:

- Voith specification VN 108
- Wet end: ISO VG 150, CL 150 DIN 51517-2, FAG FE 8 wear ≤20
- Dry end: ISO VG 220, CL 220 DIN 51517-2, SKF PM oil test, FAG PM oil test
- NipcoFlex: zinc-free hydraulic oil meeting DIN 51524- 2

Metso has general specifications that cover paper machine circulation oils, zone-controlled rolls and solid rolls.

Lubricant requirements

Paper-machine lubricants are premium lubricants formulated to perform dependably under the hot, wet degradation conditions of paper-machine operation. The oil must have a high resistance to oxidation and thermal decomposition, potent detergency to prevent deposit buildup on hot surfaces and excellent demulsibility and rust protection. It also must be readily filterable through filters with porosity as fine as six microns.

These features, derived from a careful blending of additives and high-quality base stocks, are essential to extending equipment life and reducing costly unscheduled downtime.

Advantages of synthetics

Synthetics are ideally suited for use in paper machine applications, and PAO-based formulations are widely used. Esters are typically used in combination with PAO to provide additive solubility and seal swell. Replacing the ester with Synesstic™ AN provides improved hydrolytic stability and boosts the overall oxidation stability and lubricity of the formulation.

Formulation data

Table 7.5.A PAO/AN base oil blends (weight %)

Component, wt.%	ISO VG 68	ISO VG 100	ISO VG 150	ISO VG 220	ISO VG 320	ISO VG 460
SpectraSyn™ 6 PAO	58	48	37	26	16	6
SpectraSyn™ 100 PAO	22	32	43	54	64	74
Synesstic™ 5 AN	20	20	20	20	20	20

Higher grades can be optimized using different grades of SpectraSyn Elite™ mPAO, which improves the viscosity index and may help wear protection. Synesstic™ 12 AN may be substituted for Synesstic™ 5 AN to improve viscometrics at the expense of reduced solubility.

Where mineral or semi-synthetic oils are being developed, the use of Synesstic™ 5 AN can aid with solubility and help to improve resistance to oxidation and hydrolysis.

Additive requirements

A typical paper machine lubricant formulation could contain a total of 0.5 to 6% of the following additives, with the remainder, depending on the viscosity grade, being the base stocks in the ratios shown in Table 7.5.A:

- Anti-wear
- Oxidation inhibitor
- Defoamant
- Demulsifier
- Rust and/or corrosion inhibitor
- Friction modifier

7.6 Lubricants for use with food machinery (incidental food contact)

Application and equipment

Machinery used in food manufacturing processes can face severe operating conditions, such as temperature extremes in bakery ovens and freezer operations. The machinery undergoes frequent washdowns and cleaning, which exposes it to water ingress and corrosion.

Typical lubricant applications, such as hydraulic systems, gearboxes, greased bearings, air compressors, vacuum pumps and heat transfer systems, are part of food-manufacturing processes. Specialized applications, such as canning and seaming, have equipment and oven chains that also need to be lubricated.

Most food manufacturers now use "food-grade" lubricants, which are formulated from specifically approved base oils and additives.

These lubricants are designed to minimize health risks to consumers in the event of incidental contact with food (refer to NSF registration classifications).

The market for "food-grade" lubricants is growing. The increasing demand for food, especially in Asia, is leading to the growth of large, mechanized food processing plants, replacing local manual operations. Increasing legislation, global harmonization and demand for high-performance lubricants in these plants encourages the use of food-grade lubricants.

Modern "food-grade" lubricants, notably those based on synthetic oils, offer performance comparable to conventional mineral oil-based grades. Additionally, their excellent performance allows companies to use these lubricants on a broad range of machinery beyond food-processing equipment. This reduces the number of lubricants in stock and minimizes the risk of cross-contamination.

With the growing demand for "food-grade" lubricants, more manufacturers are producing these types of lubricants. Consequently, the selection of suitable additives and base stocks for the industry is expanding including the synthetic oils.

Until 1998, the United States. Department of Agriculture (USDA) had a program that reviewed and approved incidental food contact lubricants based on criteria set by the United States Food and Drug Administration (US FDA) under 21CFR 178.3570 (Code of Federal Regulations). With the cancellation of the USDA program, companies had to ensure their products comply with US FDA regulations and self-certify their food machinery lubricants.

In 1999, NSF International took over the activities of the USDA program. NSF, an accredited third-party certification body, tests and certifies products to ensure they meet public health and safety standards. NSF administers a registration system for nonfood compounds, including lubricants for incidental food contact. Lubricant suppliers, whose products meet US FDA regulations, register with NSF, and these products are listed in the NSF "White Book™" (Nonfood Compound Listings). Registered products must display an official registration mark and include a category and registration number on their labels to indicate compliance. NSF registration is widely accepted as an industry standard globally.

Definitions

From a regulatory standpoint, the following definitions apply to products in the food industry:

Direct contact: situations where a substance, such as a lubricant, comes into direct contact with food during processing or packaging. This requires the lubricant to meet stringent safety and health standards to ensure it does not contaminate or alter the food.

Indirect contact: substances that come into contact with food as part of packaging, holding, or processing, but are not intended to be added directly to the food. These substances may inadvertently become part of the food due to their use in manufacturing, packaging or handling.

Incidental contact: unintended or occasional contact with food products during the food processing cycle. This contact is limited to a trace amount, not exceeding 10 parts per million (ppm). Incidental contact lubricants are specifically formulated to be safe and do not compromise food safety. To that end, all ingredients in these lubricants must comply with US FDA regulations, specifically 21CFR 178.3570, which lists approved chemical compounds and additives. The lubricant formulation is reviewed by NSF to ensure it is odorless, colorless and tasteless.

NSF registration classifications

For finished lubricants, there are a number of classifications that can be applied:

- H1 and HX-1: lubricants (H1) and their components (HX-1) that could have incidental contact with food
- HT-1 and HTX1: heat transfer oils (HT-1) and their components (HTX1) that could have incidental contact with food
- H2 and HX-2: lubricants (H2) and their components (HX-2) that have no possibility of contacting food (the majority of lubricants and additives in use would fall into this category)
- HT-2 and HTX2: heat transfer oils (HT-2) and their components (HTX2) that have no possibility of contacting food
- H3 and HTX3: soluble oils (H3) and ingredients for soluble oils (HTX3) applied to certain equipment elements in contact with food to clean them and provide rust protection

Lubricant requirements

Incidental food contact lubricants should be colorless, odorless and tasteless. They need to have good water resistance and provide good corrosion protection. They should provide good oxidation resistance under severe high-temperature applications and provide good anti-wear properties. Highly refined mineral oils, PAOs, ANs, esters and polyglycols can all be used as the base oil for these lubricants, provided they meet the applicable regulatory requirements.

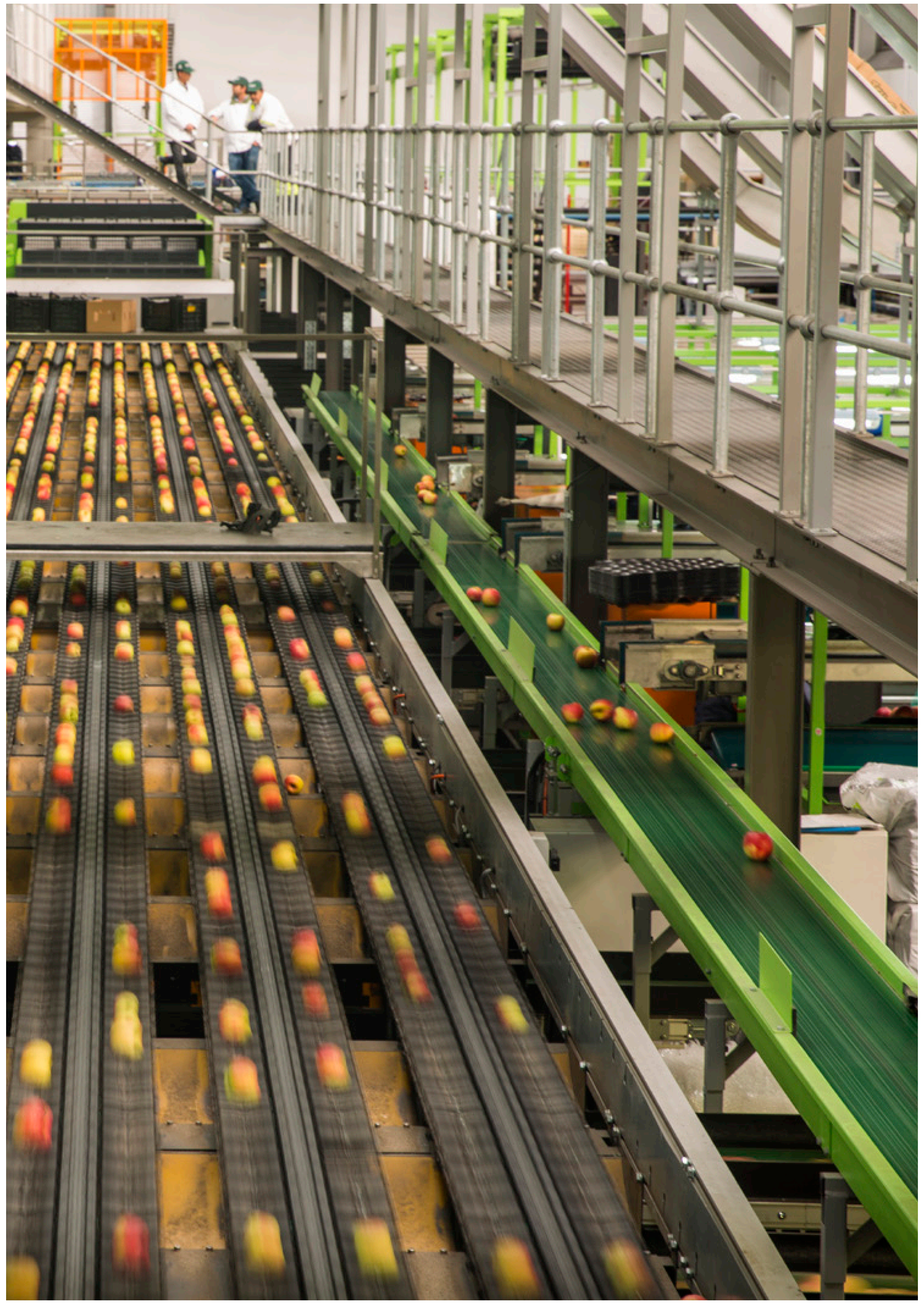
Advantages of synthetics

For long life and wide operating ranges, fully synthetic products are recommended. In addition to improved oxidation stability, PAO- based formulations offer two additional advantages over standard mineral oil-based grades:

- Very low pour points and high viscosity indices, offering a wide operating temperature range
- Lower traction forces, which offer the opportunity for energy savings, particularly in gearbox applications

SpectraSyn™ PAO (see Table 3.0.A) base stocks meet the requirements for a technical white mineral oil, 21CFR 178.3620(b), and are listed in the NSF "White Book™" as an H1 lubricants for incidental food contact.

Synesstic™ 5 AN and Synesstic™ 12 AN, as well as SpectraSyn Elite™ 65 mPAO and SpectraSyn Elite™ 150 mPAO base stocks are also listed in the NSF "White Book™" within category codes H1 and HX-1 as lubricants or components for lubricants for incidental food contact.



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Formulation data

Table 7.6.A PAO base stock formulations (weight %) (base oil only — calculated, no additives)

ISO viscosity grade	32	46	68	100	150	220	320	460
SpectraSyn™ 6 PAO	100	10		55	38	23	8	
SpectraSyn™ 8 PAO		90						
SpectraSyn™ 10 PAO			100					
SpectraSyn™ 40 PAO				45	62	77	92	88
SpectraSyn™ 100 PAO								12

Synesstic™ AN can also be used at around a 5% treat rate to provide additive solubility and seal swell capability for the PAO.

The use of Synesstic™ AN at higher treat rates will improve the thermal and oxidation stability as well as reduce the hydrolytic stability problems often encountered with esters. Solubility for additives and oxidation products (sludge formation) will also be improved.

Additive requirements

A typical food-grade formulation would contain a total of 0.5 to 5% of the following additives, with the remainder depending on the viscosity grade, being the base stocks in the ratios shown in Table 7.6.A:

- Oxidation inhibitor
- Rust and/or corrosion inhibitor
- Defoamants
- Metal deactivators and anti-wear
- A tackifier may be used to reduce dripping

Typical formulations

The following formulations could be used to make an incidental food contact hydraulic or gear oil.

Table 7.6.B Typical formulations

ISO VG 46 food-grade hydraulic oil	wt.%
SpectraSyn™ 6 PAO	84
SpectraSyn™ 100 PAO	11.5
Additive package*	4.5
ISO VG 220 H1 gear oil	**wt.%**
SpectraSyn™ 6 PAO	19.5
SpectraSyn™ 40 PAO	76
Additive package*	4.5

*Additive package meets the requirements for incidental food contact lubricants as per 21CFR 178.3570 and NSF HX-1.

Other additive packages that meet the requirements for incidental food contact lubricants are also available.

Possible upgrades to these formulations would include the use of Synesstic™ AN for added hydrolytic stability and additive solubility, and/or SpectraSyn Elite™ mPAO for improved film thickness and low-temperature properties.

Supporting test data can be found in Table 7.6.C.

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Table 7.6.C ISO VG 46 hydraulic oil formulations meeting requirements for incidental food contact

Property	Test method	Mineral base stocks	PAO base stocks	PAO/15% Synesstic™ 5 AN*
Kinematic viscosity @40°C, cSt	ASTM D445	48.6	45.4	45.9
Kinematic viscosity @100°C, cSt	ASTM D445	7.2	7.6	8.0
RPVOT, minutes	ASTM D2272	571	1,063	1,218
Thermal stability	ASTM D2070			
CU/Steel appearance		8/7	10/10	8/8**
Sludge, mg/100 ml		34.1	43.6	15.5**
Cincinnati Milacron	Thermal Stability Procedure A***			
Cu/Fe appearance		5/2	10/10	8/8
Cu/Fe deposit, mg		5.9/2.3	8.9/6.5	3.6/3.2
Total sludge, mg		41.1	43.6	9.2
Initial/final viscosity, cSt		48.6/50.0/213.8	45.3/46.5	47/47.29
% Viscosity change		2.84	2.55	0.62
Initial/final TAN		0.67/0.32	0.50/0.30	0.71/0.41
4 ball wear (167F, 1,200 rpm, 40kg)	ASTM D4172			
Scar diameter, mm		0.37	0.40	0.35

*ExxonMobil Chemical test results — single sample results unless indicated.

**Average of two test results.

***This procedure was adopted from the Fives Cincinnati Thermal Stability Test Procedure "A", Fives Cincinnati Manual 10-SP-89050.

The test results are typical values and are not intended to be specifications.

Source: ExxonMobil data

7.7 Miscellaneous lubricants

7.7.1 Heat-transfer oils

Application and equipment

Heat-transfer fluids are designed for use in circulating, liquid phase, heating, and cooling systems. They provide a circulating medium that absorbs heat in one part of a system (e.g., a solar heating system or a remote oil-fired system) and releases it to another part of the system. In properly designed systems, heat-transfer fluids will perform within their respective temperature ranges for extended periods without breakdown or corrosion. Heat-transfer fluids require high resistance to cracking (molecular breakdown) when used at temperatures above 260°C (500°F). Available in various types and operating ranges, these fluids provide benefits such as economy, efficient operation, minimum maintenance and precise temperature control.

Heat-transfer systems can be either closed or open to the atmosphere. To prevent oxidation in a closed system, an inert gas can be used in the expansion tank (or reservoir) to exclude air. If the system is open and the fluid is exposed simultaneously to air and to temperatures above 66°C (150°F), the fluid must also have good oxidation stability since a protective gas blanket cannot be contained.

The basic underlying technology for heat-transfer systems has remained unchanged for some time. More complex control systems have been developed to provide efficient control of the heat-transfer system. Energy efficiency and compliance with environmental regulations are key focus areas.

Lubricant requirements

Heat-transfer fluids tend to be categorized into three main types:

- Mineral- or synthetic hydrocarbon-based fluids (commonly called "hot oils") are essentially base oils perhaps containing some antioxidant additive. Almost any API base-oil category can be used (Group I to IV). This type represents the most widely used category of heat-transfer oils.
- Synthetic aromatic fluids are mainly aromatic fluids based on benzene, with the three main types being polyphenyl, alkylated benzenes and diethyl benzene.
- Specialty fluids, including silicone and fluorocarbon fluids.

Heat-transfer fluids need to be matched to the particular system in which they will operate. The properties of the fluid will define the thermal efficiency and safety of the system.

One of the most important parameters is the bulk-temperature rating, which is the temperature at which the fluid can operate for long periods without significant deterioration. A fluid with excellent thermal stability is required for most applications. The hydrocarbon fluids tend to be used up to a maximum of around 300°C, the aromatic products up to around 350°C (depending on the type) and the specialty products offer either higher operating temperatures or specific features such as dielectric properties or low toxicity.

Low-viscosity fluids (ISO VG 22-32) are typically used to meet pumping requirements when the system is cold.

Low vapor pressure is important to prevent the fluid from boiling. The vapor formation can cause subsequent pump cavitation.

Specific heat capacity and specific gravity properties across the operating temperature range help define the pump size and flow rates.

ASTM D5372 provides guidelines for testing the quality and condition of hydrocarbon heat-transfer fluids used in closed systems.

Advantages of synthetics

For longer life and wider operating ranges, fully synthetic products are recommended. In addition to being more oxidatively stable, PAO-based formulations offer two additional advantages over conventional mineral-oil-based grades:

- PAO base stocks have very low pour points and high viscosity indices, so they can be used for both cooling and heating. The low viscosity at a low temperature allows pump flows to be maintained.
- PAO base stocks can be used where incidental food contact lubricants are required because they meet the demand for a technical white mineral oil in 21 CFR 178.3620(b) and are listed in the NSF "White Book™," category code H1 (lubricants for incidental food contact).

The performance of PAO-based formulations could be boosted by using a percentage of Synesstic™ 5 AN (typically @ 15-30% treat rate) to provide a boost in oxidation and thermal resistance.

Synesstic™ AN is a synthetic aromatic fluid with higher thermal and oxidation stability than PAO. Synesstic™ 5 AN can be used as the base fluid alone with a small amount of selected SpectraSyn™ PAO or Esterex™ ester to provide viscosity adjustment.

Low vapor pressure is important to prevent the fluid from boiling. The vapor formation can cause subsequent pump cavitation.

Specific heat capacity and specific gravity properties across the operating temperature range help define the pump size and flow rates. ASTM D5372 provides guidelines for testing the quality and condition of hydrocarbon heat-transfer fluids used in closed systems.

Formulation data

Table 7.7.A PAO base stock formulations (weight %) (base oil only – calculated, no additives)

Component, wt.%	ISO VG 10	ISO VG 15	ISO VG 22	ISO VG 32	ISO VG 46
SpectraSyn™ 2 PAO	50	20			
SpectraSyn™ 4 PAO	50	80	70		
SpectraSyn™ 6 PAO			30	100	90
SpectraSyn™ 8 PAO					10

Table 7.7.B PAO/AN base stock formulations (weight %) (base oil only – calculated, no additives)

Component, wt.%	ISO VG 10	ISO VG 15	ISO VG 22	ISO VG 32	ISO VG 46
SpectraSyn™ 2 PAO	59	20			
SpectraSyn™ 4 PAO	21	60	60		
SpectraSyn™ 6 PAO			20	80	
SpectraSyn™ 8 PAO					80
Synesstic™ 5 AN	20	20	20	20	20

Table 7.7.C AN/PAO base stock formulations (weight %) (base oil only – calculated, no additives)

Component, wt.%	ISO VG 10	ISO VG 15	ISO VG 22	ISO VG 32	ISO VG 46
Synesstic™ 5 AN	35	60	85	100	88
SpectraSyn™ 2 PAO	65	40	15		
SpectraSyn™ 100 PAO					12

Additive requirements

A typical heat-transfer fluid formulation would contain a total of 0.5 - 2% of the following additives, with the remainder depending on the viscosity grade, being the base stocks in the ratios shown in the tables above:

- Oxidation inhibitor
- Rust or corrosion inhibitor
- Defoamant

7.7.2 Chain lubricants

Application and equipment

Industrial chains are used to transmit power in a wide variety of applications and often work under high-temperature conditions. Large chains are mainly used in conveyor systems and can be found in many industries, including textiles, automobile manufacturing, pottery and glass making (in kilns), plastic film, fiberglass insulation and in food processing (ovens).

Lubrication is vital to maintaining the life of a chain. Without lubrication, accelerated wear causes erratic operation, loss of timing, increased friction and higher power consumption. The most challenging lubrication applications involve severe heat from ovens (e.g., high-temperature conveyors). Many such chains are used in food manufacturing processes, such as bakeries, slaughterhouses and others where the use of incidental food contact lubricants is preferred.

Lubricant requirements

Chain lubrication is a difficult application because, in most cases, the components are continuously operating under boundary conditions due to low speed and oscillating conditions. The lubricant needs to penetrate between the links and pins that make up the chains and provide a protective film between the internal surfaces. With roller chains, the lubricant must also lubricate the outer surface where the rollers mesh with the drive sprockets.

The oil requirements are conflicting in that light viscosity is required to penetrate the components, but high viscosity is required for film-forming and EP properties. Consequently, solid lubricants such as graphite or molybdenum disulfide are often blended into chain lubricants. These additives provide load-carrying capacity and a backup lubricant film in case the supply of lubricant is interrupted.

For very high temperatures (above ~260°C), solid-film lubrication is used almost exclusively since liquid lubricants can rapidly disappear through evaporation. In these cases, a liquid carrier is used to carry the solid lubricant into the load zone. The liquid carrier then evaporates (smokeless and odorless products are preferred), leaving behind the solid lubricant. The lubricant can be applied in different ways depending on the speed and application. At low speed (<6 m/s), the lubricant can be applied by a brush or drip feed. At medium speed (6-12 m/s), an oil bath can be used and at high speed (>12 m/s), the oil is sprayed onto the chain.

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Advantages of synthetics

Synthetic-based oils are commonly used for high-temperature applications (e.g., above 120°C) and need to be able to handle conditions as high as 260°C.

PAO-, ester-, and AN-based synthetic fluids can be effectively used for industrial chain lubrication in "hot" applications. Typically, these synthetic fluids are formulated with polyisobutene (a thickening agent) and additives. The additives can be ashless or ash-containing (generally some combination of the two). Esterex™ esters that can be used for "hot" applications include adipates and trimellitates, in combination with PAOs, which provide a more stable alternative to polybutenes. Use of the Esterex™ polyol esters or Synesstic™ AN should lead to improved oxidative and thermal stability.

SpectraSyn™ PAO, SpectraSyn Elite™ mPAO and Synesstic™ AN products are recommended for incidental food contact applications — see Section 7.6.

Formulation data

Table 7.7.D Base stock formulations with PAO/ester

Component, wt.%	ISO VG 68	ISO VG 100	ISO VG 150	ISO VG 150	ISO VG 220	ISO VG 320
Esterex™ TM111 ester			87		52	
Esterex™ NP343 ester	69	60		50		41
SpectraSyn™ 40 PAO			13		48	
SpectraSyn™ 100 PAO	31	40		50		59

Table 7.7.E Base stock formulations with PAO/AN

Component, wt.%	ISO VG 68	ISO VG 100	ISO VG 150	ISO VG 150	ISO VG 220	ISO VG 320
Synesstic ™ 12 AN	45	90	75	87	45	55
SpectraSyn™ 8 PAO	55	10				
SpectraSyn™ 40 PAO			25		55	
SpectraSyn™ 100 PAO				13		45

Additive requirements

A synthetic oven chain oil formulation would contain a total of 0.5 to 6% of the following additives, with the remainder, depending on the viscosity grade, being the base stocks in the ratios shown in Table 7.7.E:

- Extreme pressure anti-wear
- Oxidation inhibitor
- Detergent
- Corrosion passivator
- Friction modifier*
- Defoamant

*Optional, application dependent

8.0 Lubricating greases

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8.0 Lubricating greases

Derived from the Latin word "crassus," meaning "fat,"[6] a grease is traditionally described as a three-dimensional matrix of thickener particles with the spaces in the matrix filled with a lubricating oil — like a sponge. As the matrix is compressed under load, the oil is released to provide its lubricating function.

The films that separate moving surfaces are a combination of the thickener and lubricant, and it is the properties arising from the combination of thickener and oil that make grease so useful.

Because of the thickeners, greases generally remain in place upon application. The thickener acts as a seal, keeping oil in and contamination out. This has the corresponding negative effect of keeping internal wear debris within the grease matrix. However, the fact that the grease remains in place is vital to helping reduce the effects of corrosion, especially on standby equipment where oil films drain away. Grease lubrication also has advantages for noise reduction and in its ability to deal with shock loading.

The lack of fluidity reduces the grease's ability to provide a cooling function, but in many applications, temperatures are relatively low and cooling can be implemented through suitable design features (e.g., electric motor fans). Semi-fluid greases act like thick oil. These materials will flow under gravity (slump) and will splash because of mechanical motion. This behavior helps with heat transfer, and the materials retain the ability to provide a sealing function.

Compared to oils, greases require less maintenance, and even when replenishment is required, this can be achieved automatically, either individually for each bearing or via a centrally pumped multiple-discharge system.

Greases are used in the temperature range from –70°C to 350°C and are used to lubricate machine elements such as antifriction and plain bearings, gears, slideways, joints, and other equipment. Greases can also act as sealants or corrosion protection products.

In general, the benefits of grease lubrication far outweigh the disadvantages, and due to their versatile properties, they are used in practically all areas of industry to solve lubrication problems that cannot be solved using lubricating oils. It is, therefore, no surprise that between 80 and 90% of all rolling-element bearings are now grease-lubricated.[7]

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6 Retrieved August 5, 2024 from Encyclopedia.com: http://www.encyclopedia.com/doc/1O27-grease.html.

7 A. Begg, "SKF Lubricant grease knowledge and sustainability," Keynote speech, ELGI 2009.

Thickeners

Thickeners are used to create a three-dimensional matrix to hold the lubricant. The final properties of the grease can be adjusted by using different types of thickeners. There are many different options, each offering certain advantages and/or disadvantages. Thickeners are generally classified as soap-based (e.g., lithium, sodium or calcium) or non-soap-based (clay or polymer). The thickener needs a good affinity with the lubricant and the ability to create a stable matrix with a uniformly dispersed lubricant.

The thickener, often thought of as merely a "sponge," actually has an extremely difficult balancing act. Thickeners require the following properties and features:

- Mechanical and thermal stability
- Ability to flow at low temperatures
- Ability to hold the lubricant in its structure but allow some oil bleed at all temperatures
- Affinity for the surface, to remain in place even under difficult conditions such as high-pressure water spray
- Ability to protect the surface from the environment while not interfering with the surface-active additives
- Ability to provide part of the lubricant film thickness under elastohydrodynamic (EHD) lubrication conditions[8]

For the general market, traditional soap-based thickeners are still popular. However, for the high-performance market, high-temperature thickeners such as lithium complex, calcium complex, clay and polyurea thickeners are being used, with the latter becoming very popular in the electric motor bearing market.

Although many greases in the general market are still based on lithium soaps, lithium complex thickeners are becoming popular because they offer the ability to create high-performance, multipurpose greases. For electric motor bearings requiring long life at relatively high operating temperatures and low loads, polyurea thickeners have also become very popular. With increasing temperatures, polyurea thickeners combined with synthetic base oils seem to offer extended grease life.[9]

As the operating conditions for equipment increase in severity (i.e., higher speeds, loads and temperatures), the performance requirements from equipment builders become more stringent. Consequently, the properties of the lubricant grease need to improve to maintain acceptable performance. These greases must provide the lubricated component with longer service life and extended re-lubrication intervals to reduce maintenance costs.

In addition to the normal lubricating applications, greases may also need to be formulated to be biodegradable or suitable for incidental food contact.

Lubricant requirements and grease selection

In selecting a grease base-oil viscosity, the oil film thickness at the operating temperature of the application must be considered. Typically, low-viscosity oils are required for high-speed applications, while high-viscosity oils work best for slow and highly loaded applications.

At high temperatures, the thickener structure can break down, and the grease becomes more fluid-like, losing its ability to remain in place.

This property is measured by the grease dropping point. The choice of thickener is typically based on the expected service temperature.

The typical maximum service temperature for lithium soap-based grease is 135°C, while lithium complex mineral oil greases might operate up to 175°C.[10] Although the thickener may operate at these temperatures, the base oil will be affected by oxidation, and relubrication intervals may be short. Replacing the mineral oil with synthetic base oil would help either increase the maximum service temperature or extend the relubrication intervals due to the better thermal and oxidative stability of the oil.

Another important feature is mechanical stability. The thickener structure can be subjected to significant shear in service, especially in rolling-element bearings and gears. This can damage the structure and result in a loss of consistency and a general softening of the grease.

8 P.M. Cann, "The influence of Temperature on the Lubrication Behaviour of Lithium Hydroxystearate Grease," 5th Annual ELGI Conference Budapest 1994.

9 A. Kemble, "Evaluation of Industrial Bearing Grease Performance," Eurogrease 1998, July/August.

10 Machinery Lubrication: www.machinerylubrication.com/Read/30674/high-temperature-lubricants .

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Grease thickeners should have good mechanical stability, as measured by the extended grease worker test (ASTM D217) or the roll stability test (ASTM D1831), which tries to simulate the stress experienced by the grease in an application.

Centralized distribution systems are often used to deliver grease to equipment in an application. In these systems, slumpability and pumpability are important factors. Good slumpability is achieved when the consistency of the grease is low enough for the grease to slump into the bottom of its container or tank and reach the pump inlet.

This allows it to be transferred to the distribution lines. If the grease is too stiff, it will not slump and the pump will run dry. Pumpability is a measure of the grease flow rate. In general, pumpability improves with softer grades of grease. Synthetic greases also tend to have better pumpability at low temperatures due to the better low-temperature fluidity of the base oils.

Another important factor is oil separation. If the thickener does not flow well in the distribution system, the oil can separate from the thickener, which results in the grease becoming firmer and clogging the distribution pipes.

In some applications, good water resistance is required to prevent the grease from being washed away.

Polymer additives and/or high-viscosity base oils may be used in this case to provide a degree of tackiness.

Advantages of synthetics

Synthetic base oils can offer significant benefits over conventional mineral base oils in lubricating greases. The potential benefits of synthetic base oils can include:

- Wider operating temperature range through better high- and low-temperature properties
- Longer life and reduced deposit formation through improved oxidation resistance and lower volatility at high temperatures
- Improved flow and lower bearing torque at low temperatures
- Energy savings, with higher VI base oil or oils with reduced traction
- Improved wear protection through thicker oil films or improved oil film formation
- Potential biodegradability and/or low toxicity
- The ability to make incidental contact food-grade lubricants

Of all the synthetic base oils, PAOs have a long history of use in greases (>40 years) and are probably the most widely used. The reasons for this include the following:

- Wide range of viscosities (2- 300 cSt @100°C)
- Wide operating temperature range
- Good oxidative stability when inhibited with antioxidants
- Low traction coefficients offering energy savings
- Compatibility with mineral oils and other base oils
- Negligible effect on most paints, elastomers or plastics
- Meeting FDA requirements for technical white mineral oil (21CFR178.3620[b])

For grease formulators, the complications of compliance with REACH legislation in Europe might be reduced by using PAO and polymer thickeners since polymers are generally exempt from the regulations.

Esters are also widely used due to their good thermal stability, low-temperature properties and lubricity, and some are biodegradable. In addition, they have good solvency, which is one of the most important factors in the choice of base oil for greases. It affects how the grease is made and how the thickener structure is formed. This can have a dramatic effect on the mechanical stability and lubricating ability of the grease. However, the high solvency of esters can often lead to problems with excessive seal swell or material compatibility. In addition, esters can be subject to hydrolysis in the presence of water, which is a common contaminant in industrial lubricants and greases.

In vegetable oil-derived greases, esters can be added to improve the low-temperature performance as well as oxidative stability.

Esters are often used as a co-base stock with PAO to boost the overall solvency characteristics. PAOs have inherently low solvency and may cause certain sealing materials to shrink. The addition of ester helps to provide solvency and typically causes seal materials to swell. The added solvency also helps improve grease manufacturing through improved thickener efficiency.

Alkylated naphthalene (AN) is another synthetic base stock that not only offers good solvency but is thermally, oxidatively and hydrolytically stable and can replace esters in lubricant formulations. In combination with PAO or other base stocks, it offers a synergistic boost to the oxidative stability of the formulation.

Because Synesstic™ AN, SpectraSyn™ PAO and SpectraSyn Elite™ mPAO products from ExxonMobil are registered in the NSF "White Book™" as acceptable for lubricants with incidental food contact (H1), they can be combined to make high-performance H1-approved incidental food contact greases.

Other synthetic base oils, such as polyglycols, silicones and poly-ethers, are also used, but their specific properties generally limit them to specialty lubricant greases.

Because of the broad range of base oil viscosities, synthetic greases can be prepared in several viscosity grades ranging from ISO VG 15 to 1500. These greases can be used in a wide range of applications and operating temperatures, depending on grade. They are not only used in numerous industrial applications but also find significant usage in the automotive, marine, and aerospace sectors.

Synthetic greases have become the products of choice for many users in industries worldwide. Their reputation is based on their exceptional quality, reliability and versatility, as well as the performance benefits they deliver.

Formulation data

A grease is typically made up of the following combination of components:

- Base stock 65–95%
- Thickener 5–35%[11]
- Additives 0–15%

As with fluid lubricants, blends of base stocks, as well as pre-mixed additive packages or additive components, can be used.

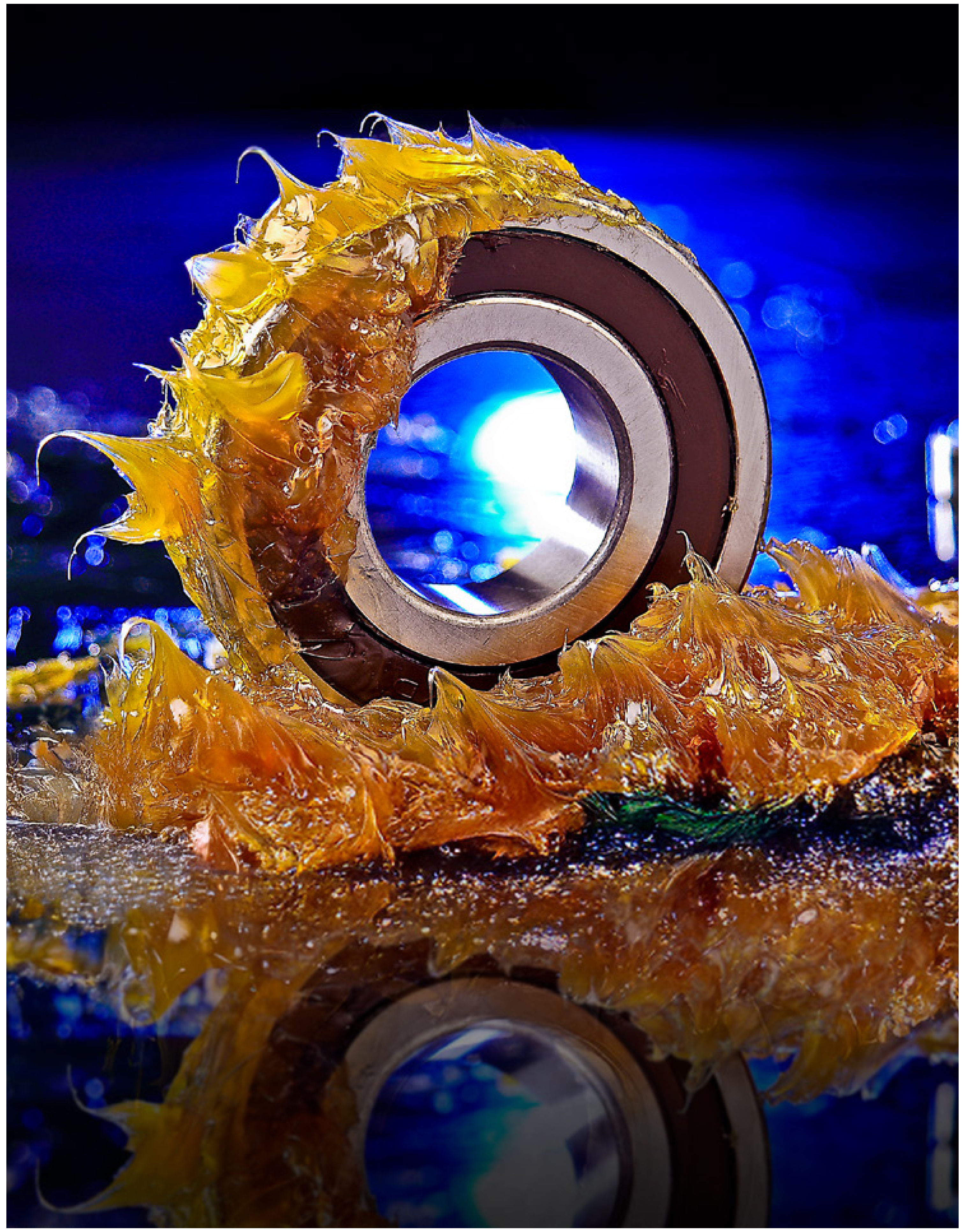
Typical additives employed are anti-wear, rust inhibitors and oxidation inhibitors. Depending on the application involved, metal passivators, polymers (viscosity modifier or tackifier) and extreme pressure additives may be used.

Considerable formulation science and a deep understanding of the manufacturing process are required to achieve all of the performance features of premium greases.

API Group IV PAO-based greases

All SpectraSyn™ PAO and SpectraSyn Elite™ mPAO grades are suitable for use in greases. The low-viscosity grades offer good volatility and low-temperature properties, while the higher-viscosity grades offer good film thickness and improved wear protection. All SpectraSyn™ PAO grades are registered with the NSF as lubricants (H1 classification) that could have incidental contact with food.

Table 8.0.A shows the benefits in low- and high-temperature tests of using SpectraSyn™ PAO base oil over an API Group I mineral oil. The use of synthetic base stocks like PAO instead of mineral base stocks can significantly improve low-temperature performance as well as grease life, including oxidation stability of the grease at elevated temperatures.



11 "Calcium sulfonate complex greases" 2016, STLE: https://www.stle.org/images/pdf/STLE_ORG/BOK/LS/Grease/Calcium%20sulfonate%20complex%20greases.pdf

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Table 8.0.A Comparison of high- and low-temperature properties between PAO and mineral-oil-based ISO VG 100, NLGI 2 greases

Component, wt.%		110 cSt @40°C mineral grease	110 cSt @40°C PAO grease
SpectraSyn™ 100 PAO			24.7
SpectraSyn™ 6 PAO			50.2
Group I 600N base stock		82.2	
Generic grease additive package		Approximately 4%	Approximately 4%
Lithium complex thickener content (calculated)		8.6	13.8
Property	**Test method**	**110 cSt @40°C mineral grease**	**110 cSt @40°C PAO grease**
Full scale penetration, unworked/worked, 0.1 mm	ASTM D217	291 / 287	269 / 276
Dropping point, °C	ASTM D2265	>308	>308
Low-temperature performance			
Low-temperature torque, @-40°C	ASTM D1478		
Starting torque, g-cm		14,200	2,321
Running torque (after 1 hour), g-cm		3,130	306
Low-temperature mobility @-18°C(0°F), g/min	LT-37 U.S. Steel	8.9	25.3
Oxidation resistance			
PDSC @180°C oxidation stability/life, minutes	ASTM D5483	56.5	96.1

Note: Component percentages do not include the use of complexing agents or other thickener components.

Source: ExxonMobil data

Table 8.0.B below compares two industrial ISO VG 320 greases: one with metallocene PAO in combination with alkylated naphthalene versus conventional high viscosity PAO and alkylated naphthalene. The combination of metallocene PAO and alkylated naphthalene improves low-temperature performance for example for centralized lubrication systems where the grease is pumped to the lubrication points. In addition, the alkylated naphthalene not only provides solubility, but also boosts oxidation stability which improves overall grease life. These results are evident in both PDSC and FE9 tests results, which can help extending re-lubrication grease intervals and reducing grease consumption.

Table 8.0.B Comparison of ISO VG 320 industrial greases, low- and high- temperature properties between conventional PAO (PAO) and metallocene PAO (mPAO)-based greases with alkylated naphthalene (AN)

Component, wt.%		PAO and AN grease	mPAO and AN grease
Lithium complex thickener content		15.7	16.0
SpectraSyn™ 6 PAO		24.8	35.3
SpectraSyn™ 100 PAO		50.9	-
SpectraSyn Elite™ 300 mPAO		-	37.3
Synesstic™ 5 AN		4.5	7.3
Grease additive package		4.1	4.1
Target mineral oil viscosity, cSt @40°C		320	320
NLGI class		2	2
Properties	**Test method**	**PAO and AN grease**	**mPAO and AN grease**
Full scale penetration, unworked/worked, 0.1 mm	ASTM D217	282 / 276	286 / 288
Dropping point, °C	ASTM D2265	275	>308
Low temperature performance			
Low temperature torque @-54°C	ASTM D1478		
Starting torque, g·cm		4,050	1,684
Running torque (1 hour), g·cm		683	351
Low-temperature mobility @-18°C, g/min	LT-37 U.S. Steel	8.2	34.4
Oxidation resistance			
PDSC @210°C oxidation stability/life, minutes	ASTM D5483	18.1	23.3
FAG FE9 bearing test @160°C, 6,000 rpm, 1.5 kN	DIN 51821		
L10 life, hours		53	79
L50 life, hours		74	128

Source: ExxonMobil data and models

SpectraSyn™ MaX 3.5, our new generation polyalphaolefin, is manufactured using the latest technology which brings low viscosity/low volatility properties with an advanced PAO molecular structure. The benefits of such a product could be utilized in higher speed applications where typically low base oil viscosity greases are desired. In addition, SpectraSyn™ MaX 3.5 can bring a significant advantage in improving energy efficiency compared to Gr III formulated greases.

API Group V synthetic-based greases

Adipate and polyol esters: Esterex™ A32, A34, A41, A51, NP343 and NP451 esters.

These products are suitable for use in low- and high-temperature applications (-37°C to over 177°C) and where readily or inherently biodegradable esters (see Section 4.5.1) are required. In combination with PAO, they aid additive solubility by providing increased polarity. The polyol esters provide greater oxidative and thermal stability than adipates.

Synesstic™ 5 and Synesstic™ 12 AN

When used in combination with PAO, the resulting grease has good low-temperature pumpability and good high-temperature properties. Additionally, the solvency of Synesstic™ AN helps to reduce the amount of thickener required and aids additive solubility while providing hydrolytic stability. The good lubricity of Synesstic™ AN products helps to improve the fretting and wear characteristics of greases. Table 8.0.C compares the wear and high-temperature properties of AN-based grease versus a PAO-based grease.

Table 8.0.C Comparison of the anti-wear and high-temperature properties between PAO and AN-based ISO VG 100, NLGI 2 greases

Component, wt.%		110 cSt @40°C AN grease	110 cSt @40°C PAO grease
SpectraSyn™ 100 PAO			24.7
SpectraSyn™ 6 PAO			50.2
Synesstic™ 12 AN		81.8	
Grease additive package		Approximately 4%	Approximately 4%
Lithium complex thickener content (calculated)		14.3	21.3
Property	**Test method**	**110 cSt @40°C AN grease**	**110 cSt @40°C PAO grease**
Full scale penetration, unworked/worked, 0.1 mm	ASTM D217	280/282	269/276
Dropping point, °C	ASTM D2265	>308	>308
Anti-wear/EP performance			
4 ball wear	EP Testing		
Wear, 40kg, 120 rpm, 1 hr @75°C, mm	ASTM D2266	0.38	0.51
EP, load weld Index, kg	ASTM D2596	39.4	44.1
EP, weld load, kg	ASTM D2596	250	315
Fretting wear, mg	ASTM D4170	9.2	20.3
Oxidation resistance			
PDSC @180°C oxidation stability/life, minutes	ASTM D5483	87.9	96.1
FAG FE9 Bearing test (DIN 51821) @140°C, 6,000 rpm,1.5kN	DIN 51821		
L10 life, hours		180.5	36.6
L50 life, hours		488.5	62.7

All results are single-sample results unless indicated otherwise.
The test results are typical values and are not intended to be specifications.
Note: Component percentages do not include the use of complexing agents or other thickener components.
Source: ExxonMobil data

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9.0 Appendices

9.0 Appendices

9.1 Additive glossary

Many kinds of chemical additives are used in the manufacture of high-quality lubricating oils and greases. They are either single-purpose materials or multipurpose materials. This appendix includes descriptions of some commonly used additive types.

Anti-wear agents

Such materials adsorb or concentrate on metal surfaces to form films that minimize the direct metal-to-metal contact. The name applies to materials that enhance the anti-wear characteristics of petroleum oils to permit significantly higher loadings that can be handled by straight petroleum oils. These materials should be non-staining and non-corrosive. They are typically derived from phosphorous, zinc, sulfur, boron or combinations of these elements. They are generally required when the application is operating in elastohydrodynamic (EHD) or boundary regimes.

Defoamants

When added to fluids, defoamants act to alter the surface tension of a fluid to promote the rapid breakup of foam bubbles by weakening the oil films between the foam bubbles. Typically based on polysiloxanes or polyacrylates, they are effective at very low treat rates but may adversely affect air-release properties.

Demulsifiers

These assist the natural ability of the oil to separate rapidly from water and help inhibit rust.

Detergents

Detergents based on metal salts are added to oils to provide cleanliness and help reduce deposit buildup. Neutral detergents are used for cleanliness, while over-based detergents (high alkalinity) help neutralize any acidic buildup in the oil (e.g., from the combustion process in an engine).

Dispersants

These products help suspend organic deterioration and soot accumulation in the lubricant to prevent them from binding together, thereby minimizing their precipitation as harmful deposits.

Extreme-pressure agents

These materials are more active than the anti-wear agents and usually react with the metal surface at higher temperatures to provide sufficient protection to carry even heavier loads than the anti-wear agents.

For example, automotive hypoid gears require lubricants that contain very active extreme-pressure agents. They typically are based on sulfur or heavy-metal salts.

Friction modifiers

A general category of materials based on long-chain polar materials that are used to alter the frictional characteristics of a lubricant. These are surface-active compounds. They may be used to increase the lubricity or slipperiness where the coefficient of friction may be important or to improve fuel economy/energy conservation.

Metal deactivators

These additives retard the oxidation-promoting catalytic effect of metals in a lubricating system. The metal surfaces or particles are covered by the agent, which acts as a barrier to prevent the catalytic effect. The most catalytically active metal is copper, the second is lead, and the third is iron.

Oxidation inhibitors

Some additive agents function as peroxide decomposers, chain stoppers, and/or metal deactivators. Peroxide decomposers destroy the precursor of radical sources by converting the peroxides into harmless compounds. Chain stoppers interrupt the chain reaction between oxygen and hydrocarbon radicals to prevent or slow the formation of acidic materials, propagated materials, and sludge.

Pour-point depressants

These improve the low-temperature fluidity of mineral oils and reduce wax formation at low temperatures.

Rust and corrosion inhibitors

Most lubricating oils contain rust and corrosion inhibitors to enhance their ability to minimize rusting and corrosion. They typically are based on calcium sulfonate or alkylated succinic acids. Depending on the metals to be protected, different chemistry and mechanisms are used.

Seal swell agents

These are fluids that help modify the swelling characteristics of elastomers. They are typically required where high levels of highly paraffinic base oils are used. Esters and alkylated naphthalene can be used in this role.

Tackifier

These are additives in greases with the ability to stick well and form sufficiently long threads when two surfaces separate so that the grease redistributes itself between the surfaces.[12]

Viscosity index improvers

When added to oils, these high-molecular-weight polymers improve the viscosity index by coiling and uncoiling in response to temperature. They may help lower the pour point at low temperatures while providing sufficient viscosity at high temperatures. They can be subject to breakdown through thermal or mechanical stress.

Viscosity thickener

A thickening agent or thickener is a substance, e.g., high Viscosity PAO, which can increase the viscosity of a liquid without substantially changing its other properties.

12 Lubes'n'Greases: www.lubesngreases.com/magazine/24_10/on-the-right-tack/

9.2 Acronyms and abbreviations

The following acronyms or abbreviations are used in this document:

AB	Alkyl benzene
ACEA	Association des Constructeurs Europeens d'Automobiles (European Auto Manufacturers Association)
AGMA	American Gear Manufacturers Association
AIST	Association for Iron and Steel Technology
AMT	Automated manual transmission
AN	Alkylated naphthalene or acid number
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
AT	Automatic transmission
ATF	Automatic transmission fluid
BEV	Battery electric vehicle
CCGT	Combined-cycle gas turbines
CCR	Conradson carbon residue
CCS	Cold-cranking simulator
CEC	The Co-ordinating European Council
CFR	Code of Federal Regulations
CNG	Compressed natural gas
COC	Cleveland Open Cup
cP	Centipoise
cSt	Centistoke
CVT	Continuously variable transmission
DCT	Dual clutch transmission
DFI	Dynamic friction index
DHT	Dedicated hybrid transmission
DIN	Deutsche Institut für Normung (German national standards organization)
DPF	Diesel particulate filter
EDU	Electric drive unit
EGR	Exhaust gas recirculation
EHD	Elastohydrodynamic
EHL	Elastohydrodynamic lubrication
EMD	Electro-motive diesel
EO	Engine oil
EP	Extreme pressure
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FDA	Federal Drug Administration
FZG	Forschungstelle für Zahnräder und Getriebebau (German Research Institute for Gears and Gearboxes)
GE	General Electric
GHG	Greenhouse gas
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HEV	Hybrid electric vehicle
hp	Horsepower
HTHS	High temperature, high shear
HVI	High viscosity index
ICE	Internal combustion engine
ILSAC	International Lubricant Standardization and Approval Committee
in	Inch
ISO	International Standards Organization
JAMA	Japanese Automobile Manufacturers Association
JASO	Japanese Automotive Standards Organization
kg	Kilograms

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KV	Kinematic viscosity
lbs	Pounds
LMOA	Locomotive Maintenance Officers Association
LPG	Liquified petroleum gas
LSD	Limited slip differential
LuSC list	Lubricant Substance Classification list
LVLV	Low volatility low viscosity
MRV	Mini-rotary viscometer
MSDS	Material Safety Data Sheet
MT	Manual transmission
MTM	Mini traction machine
MW	Molecular weight
NLGI	National Lubricating Grease Institute
NMMA	National Marine Manufacturers Association
NSF	National Sanitation Foundation
NVH	Noise, vibration, and harshness
OD	Outer diameter
ODI	Oil drain interval
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
Pa	Pascal
PAG	Polyalkylene glycol
PAO	Polyalphaolefins
PDSC	Pressure differential scanning calorimetry
PHEV	Plug-in hybrid electric vehicle
PIB	Polyisobutylene
POE	Polyol ester
ppm	Parts per million
pt	Point
R&O	Rust and oxidation inhibited
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
rpm	Revolutions per minute
SAE	Society of Automotive Engineers
SAPS	Sulfated ash, phosphorus, and sulfur
SCR	Selective catalytic reduction
SDS	Safety Data Sheet
SFI	Static friction index
SG	Specific gravity
SH&E	Safety, Health & Environment
SRR	Slide to Roll Ratio
SSI	Shear stability index
STI	Stop time index
SUS	Saybolt second universal (or SSU)
TAN	Total acid number
TBN	Total base number
TC-W3	Two-cycle water-cooled engine oil specification
TGF	Top groove fill
TISI	Thai Industrial Standards Institute
TMP	Trimethylolpropane (type of ester)
TÜV	Technischer Überwachungsverein (Technical Inspection Association)
US FDA	United States Food and Drug Administration
USDA	United States Department of Agriculture
VG	Viscosity grade
VI	Viscosity index
VM	Viscosity modifier
WDK	Weighted deposits demerits
WLTC	Worldwide Harmonized Light Vehicles Test Cycle

9.3 Lubricant grade classifications

9.3.1 ISO viscosity classification (ISO 3448)

In 1975, ISO developed a system of classifying viscosity grades across a wide range of lubricants, referencing the typical temperatures in industrial applications.

The system defines 20 grades where the grade is the kinematic viscosity measurement, from 2 to 3,200 cSt @40°C. Each grade is defined by its midpoint viscosity @40°C with a range of +/- 10% of that midpoint viscosity. The grades increase in value such that the next midpoint viscosity is approximately 50% higher than the previous one.

Generally: The comparable ISO grade of a given product whose viscosity in Saybolt Universal Seconds (SUS) at 100°F is known and can be determined by using the following conversion formula:

SUS @100°F ÷ 5 = cSt @40°C

		Kinematic viscosity, cSt @40°C	
ISO viscosity grade	Midpoint kinematic viscosity cSt @40°C	Minimum	Maximum
ISO VG 2	2.2	2.00	2.4
ISO VG 3	3.2	2.9	3.5
ISO VG 5	4.6	4.1	5.1
ISO VG 7	6.8	6.1	7.5
ISO VG 10	10	9.0	11.0
ISO VG 15	15	13.5	16.5
ISO VG 22	22	19.8	24.2
ISO VG 32	32	28.8	35.2
ISO VG 46	46	41.4	50.6
ISO VG 68	68	61.2	74.8
ISO VG 100	100	90.0	110
ISO VG 150	150	135	165
ISO VG 220	220	198	242
ISO VG 320	320	288	352
ISO VG 460	460	414	506
ISO VG 680	680	612	748
ISO VG 1000	1,000	900	1,100
ISO VG 1500	1,500	1,350	1,650
ISO VG 2200	2,200	1,980	2,420
ISO VG 3200	3,200	2,880	3,520

Source: Permission to reproduce extracts from British Standards is granted by BSI. British Standards can be obtained in PDF or hard copy formats from BSI Knowledge: https://knowledge.bsigroup.com or by contacting BSI Customer Services for hardcopies only: Tel: +44 (0)20 8996 9001, Email: cservices@bsigroup.com.

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9.3.2 Former AGMA viscosity classification for gear oils

ISO viscosity grade	Mid-point kinematic viscosity @40°C, cSt	Kinematic viscosity limits @40°C, cSt		Former AGMA grade equivalent
		Min	Max	
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	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	1,350	1,650	9
ISO VG 2200	2,200	1,980	2,420	10
ISO VG 3200	3,200	2,880	3,250	11

Source: Extracted from ANSI/AGMA 9005-F16, Industrial Gear Lubrication, with the permission of the publisher, the American Gear Manufacturers Association, 1001 North Fairfax Street, Suite 500, Alexandria, Virginia 22314.

9.3.3 NLGI lubricating grease classification

NLGI grade	60 stroke worked penetration @25°C
NLGI No. 000	445-475
NLGI No. 00	400-430
NLGI No. 0	355-385
NLGI No. 1	310-340
NLGI No. 2	265-295
NLGI No. 3	220-250
NLGI No. 4	175-205
NLGI No. 5	130-160
NLGI No. 6	85-115

The grades are defined as ranges of the values of the 60-stroke worked penetration, in tenths of millimeters, as determined by the ASTM designation D217, "Cone penetration of lubricating grease".
Source: NLGI, 118 N Conistor Lane, Suite B-281, Liberty, MO 64068

9.3.4 API base oil classification

Group	Viscosity index	Saturates		Sulfur
I	>= 80 - <120	<90%	and/or	>0.03%
II	>= 80 - <120	≥90%	and	≤0.03%
III	>= 120	≥90%	and	≤0.03%
IV	Polyalphaolefins			
V	All other products not meeting the requirements of the first four groups			

Source: API Base Oil Interchangeability Guidelines for Passenger Car Motor Oils and Diesel Engine Oils, API 1509, Appendix E, E.1.3 Base Stock Categories. Reproduced courtesy of the American Petroleum Institute.
Visit www.api.org/products-and-services/engine-oil/documents/api-1509-documents, API 1509, Engine Oil Licensing and Certification System, 22nd Edition, October 2023.

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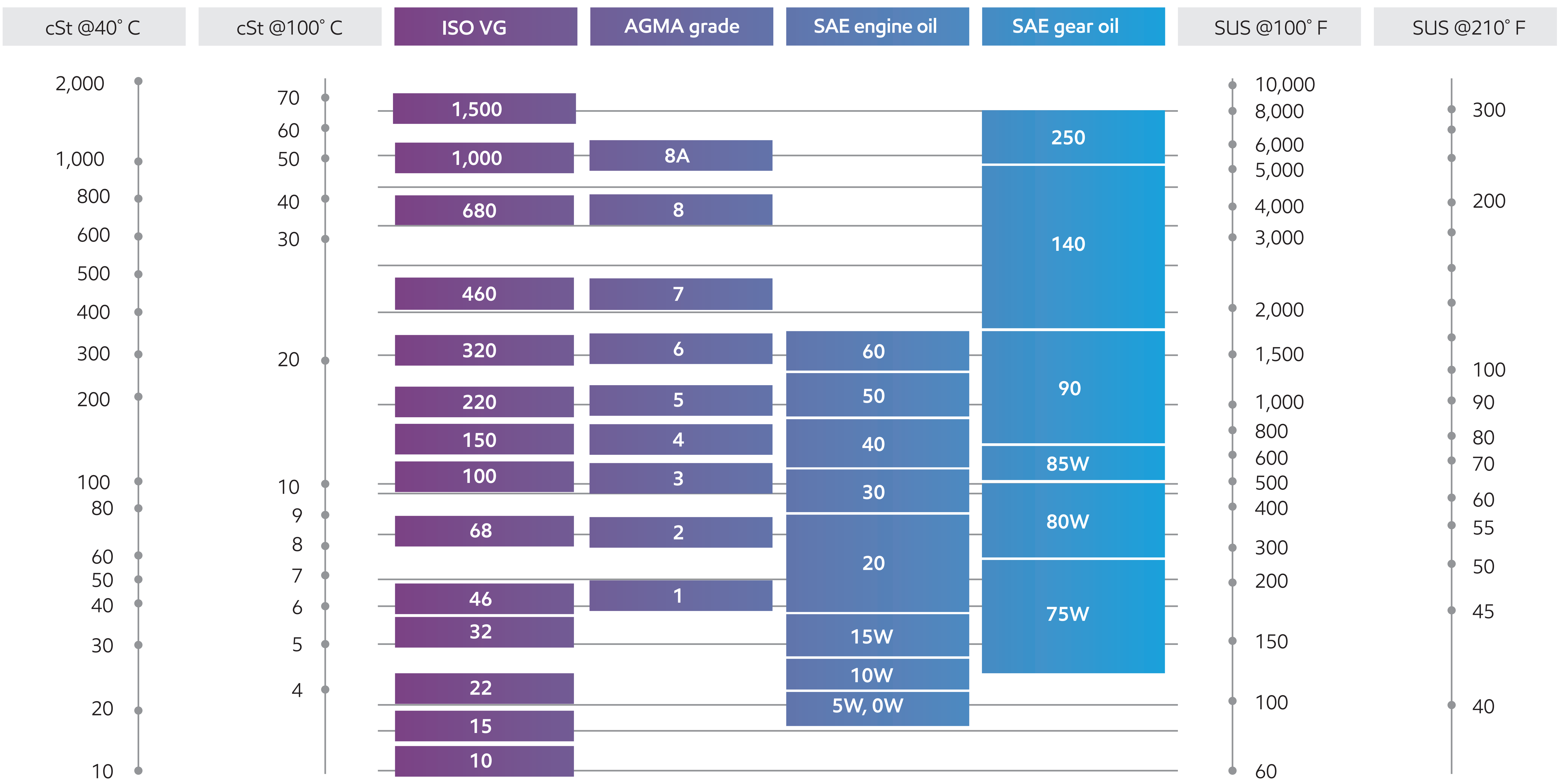
9.3.5 Automotive engine oil specifications

- For ILSAC specifications for passenger car and diesel engine oils, visit: www.api.org/products-and-services/engine-oil/documents
- For ACEA general requirements for light-duty engine oil, visit: www.acea.auto
- For JASO specifications for gasoline engine oils, visit: www.jalos.or.jp/onfile/pdf/GEO_E1909.pdf

9.4 Comparison of viscosity classifications



This is a rough guide for comparing equivalent viscosities under different classifications.
Viscosities are related horizontally only.
ISO VG are specified at 40°C.
AGMA grades are specified at 40°C.

SAE 75W, 80W and 5W and 10W are specified at low temperature. Equivalent viscosities at 40°C and 100°C are shown.
SAE 20 to 50 and 90 to 250 are specified at 100°C.
Source: Data compiled by ExxonMobil

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