Synthetic lubricant base stocks formulations guide

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1.0 Introduction

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1.0 Introduction — Using this guide

Formulators using synthetic base stocks are being asked to create more sophisticated and advanced lubricants every day. This "Synthetic Lubricant Base Stocks Formulations Guide" can provide a head start in developing lubricant formulations and offers assistance in making the best base stock choices for many lubricant applications.

The guide provides a handy reference source to quickly identify the performance characteristics of ExxonMobil Chemical's entire family of synthetic base stocks — SpectraSyn™, SpectraSyn Plus™ polyalphaolefins (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 a recommended combination for a given lubricant viscosity grade. These base stock combinations represent many of the core industrial and automotive synthetic lubricant formulations, from passenger car engines to compressors and hydraulic systems.

You may find right on these pages a base stock formulation and, in some cases, an additive package that works for you. At a minimum, we think you'll find a starting point from which to advance your formulation efforts. Either way, you can count on the support of your ExxonMobil Chemical sales representative or marketing technical support team. You can also visit our web site at www.exxonmobilsynthetics.com for a complete listing of our products and global sales offices. **Ready to save time, money and put your application's development on a fast track? Just turn the page and get started.**

2.0 Lubricant formulators FAQs

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2.0 Lubricant formulators FAQs

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

A: ExxonMobil Chemical 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 ester products and novel alkylated naphthalene products. This broad portfolio gives us the comprehensive understanding of synthetic lubricant formulations that is necessary to help our customers develop innovative and marketable products.

Q: How can this formulations guide help me?

A: This guide is intended to provide the formulator with a head start in 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 most core automotive 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 achieve the 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. This guide contains some formulations that have specific additive recommendations and shows additional performance testing. These tests have also been validated in laboratory testing. As with all formulations, however, some adjustment 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 Chemical base stocks. In some cases, we've also recommended 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.

Q: Can I substitute additives I may already be using for the additive packages shown in the guide?

A: Where specific additives are recommended, it is because they are in common use and commercially available. We're not recommending any one additive over another, and you may achieve a better result with a different additive. We are providing the recommendations as examples.

Q: Can I obtain a product sample?

A: Product samples are available for all of our synthetic base stocks. Please contact your ExxonMobil Chemical sales representative to make arrangements. You can visit our web site at www.exxonmobilsynthetics.com to contact us.

Q: Are there any limitations to product availability?

A: ExxonMobil Chemical has manufacturing, distribution, and sales support facilities around the world. All of the products listed in this guide are commercial products 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 personal care products to textile lubricants. Our technical support staff is available to help with formulation recommendations beyond those covered in this guide. Please contact your ExxonMobil Chemical sales representative for assistance.

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

A: ExxonMobil Chemical offers numerous value-added services to our customers, including formulation assistance, performance testing, product development assistance and global product 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 your ExxonMobil Chemical sales representative or from our web site at www.exxonmobilsynthetics.com

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 distributor 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 warranted.

3.0 Synthetic base stock grade slate summary

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3.0 Synthetic base stock grade slate summary

PAO	These 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.
mPAO	These products use metallocene catalyst technology to provide PAOs with a more uniform, comb-like structure and narrow molecular weight distribution to provide high VI, low temperature and shear stability properties versus conventional base stocks.
AN	These are manufactured through the alkylation of naphthalene with linear alpha-olefins. The resulting API Group V fluids offer very good thermal, oxidative and hydrolytic stability. They offer good solvency and are useful base stocks to improve the performance of most lubricants.
Esters	Combination of alcohols and acids are used to make organic esters that have various features, such as high thermal and oxidative stability, low volatility, lubricity, solvency and biodegradability depending on the specific ester (see Section 9.6). 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

Product type	Product name	Product description	S.G @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
PAO	SpectraSyn™ 2	Low viscosity PAO	0.798	1.7	5.0	252	n/a	-66	157
	SpectraSyn™ 2B		0.799	1.8	5.0	n/a	n/a	-54	149
	SpectraSyn™ 2C		0.798	2.0	6.4	n/a	n/a	-57	>150
	SpectraSyn™ 4		0.820	4.1	19	2,900	126	-66	220
	SpectraSyn™ 5		0.824	5.1	25	4,920	138	-57	240
	SpectraSyn™ 6		0.827	5.8	31	7,800	138	-57	246
	SpectraSyn™ 8		0.833	8.0	48	19,000	139	-48	260
	SpectraSyn™ 10		0.835	10	66	39,000	137	-48	266
	SpectraSyn™ 40	High viscosity PAO	0.850	39	396	n/a	147	-36	281
	SpectraSyn™ 100		0.853	100	1,240	n/a	170	-30	283
	SpectraSyn Plus™ 3.6	Low viscosity PAO with improved volatility and CCS	0.816	3.6	15.4	2,000	120	<-65	224
	SpectraSyn Plus™ 4		0.820	3.9	17.2	2,430	126	<-60	228
	SpectraSyn Plus™ 6		0.827	5.9	30.3	7,400	141	<-54	246
mPAO	SpectraSyn Elite™ 65	High viscosity, high VI, mPAO	0.846	65	614	n/a	179	-42	277
	SpectraSyn Elite™ 150		0.849	156	1,705	n/a	206	-33	282
	SpectraSyn Elite™ 300		0.849	303	3,358	n/a	241	-33	286
AN	Synesstic™ 5	Alkylated naphthalene	0.908	4.7	29.0	n/a	74	-39	222
	Synesstic™ 12		0.887	12.4	109	n/a	105	-36	258
Esters	Esterex™ A32	Adipate esters	0.928	2.8	9.5	985	149	-65	207
	Esterex™ A34		0.922	3.2	12	1,970	137	-60	199
	Esterex™ A41		0.921	3.6	14	3,286	144	-57	231
	Esterex™ A51		0.915	5.4	27	16,970	136	-57	247
	Esterex™ P61	Phthalate esters	0.967	5.4	38	n/a	62	-42	224
	Esterex™ P81		0.955	8.3	84	n/a	52	-33	265
	Esterex™ TM111	Trimellitate esters	0.978	11.9	124	n/a	81	-33	274
	Esterex™ NP343	Polyol esters	0.945	4.3	19	2,540	136	-48	257
	Esterex™ NP451		0.993	5.0	25	7,610	130	-60	255

Typical properties — not to be construed as specifications

Source: ExxonMobil data

Table 3.0.B Typical applications

Product names	Gasoline & diesel engines	Automatic transmis-sions	Industrial/ automotive gears & transmis-sions	Hydraulic systems	Industrial bearings	Rotary air and gas compressor	Hydro-carbon refrigeration compressor	Grease	Turbines	Heat transfer fluid	Automotive hydraulic fluids	Mist lubricant
SpectraSyn™ 2		●	•	●			•	•		●	●	
SpectraSyn™ 4	●	●	●	●		•	•	•	●	•		●
SpectraSyn™ 5	●		●	●	●	●	•	●	●			●
SpectraSyn™ 6	●		●	●	●	●	•	●	●			●
SpectraSyn™ 8	●		•	•	•	●	•	•	•			•
SpectraSyn™ 10			•	•	•	●	•	•	•			•
SpectraSyn™ 40	●		●	●	●	●	•	●	•			•
SpectraSyn™ 100			●	●	●	●		●	•			•
SpectraSyn Plus™ 3.6	●	●	●	●		•	•	•	●	•		●
SpectraSyn Plus™ 4	●	●	●	●		•	•	•	●	•		●
SpectraSyn Plus™ 6	●	●	●	●		•	•	•	●	•		●
SpectraSyn Elite™ 65	●	●	●	●	●	●	•	●	•			•
SpectraSyn Elite™ 150	●	●	●	●	●	●	•	●	•			•
SpectraSyn Elite™ 300	●	●	●	●	●	●	•	●	•			•

● Most common application uses
• Less commonly used

4.0 Industry trends

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4.0 Industry trends

Updated each year, "The Outlook for Energy: A View to 2040" 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 Energy outlook

Key findings include:

- Efficiency will continue to play a key role in solving our energy challenges.
- Energy demand in developing nations (non-OECD) will rise 65% by 2040 compared to 2010, reflecting growing prosperity and expanding economies.
- With this growth comes a greater demand for electricity.
- Growth in transportation sector demand will be led by expanding commercial activity as our economies grow.
- Technology is enabling the safe development of once hard-to-produce energy resources, significantly expanding available supplies to meet the world's changing energy needs. Oil will remain the No. 1 global fuel, while natural gas will overtake coal for the No. 2 spot.
- Evolving demand and supply patterns will open the door for increased global trade opportunities.

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

4.2 Lubricant industry trends

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

These demands are coupled with 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 these base stocks.

Driven by demands for increased productivity and better reliability, equipment manufacturers expect lubricants to operate under more severe operating conditions.

Energy savings and efficiency are important to cost performance. Limiting emissions and managing waste generation/disposal concerns are important to environmental performance.

To maintain raw material availability, companies look at alternate sources of material that provide additional flexibility in their manufacturing process.

The use of API Group I base stocks is, in general, being reduced as demand for higher-quality lubricants continues. In the U.S., API Group II base oils are dominant, as they are derived from refineries orientated toward strong gasoline production. In Asia, API Group III base oils are dominant because they come from refineries focused on distillate product. In Europe, API Group III oils dominate the automotive market due to high equipment manufacturer and market specifications.

API Group IV and V oils will continue to grow in use to meet the more stringent specifications for extended drain intervals and 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 that new cars must meet.

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 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 CO_2 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 use 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.

On commercial vehicles, electronic control of transmissions 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.

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 cities 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 in order to support local agriculture and to 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 drive 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 lower volatility characteristics are desired to help achieve the more stringent fuel economy and emission targets, but are essentially contradictory in nature. The lower the viscosity of the oil, the higher the amount of low-molecular-weight species, and the higher the volatility. 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 need 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 increasing use of additives for particulate handling.

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

4.4 Industrial segment trends

With reference to our report in "*The Outlook for Energy: A View to 2040*," the energy demand in the industrial segment is projected to grow by 30% over the forecast period. 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 doing more work, achieving 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, 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.

The turbines are getting larger and are being installed in more remote locations where wind is 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, it needs to be coupled with advanced lubricant technology in order to increase the overall reliability of the wind turbine system.

4.5 Sustainability trends

The growing awareness of environmental related issues is helping to drive consumers to ask for "green products." The use of renewable biofuels in vehicles is growing as government legislation mandates their use in some countries. Lubricants produced from biodegradable or renewable base stocks are also becoming more common.

At ExxonMobil Chemical, we subscribe to an environmentally conscious life cycle approach to product testing, as outlined in ISO 14000. Making wise manufacturing decisions requires reliable information and a science-based approach. Thus, we support the use of Life Cycle Assessment (LCA) in product evaluation. LCAs identify and evaluate the potential environmental impacts of a product or process, from raw material extraction to disposal and end-of-life. This is widely known as the "cradle-to-grave" approach. By quantifying and then comparing the environmental impacts of a product or process, LCA results can help us make science-based decisions, in areas such as product development, strategic planning, marketing and influencing public policy.

We also focus on efficient manufacturing processes that have lower environmental impact, and on innovation to support the development of products for the lubricant industry. For example, the innovative SpectraSyn Elite™ mPAOs that have high VI and improved shear stability are well-suited to meet the lubricant challenges in the wind industry, as well as to extend drain intervals. Most of our Esterex™ esters are readily or inherently biodegradable (see Section 9.6) and may be used to support the formulation of lubricants that may come in contact with the environment.

At ExxonMobil Chemical, we believe reducing, reusing, recycling and recovering are important aspects of a sustainable business. For more information, please visit www.exxonmobilchemical.com/sustainability.

5.0 Automotive applications

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5.0 Automotive applications

5.1 Passenger vehicle engine oils

Application and equipment

Most passenger cars use a four-stroke internal combustion engine as the primary power source. These are typically fueled by gasoline or diesel although alternate fuels such as liquefied petroleum gas (LPG), compressed natural gas (CNG), methanol, ethanol or hydrogen can also be used. The basic engine design is similar in all cases, with power being provided by pistons, which are pushed by expanding combustion gases in the engine cylinders. The motion of the pistons drives the car wheels through a gearbox, which matches the engine speed to the speed of the wheels.

Engine oils provide crucial protection for all the working parts of internal combustion engines, which are becoming more sophisticated with greater power densities and improved efficiency.

The main purpose of the engine oil is to provide an unbroken film of molecules that prevents metal-to-metal contact and reduces friction inside an engine. Lubrication is accomplished by a combination of oil being 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 and superchargers are commonly used to increase the power and efficiency of small internal combustion engines. The oil also has to lubricate and cool these components, which increases the stress on the oil, as superchargers and turbochargers produce temperatures well above what the engine experiences.

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 blowby
- Help improve fuel economy and reduce emissions

Engine oils are categorized in two different ways:

1) **Viscosity classification** — typically, multigrade oils are specified according to SAE J300 (see appendix 9.3.1).

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

Due to improved fuel economy requirements, the traditional 15W-40 multigrade oil has steadily been replaced by lower-viscosity grades. The most common grade of oil for cars today is 5W-30, however there is a trend toward lower viscosity lubricants including 0W to achieve further improvement in fuel efficiency.

Performance specification levels continue to increase in severity as engine technology improves and emissions legislation dictates more severe operating conditions. To achieve optimal engine performance, these hardware changes necessitated the introduction of specific lubricants. The performance requirements of crankcase lubricants are captured with the API, ILSAC, ACEA, JAMA and global lubricant specifications. All of these meet — or are being developed to meet — the changing lubricant requirements of modern engine hardware.

Due to 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 the norm. Providing the performance and protection needed while still meeting the limitations of each specification is a delicate balance.

Advantages of synthetic oils

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

The highest performance standards for engine oils can be met using PAO base stocks such as SpectraSyn™ or SpectraSyn Plus™ PAO. These synthetic base stocks offer numerous advantages over mineral oil base stocks, including:

- Better oxidative and thermal stability for long service life
- Better volatility for reduced engine oil emissions
- 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

In addition, the use of Synesstic™ AN base stocks 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 suggested engine-oil formulations described on the following pages provide a basic guideline to develop various engine oil grades based on ExxonMobil Chemical's SpectraSyn™ PAO. The engine-oil license performances (i.e., API SN/ILSAC GF-5, ACEA A1/B1, A5/B5) are indicated in the table but are linked to the specific additive package used and should be confirmed with the additive supplier. The key physical properties, as defined by SAE J300, are met, and should provide a good starting point for lubricant formulators.

The highest performance standards for engine oils can be met using PAO base stocks such as SpectraSyn™ or SpectraSyn Plus™ PAO.

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

Component		0W-20 (wt.%)	0W-30 (wt.%)	0W-40 (wt. %)	5W-30 (wt. %)	5W-40 (wt. %)	5W-50 (wt. %)	10W-60 (wt. %)
Performance level		API SN	API SN	API SN	API SN	API SN	API SN	API SN
SpectraSyn™ 4		16.6	28.7	34.1				
SpectraSyn™ 6		66.5	50.0	40.0	43.1	48.5	42.6	
SpectraSyn™ 8					39.8	28.5	31.5	71.3
Esterex™ NP343		2.0	2.0	2.0	2.0	2.0	2.0	2.0
Infineum DI		12.0	12.0	12.0	12.0	12.0	12.0	12.0
Infineum VM		2.6	7.0	11.6	2.8	8.7	11.6	14.4
Infineum ppd		0.3	0.3	0.3	0.3	0.3	0.3	0.3
KV @100°C, cSt	**ASTM D 445**	8.6	10.8	14.0	10.5	14.3	17.3	22.8
KV @40°C, cSt	**ASTM D 445**	47.2	58.9				103.8	
TBN, mg KOH/g	**ASTM D2896**	8.5	8.5	8.4	8.3	7.8	8.4	8.4
HTHS @150°C, mPa-s	**CEC L-36-A-90**	2.8	3.1	3.6	3.2	3.8	4.2	5.1
MRV, cP @-30°C	**ASTM D 4684**							16,500
MRV, cP @-35°C	**ASTM D 4684**				12,000	15,900	19,200	
MRV, cP @-40°C	**ASTM D 4684**	13,400	15,400	17,600				
CCS, cP @-25°C	**ASTM D 5293**							5,334
CCS, cP @-30°C	**ASTM D 5293**				5,770	5,640	6,160	
CCS, cP @-35°C	**ASTM D 5293**	6,133	5,763	5,830				
NOACK Volatility, wt.%	**CEC L-40-A-93**	8	9	10	6	7	7	6

Source: ExxonMobil data

SpectraSyn Plus™ 3.6 PAO

SpectraSyn Plus™ 3.6 PAO is a high-performance API Group IV fluid manufactured through a proprietary process. SpectraSyn Plus™ 3.6 PAO offers improved NOACK performance and lower CCS viscosity than a conventional PAO with equivalent viscosity. It is this combination of low volatility and low-temperature fluidity that enables formulators and blenders to improve the performance of their lubricants.

SpectraSyn Plus™ 3.6 PAO can provide low temperature and volatility benefits to compensate for Group III and Group II+ base stocks in top-tier engine-oil applications. SpectraSyn Plus 3.6 PAO can also be used to formulate other high-performing automotive, aviation and military applications requiring excellent volatility and low-temperature performance.

Synesstic™ AN

Synesstic™ AN base stocks are API Group V fluids that can be used to replace esters in fully synthetic engine oils. The use of Synesstic™ AN can help improve the performance of engine oil by providing a boost in oxidative stability while still providing the necessary solvency for seal swell and deposit control. Fully synthetic PAO-based engine oils formulated with Synesstic™ 5 AN showed very good improvements in oxidative stability in oxidative screening tests and significantly reduced cam wear in engine tests.

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

Component		5W-30 (Mass %)		5W-40 (Mass %)	
SpectraSyn™ 4		17.0			
SpectraSyn™ 6		53.0		45.0	
SpectraSyn™ 8				25.0	
Synesstic™ 5		10.0		10.0	
Infineum DDI*		11.5		11.5	
Infineum VM		8.5		8.5	
Property			Spec.		Spec.
Kinematic viscosity @100°C, cSt	**ASTM D445**	11.75	9.3 - <12.5	13.25	12.5 - <16.3
Kinematic viscosity @40°C, cSt	**ASTM D445**	68.44		81.80	
Viscosity index	**ASTM 2270**	168		164	
Pour point, °C	**ASTM D097**	-45		-42	
CCS @-30°C max, cP	**ASTM D5293**	3,716	6,600 max	5,324	6,600 max
CCS @-35°C max, cP	**ASTM D5293**	6,596	6,200 min	9,901	6,200 min
MRV @-35°C max, cP	**ASTM D4684**	10,118	60,000 max	14,658	60,000 max
HTHS @150°C min, cP	**ASTM D4683**	3.19	2.9 min	3.55	2.9 min

*Additive package meets API SL/CF, ILSAC GF-3, ACEA A1-96
Source: ExxonMobil data

SpectraSyn Elite™ mPAO

Further enhancement of the performance of synthetic engine oils can be achieved through the use of the SpectraSyn Elite™ series of mPAOs, which can provide improved wear protection through a boost in HTHS viscosity.

In the following example, 5W-30 and 10W-30 fully formulated engine oils were top treated with 2%, 5% and 8% of SpectraSyn Elite™ 150 mPAO. In each case, there was a boost to the HTHS viscosity, while the properties of the finished oil still met the SAE J300 viscosity requirements. Using this approach in practice during the formulation phase would allow for some optimization in the use of the viscosity modifier.

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

Property	Test method	5W-30	5W-30 + 2% SpectraSyn Elite™ 150	5W-30 + 5% SpectraSyn Elite™ 150	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	10W-30 + 5% SpectraSyn Elite™ 150	10W-30 + 8% SpectraSyn Elite™ 150	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	10.80	11.52	12.29	>9.3 <12.5
HTHS @ 150°C, cP	**ASTM D5481**	3.060	3.209 **(+4.9%)**	3.398 **(+11.0%)**	3.606 **(+17.8%)**	>2.9

Source: ExxonMobil data

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 lube specification. Generally, viscosity modifiers are also required and the treat rates are determined by 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
- Defoamants
- Pour point depressants
- Antiwear additives
- Rust Inhibitors
- Viscosity modifiers
- Friction modifiers

5.2 Commercial vehicle engine oils

Application and equipment

Most commercial vehicles, such as trucks and buses, use a four-stroke internal combustion engine as the primary power source. These are typically fueled by diesel, although some alternate fuels such as LPG, CNG and ethanol are also being used. Hybrid-engine technology combining internal combustion engines with electric motors is also commercially available.

The basic engine design is similar in all cases, with power provided by pistons that are pushed 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 speed of the wheels.

Engine oils provide crucial protection for the working parts of internal combustion engines, which are becoming more sophisticated with greater power densities and improved efficiency.

The main purpose of the engine oil is to provide an unbroken film of molecules that prevents metal-to-metal contact and reduces friction inside an engine. Lubrication 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, increasing the power and efficiency of engines. The engine oil also has to lubricate and cool these components, which increases stress on the oil because the turbochargers produce temperatures well above those experienced by the engine. Compared to engine oil in passenger vehicles, oils for commercial vehicles must have substantially higher performance in order to maximize vehicle productivity. This means longer intervals between oil drains and better cleanliness and wear protection to extend overhaul periods.

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 engine components clean
- Provide effective sealing of the cylinders to minimize exhaust gas blow-by
- Help improve fuel economy and reduce emissions

Vehicle engine oils are categorized in two different ways:

1) **Viscosity classification** — typically multigrade oils are specified according to SAE J300 (see appendix 9.3.1).

2) **Performance specifications** — defined by API, ACEA or various OEMs such as Mercedes Benz, Volvo, Scania, Mack, Cummins, MAN, etc.

Improved fuel efficiency is a key focus to address fuel cost and to reduce emissions. The traditional 15W-40 multigrade oil is steadily being replaced by lower-viscosity grades. Most modern commercial vehicles now operate on 10W grades, with 5W and 0W grades being considered for further improvements in fuel efficiency. The key concern in moving to low-viscosity oils is engine durability, where major overhauls are not expected until after 1 million operating miles (or 1.6 million km).

Performance specification levels continue to increase in severity as engine technology improves and emissions legislation dictates more severe operating conditions. The performance requirements of crankcase lubricants are captured with in API, ACEA and global OEM lubricant specifications. All of these specifications meet — or are being developed to meet — the changing requirements of modern engine hardware and of legislative rules that mandate specific fuel-efficiency targets.

Commercial diesel engine oils have a much longer drain interval than passenger vehicles. The intervals are on the order of 13,000 to 19,000 miles (20,000 to 30,000 km) or higher. Strong oxidation performance is therefore important. At the same time, wear protection and cleanliness are also critical for engine durability.

The higher detergent/dispersant levels required to handle the higher soot levels in commercial diesel engines can have a negative impact on the low-temperature properties of the oil. Increasing levels of PAOs may be required in semi- or full-synthetic oils, based on API Group III base stocks, in order to meet the low-temperature requirements.

Another concern with heavy-duty engine oils is the use of bio-based diesel fuel, which can accumulate in the engine oil. In addition to affecting the oil's viscosity, the bio-diesel can lead to problems with oxidation stability, which can promote sludge formation and corrosion.

To reduce exhaust gas emissions, many vehicles today utilize exhaust gas after-treatment devices, such as SCR systems, exhaust-gas recirculation (EGR) and diesel particulate filters (DPF). Each of these has an impact on the oil requirements. In the case of SCR, the effect is fuel sulfur and lube-oil additive limitations to reduce catalyst poisoning. In the case of EGR, the effect is increased soot handling while with DPF, the effect is lube-oil fuel dilution.

Advantages of synthetic oils

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

The highest performance standards for engine oils can be met using PAO base stocks such as SpectraSyn™ or SpectraSyn Plus™ PAO. These synthetic base stocks offer numerous advantages over mineral oil base stocks, such as:

- Better oxidative and thermal stability for long service life
- Better volatility for reduced engine oil emissions
- 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 perhaps enhance film thickness. SpectraSyn Elite™ mPAO has been shown to boost HTHS viscosity at low treat rates (see Table 5.1.C). 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 suggested engine-oil formulations described on the following page provide a basic guideline to develop fully synthetic engine oil based on ExxonMobil Chemical's SpectraSyn™ PAO. The engine-oil license performances are indicated in the table, but are linked to the specific additive package used and should be confirmed with the additive supplier. The key physical properties, as defined by SAE J300, are met and should provide a good starting point for lubricant formulators.

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

Component		SAE 5W-30 (wt.%)
Performance level		ACEA E4-08 Issue 2 ACEA E7-8 Issue 2
SpectraSyn™ 6		63.36
Esterex™ NP343		5.00
Infineum DI		19.90
Infineum VM		11.74
KV @100°C, cSt	**ASTM D 445**	12.4
KV @40°C, cSt	**ASTM D 445**	76.4
TBN, mg KOH/g		16.4
HTHS @150°C, mPa-s	**ASTM D 4683**	3.7
MRV, cP @-20°C	**ASTM D 4684**	2,910
MRV, cP @-35°C	**ASTM D 4684**	24,300
CCS, cP @-25°C	**ASTM D 5293**	3,540
CCS, cP @-30°C	**ASTM D 5293**	6,340
CCS, cP @-35°C	**ASTM D 5293**	11,340
NOACK volatility, wt.%	**ASTM D 5800**	8

Source: Infineum, used with permission.

Synesstic™ AN

Synesstic™ AN are API Group V fluids that can be used to replace esters in fully synthetic engine oils. The use of Synesstic™ AN can help improve the performance of engine oil by providing a boost in oxidative stability while still providing the necessary solvency for seal swell and deposit control.

Fully synthetic PAO-based engine oils formulated with Synesstic™ 5 AN, instead of ester, showed improved oxidative stability in oxidative screening tests and significantly reduced cam wear in engine tests. In the example below, the addition of Synesstic™ 5 AN helps reduce the level of piston deposits and carbon top groove fill seen using API CI-4 quality oil based on Group III base stocks in a Caterpillar 1-K diesel engine test.

Table 5.2.B Benefit of Synesstic™ AN

API CI-4 formulation using Group III base stock Caterpillar 1-K diesel engine test	Without AN	With AN
Wt.% Synesstic™ 5	0	20
Weighted deposit 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 through the use of 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.C).

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 lube specification. Generally, viscosity modifiers are also required, and the treat rates are determined by 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
- Antiwear additives
- Defoamants
- Rust inhibitors
- Viscosity modifiers
- Friction modifiers

Table 5.2.C Fully synthetic engine oil blends with SpectraSyn Elite™

Component		5W30	5W30	5W30	5W30	5W30	5W30
SpectraSyn™ 6			59.60%	70.00%	63.40%	70.00%	74.00%
SpectraSyn™ 40			28.40%	--	--	--	--
SpectraSyn™ 100			--	18.00%	--	--	--
SpectraSyn Elite™ 65			--	--	24.60%	--	--
SpectraSyn Elite™ 150			--	--	--	18.00%	--
SpectraSyn Elite™ 300			--	--	--	--	14.00%
Low/mid saps DDI			12.00%	12.00%	12.00%	12.00%	12.00%
		Spec.					
KV @ 40°C, cSt	**ASTM D445**		64.04	62.21	60.75	60.78	58.33
KV @ 100°C, cSt	**ASTM D445**	9.3 – <12.5	10.5	10.5	10.4	10.6	10.6
VI, ASTM D2270			153	160	160	165	173
Pour Point, °C	**ASTM D97**		-57	-60	-66	-60	-63
CCS @ -30°C, cP	**ASTM D5293**	<6,600	6,301	5,529	5,078	4,834	3,846
MRV @ -35°C, cP	**ASTM D4684**	<60,000	11,734	10,509	9,417	8,723	7,443
HTHS @ 150°C, cP	**ASTM D5481**	>2.9	3.2	3.3	3.2	3.4	3.4
NOACK @ 250°C, % wt loss	**ASTM D5200**		7.8	9.0	8.6	9.8	8.7

5.3 Automotive transmission oils

Application and equipment

Automotive vehicles require a power-transmission system to transfer the engine power to the driving wheels. As well as transferring power, the powertrain typically has a number of other components, including a clutch mechanism, a gear system and differential mechanism.

Clutch mechanism. The powertrain provides a clutch mechanism for disengaging the drive 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 and are found on tractors or off-road vehicles. In these cases, the frictional properties of the lubricants are important to ensure effective operation of the clutches while still lubricating the rest of the transmission system.

More recently, dual-clutch transmissions (DCT) have been developed. In effect, DCTs are two transmissions working in parallel. One gearbox has 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. This provides a fast and smooth gearshift. 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.

Automatic transmissions are typically driven through a torque convertor, which is a simple hydraulic pump, the fluid from which drives a turbine. At low engine speeds, the torque generated is insufficient to drive the vehicle, so the vehicle can be stopped without having to disconnect the engine from the power train. The gearbox itself is usually a planetary gearbox that provides the 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. These clutches and brakes are operated by hydraulic servomechanisms. The driver selects a drive range and the gears are automatically changed within that range, taking signals from speed sensors on the output of the gearbox. More modern transmissions use electronic control instead of hydraulics. 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 90° to the driving wheels. The gears are usually of the hypoid type, which allow 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 major function of lubricants for powertrain systems is to control friction between the moving parts — reducing friction in gears and bearings while providing the correct degree of friction in clutches and synchromeshes. Transmission oils also have to operate as hydraulic fluids, to transmit power or provide 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 is desirable.

In manual transmissions, multigrade oils meeting API GL-4 or GL-5 specifications are typically recommended. In some small vehicles, automatic transmission fluids (ATF) are used. Small machinery applications, such as scooters or gardening machinery, may use a semi-fluid grease to lubricate the transmission.

For automatic transmissions, a common fluid is used for the torque convertor, clutches and gears. Automatic transmission fluids are usually light-viscosity oils suitable for good power-transfer efficiency and heat transfer. The frictional characteristics also have to be matched to the various clutches and brake materials used to control the gear selection. Automatic transmissions tend to operate at high temperatures with a high degree of mechanical shearing. Typical requirements for lubrication products include good oxidation stability, low foam formation and good 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.

For hydrostatic drives, the system is essentially a high-pressure hydraulic system, and the fluid needs to meet the requirements for that type of service. High-viscosity-index products with good oxidation stability, low foam formation and good antiwear properties are required. In smaller machines, automatic transmission fluid (ATF) is used, while 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

A number of 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
- Improved solubility characteristics
- High efficiency

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

Properly formulated PAO gear oils will show improvement 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. PAO and 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.

The use of SpectraSyn Elite™ mPAO increases the viscosity index and significantly improves the low-temperature performance.

Additive requirements

Finished gear lubricants are typically composed of high-quality base stocks with between 5 and 10% additive, depending on desired performance characteristics. These additives include:

- Rust inhibitor
- Oxidation inhibitor
- Corrosion passivator
- Antiwear*
- Extreme pressure friction modifier*
- Dispersant polymer*
- Defoamants

*Not always required; application dependent

Formulation data

The following formulations provide a suitable starting point with which to develop fully synthetic transmission oils.

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

Formulation		PAO formulation	SpectraSyn Elite™ 150	SpectraSyn Elite™ 65	
SpectraSyn™ 6		40.0	41.4	27.5	
SpectraSyn™ 100		32.5			
SpectraSyn Elite™ 150			31.1		
SpectraSyn Elite™ 65				45.0	
Synesstic™ 5		20.0	20.0	20.0	
Additive package*		7.5	7.5	7.5	
Property	Method				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 L45-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 192hrs @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

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

	Formulation	PAO formulation	mPAO formulation	
	SpectraSyn™ 6	19.0	2.3	
	SpectraSyn™ 100	53.5		
	SpectraSyn Elite™ 65		70.2	
	Esterex™ A32	20	20	
	Additive package*	7.5	7.5	
Property	Method			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 192hrs @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.
Source: ExxonMobil data

Table 5.3.C Fully synthetic ATF

	Transmission type	Planetary gear automatic	
	API/ACC performance level	Dexron® IIIH and Allison TES-295	
	Formulation	Mass %	
	Infineum DI	16.0	
	SpectraSyn™ 4	79.0	
	SpectraSyn™ 6	5.0	
Analytical inspections	Test method	Results	Dexron IIIH limits
Viscosity at 100°C, cSt	ASTM D445	6.8	report
Brookfield at -40°C, cP	ASTM D2983	4,780	20,000 max

Source: Infineum, used with permission.

Note: For comparison, a mineral oil based Dexron® IIIH ATF would have a Brookfield viscosity @-40°C of approx. 18,000 cP.

5.4 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 the 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. For premixed fuel-oil systems, the product owner's manual will guide the user to the recommended fuel-to-oil ratio. This ratio can vary from 16:1 to 50:1, depending on the engine speed. 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 re-circulated 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 lawn mowers.

Lubricant requirements

The smaller sizes and lower oil volumes, as well as the higher speeds and power densities, of small engines mean that the performance requirements for engine lubricants are different from those for passenger cars.

Many small engines are air-cooled and therefore 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 means that conventional engine oils are unsuitable for motorcycle applications, because the friction modifiers used to provide better fuel economy will interfere with the clutch operation. Similarly, the engine oil also lubricates the motorcycle gearbox, which is subject to very high speeds and loads. This means that the lubricant also has to protect against pitting and shearing.

Therefore, a lubricant for a modern four-stroke engine has to be well formulated to balance the 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. Typically used in motor scooters, lawn and garden equipment, snowmobiles and personal watercraft.

Ashless. Used in NMMA TC-W3® outboard engine oils, as well as some snowmobiles and personal watercraft. This specification needs an additive package, which reduces the buildup of combustion-chamber deposits (which can lead to pre-ignition).
Since Japan has been the leading country for the production of two-stroke engines, the specifications are typically set by the Japanese Standards Organization (JASO). The minimum requirement for most manufacturers is to meet the JASO FC certification. The API TC service designation is predominant in the U.S., while, in Europe, the OEMs have implemented an ISO EGD specification with greater detergency than 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 engine gearbox and clutch, so friction characteristics have to 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 superior quality of synthetic lubricants can provide maximum protection and outstanding performance in small engines. In addition, the superb low-temperature properties of synthetic base stocks offer a great match for the low-temperature needs of snowmobiles and snowblowers.

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

Combined with an appropriate additive package, synthetic esters and/or AN, in combination with PAO fluids, may lead to improvements in lubricity and offer excellent antiwear performance in all areas, particularly with respect to high-lift camshafts and other heavily loaded valve-train components. The good low-temperature flow characteristics of synthetics can protect the valve gear even in the most severe winter conditions, and can also improve cold-start performance.

Synthetic two-stroke oils provide the ultimate protection for two-stroke engines, which tend to operate at higher temperatures. The pistons expand at high temperatures, thus decreasing the piston-to-cylinder wall clearance. This increases engine friction, as well as 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 provide improved engine performance. The use of Synesstic™ 12 AN in such applications has been shown to provide good results.

In two-stroke applications, esters are more common for synthetic formulations and offer high viscosity and high-viscosity indices, good low-temperature flow, biodegradability (see Section 9.6) 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™ NP451 (see Section 9.6) can make it an excellent choice for two-stroke oils for these applications.

Synesstic™ AN base stocks have also exhibited good lubricity in JASO engine tests, and are inherently biodegradable (see table in Section 9.6).

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.

Component	Treat rate	Function
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
Additives	3-20%	Antiwear and detergency

Synthetic two-stroke JASO FD/API TC oil

JASO FC/API TC oil	Treat rate
Infineum additive package	2.25% (API TC) , 2.5% (JASO FD)*
Solvent	25%
Polyisobutylene	25%
Esterex™ NP343 or NP451	48.5 – 48.75%

*Source: Infineum, used with permission

Table 5.4.A Synthetic two-stroke oil with Synesstic™ AN

Formulation		Mass%		
Infineum additive package (meets JASO FD, ISO-L-EGD, API-TC)	40.0	40.0	40.0	
Infineum ppd	0.3	0.3	0.3	
Exxsol™ D80 (solvent)	23.0	18.7	19.0	
Synesstic™ 5	--	41.0	32.8	
Synesstic™ 12	36.7		8.2	
JASO engine test results				JASO FD limits
Lubricity index	111*	91	96	≥95
Torque index	99	100	100	≥98
Smoke index	106	†	†	≥85

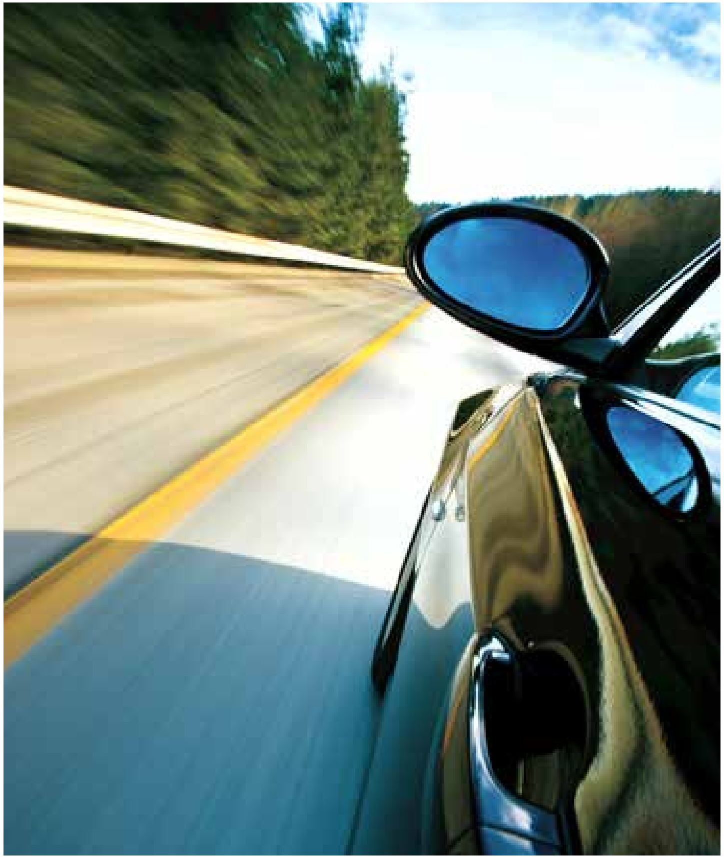
*Average of 105 and 116
†Predicted pass
Source: ExxonMobil data

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.

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

- Antiwear
- Detergent
- Dispersant
- Oxidation inhibitor
- Rust and corrosion inhibitors

Table 5.4.B Fully synthetic four stroke small engine oil (meets API SL, JASO T903 MA2)

Formulation	5W-40 (weight %)
Infineum DI package	8.0
Infineum viscosity modifier	10.0
SpectraSyn™ 6	82.0

Test	Test method	Results	Limits
KV @100°C, cSt	**ASTM D445**	14.6	12.5min, <16.3
CCS @-30°C, cP	**ASTM D5293**	3,920	6,600 max
MRV @-35°C, cP	**ASTM D4684**	23,300	60,000 max
HTHS @150°C, cP	**JPI-5S-36**	3.7	2.9 min
JASO friction	**JASO T904 MA2**		
Dynamic friction characteristic index, DFI		1.90	≥1.80 and <2.50
Static friction characteristic index, SFI		1.95	≥1.70 and <2.50
Stop time index, STI		1.82	≥1.90 and <2.50

Source: Infineum, used with permission

6.0 Other engine applications

Energy lives here™

6.0 Other engine applications

6.1 Marine and industrial diesel engines

Application and equipment

Marine and industrial engines are primarily diesel engines ranging in size from a small truck-size diesel engine to the largest diesel engines ever built, the latter being larger than the average two-story house.

The following information primarily refers to marine engines, but also applies to industrial engines, as these are often installed onshore as power-generation drives.

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 for main propulsion engines in large vessels, such as container ships. They are typically connected directly to the ship's propeller and, therefore, run at slow speeds (50–200 rpm). Because of their immense size, they use a crosshead design in order 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.

The cylinder oil that is injected into the cylinders passes through the system in a once-through manner with the cylinder oil being 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 the 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-up.

The turbochargers for these engines are very large and typically have their own lubrication system, which, due to the high temperatures, is normally 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 the 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 similar to 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 key issue, particularly in the fast ferry market, which has helped make this an area where synthetic engine oils have been successful.

Lubricant requirements

Two-stroke engines. The cylinder oil that is injected into the cylinders to lubricate the piston rings and cylinder liner is typically an SAE 50 viscosity oil with a high alkalinity: a total base number (TBN) of 40–70, depending on the sulfur level of the residual fuel being used. The system oil is normally SAE 30 viscosity oil with a 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

Typically, no synthetic base stocks are 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 may be offered by synthetic oils.

For the system oil, the use of Synesstic™ AN may offer a boost in oxidation stability while providing some solvency for fuel contamination.

For medium-speed engines running on residual fuel, the high volumes and fuel contamination makes 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.

High-speed engines running on distillate fuel can benefit from the use of fully synthetic engine oils, which, relative to mineral oils, can provide improved wear protection, lower volatility, 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™ or SpectraSyn Plus™ PAO can be used in combination with mineral oils (part-synthetic formulations), Esterex™ esters or Synesstic™ AN. Esters and AN are useful base stocks to provide 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 in order to realize high power outputs from small engines. The engines tend to run hotter than normal due to small cooling-water systems. This, coupled with long periods of idling and sudden speed/load changes, makes locomotive applications severe.

Both two-stroke and four-stroke engines are used and run on distillate fuel, although bio-diesel blends are becoming acceptable for use.

The Locomotive Maintenance Officers Association (LMOA) in the U.S. operates a classification system for locomotive diesel-engine lubricants. The current classification is Generation 5 (must also meet API CD), which was intended to provide extended drain intervals, although drain periods are highly dependent on the duty-cycle of the locomotive.

This classification system is an industry guideline, and engine manufacturers typically approve lubricants after field evaluations, then claim compliance with the LMOA requirements. The two main manufacturers in the U.S. are General Electric (GE) and Electro-Motive Diesels (EMD).

Lubricant requirements

Typical lubricants are SAE 30 or SAE 40 monograde engine oils with an alkalinity level of 9 or 17 TBN. One particular engine manufacturer, EMD, has silver-plated bearings and the oils used in these engines need to be free of zinc and chlorine in order to prevent corrosion. Multigrade engine oils are becoming more prevalent in an effort to improve fuel efficiency.

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 H_2S) are known as sweet gases, while those with increased levels of sulfur (up to 7% H_2S) are known as sour gases.

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

Bio-gases (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 (H_2S), 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, 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 the 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.

The majority of 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, 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 have to carry out a number of tasks, the main one being separating moving surfaces and reducing friction. This is primarily a function of viscosity, although antiwear additives are used to provide protection in areas of marginal lubrication, such as cams and piston rings. The oil then has to 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 gas engine oils

Formulation		Low ash product (weight%)	Medium ash product (weight%)	High ash product (weight%)
SpectraSyn™ 6		60.2	59.5	58.4
SpectraSyn™ 40		30	30	30
Infineum additive pack*		9.8	9.7	9.7
Infineum overbased detergent			0.8	1.9
Property	Test method			
SAE number		40	40	40
KV @100°C, cSt	**ASTM D445**	12.7	13.0	13.4
KV @40°C, cSt	**ASTM D445**	93.0	95.1	98.8
Viscosity index	**ASTM D2270**	133	134	135
TBN	**ASTM D2896**	5.72	8.38	12.44
Sulphated ash	**ASTM D874**	0.46	0.78	1.27

Finished lubricant properties are calculated from the typical values of the base oils and additive packages.
*Infineum additive package is designed for use in lubricating oils for gas engines running on natural gas,landfill gas and bio-gas. This package also meets API CF performance requirements.
Source: Infineum, used with permission

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 through the use of the SpectraSyn Elite™ series of high-viscosity mPAOs. SpectraSyn Elite™ provides improvement in viscosity index and may improve wear protection through a boost in HTHS viscosity (see Tables 5.1.C and 5.2.C).

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

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 industry sectors. The type of gas being compressed needs to be taken into account 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 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 antiwear and corrosion protection
- Good low temperature 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 8,000 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 never in contact with the gas. Occasionally, the seals are lubricated from the main oil system and the oil is led to a degassing tank before returning 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.[1]

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.

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

References: [1]Safety Aspects for selection and testing of air compressor lubricants, Hans W. Thoenes, Rheinisch-Westfalischer Technischer Uberwachungs-Verien e.V, Essen Germany.

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 good compatibility with mineral oils makes them an easy choice for upgrading lubricants. Fully formulated PAO 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 Chemical SpectraSyn™, 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 NSF "White Book™" (category code H1), lubricants for incidental food contact. These can, therefore, 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 in 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 Chemical Synesstic™ AN base stocks are also listed in the NSF "White Book," with category codes H1 and HX-1 (lubricants or components for lubricants for incidental food contact).

References: [2] "How Mobil synthetic lubricants can deliver measurable, long-term energy savings to industrial customers," ExxonMobil Lubricants Benefit Report.

The improved lubricity or lower traction properties of synthetic base stocks helps to reduce friction and save energy. For example, changing from a mineral-based lubricant to an equivalent-viscosity synthetic-based lubricant on a gas compressor provided a 16% reduction in energy use.[2] 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 reduce 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.A Ester-based compressor oils

ISO viscosity grade (formulation)		32 (weight%)	46 (weight%)	68 (weight%)	100 (weight%)
Esterex™ A51		83.5	53.1	19.7	–
Esterex™ P81		14.7	45.2	78.6	80.6
Esterex™ TM111		–	–	–	17.7
Additive package*		1.8	1.8	1.8	1.8
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.A:

- Antiwear
- 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 high 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.B:

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

*Not always required; application dependent

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

ISO viscosity grade (formulation)		32 (weight%)	46 (weight%)	68 (weight%)	100 (weight%)	150 (weight%)
SpectraSyn™ 6		84	74	63	53	42
SpectraSyn™ 100		1	11	22	32	43
Esterex™ A51		15	15	15	15	15
Property	Test method					
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°C/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 also helping to reintroduce a degree of solvency.

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

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

Performance against SAE MS1003 Compressor Specification

Viscosity grade			ISO VG 32 (wt%)	ISO VG 46 (wt%)	
Petro-Canada VHVI 4			41.1	7.3	
Petro-Canada VHVI 8			41.5	74.8	
HiTEC® 7389 multipurpose thickener			0.5	1.0	
HiTEC® 5200 compressor oil additive (contains 15% Synesstic™ 5)			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, mgKOH/g		**ASTM D974**	0.4	0.4	<0.6
Ash content, %		**ASTM D 874**	<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		**D1401**	4.5	4.8	<30
Demulsification	**Water in oil, %**	**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 @100C		**ASTM D 130**	1b	1b	1b
Rust test		**ASTM D665 B**	Pass	Pass	Pass
RPVOT, minutes		**IP229**	1,885	1,956	
CCMA modified	**Change in TAN, mgKOH/g**		-0.15	-0.15	<0.15
	Change in viscosity, %		1.5	1.7	<5
	Sludge, mg/100ml		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 D 4172, mm (40kg/1200rpm/60mins/75°C)		**ASTM D 4172**	0.34	0.39	≤0.4

In Group III stocks, the HiTEC 5200. Compressor Oil Additive meets the requirements of: DIN 51506 VDL; DIN51524 HLP; GM LJ; SAE MS1003
Data provided by the Afton Chemical Corporation and used with permission. (Source: Technical Report HiTEC® 5200 Compressor Oil Additive.)
The test results are typical values and are not intended to be specifications.

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 has to 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] The lubricant in a refrigerant system, as with many other types of equipment, can play a key role in reducing friction and energy consumption.

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

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.

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.D 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.

Advantages of synthetic oils

Synthetic base stocks such as 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 of 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.E PAO-based formulations for refrigerant lubricants (base oil blends only, weight%)

Formulation	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	18							
SpectraSyn™ 4	82	70						
SpectraSyn™ 6		30	100		69	54	38	23
SpectraSyn™ 8				100				
SpectraSyn™ 40					31	46	62	77

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.E:

- Antiwear
- 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 and 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-viscosity index 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" on page 66).

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 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, MAG). 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 the majority of hydraulic-system failures (figures up to 90% have been quoted).[1] Filtration testing is therefore an essential part of a fluid's performance requirement, particularly in the presence of water.

References: [1] "Contamination: hydraulic system enemy #1," Machine design.com, September 13, 2001.

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 viscosity index 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 antiwear additives (e.g., low-load vane pumps).
- ISO-HM: HL-type oils with antiwear 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 antiwear 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:
- Antiwear 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 antiwear-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		32		46		68	
Blend		PAO/ester	PAO/AN	PAO/ester	PAO/AN	PAO/ester	PAO/AN
SpectraSyn™ 6		74.2	77.2				
SpectraSyn™ 8				72.2	76.2	54.2	58.2
SpectraSyn™ 40		5	2	7	3	25	21
Esterex™ NP343		20		20		20	
Synesstic™ 5			20		20		20
Additive package*		0.8	0.8	0.8	0.8	0.8	0.8
Property	Test method						
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/cm³		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

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

Additional data for ISO VG 46 only		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, 3hrs @100°C	**ASTM D130**	1a	1a
Steel corrosion, 24hrs	**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
Four ball wear scar, mm	**ASTM D4172**	0.35	0.33
Seal compatibility, SRE-NBR @100°C for 168hrs	**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:

- Antiwear
- Defoamant
- Rust and/or corrosion inhibitor
- Oxidation inhibitor
- Demulsifier
- Extreme pressure, friction modifier†

†Optional; application dependent

Biodegradable base stocks

The Esterex™ ester range contains a selection of grades that meet a biodegradable classifications.

Esterex grade	kV @40°C	% Biodegradation in 28 days OECD 301F	Biodegradability classification
A32	9.5	70.2	Readily biodegradable
A34	12	80.2	Readily biodegradable
A41	14	76.5	Readily biodegradable
A51	27	58.5	Inherently biodegradable
P61	38	72.2	Readily biodegradable
P81	84	54.5	Inherently biodegradable
NP343	19	65.3 (301B)	Inherently biodegradable
NP451	25	83.2	Readily biodegradable

Source: ExxonMobil data

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. 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 are able to 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 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, 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. As a consequence, 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 has to 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.[1] This results in reduced bearing temperatures (with a subsequent reduction in cooling required) and reduced oxidation conditions, which would lead to longer oil life.

Reference: [1]A comparative study of mineral and synthetic based Hydro turbine oils, W. Dmochowski, K Brockwell & B. Liko, National Research Council Canada.

Electric power generation. Today, the trend is for smaller power stations, fuelled by natural gas to help reduce emissions. Typically these employ CCGTs, as previously described. They can be built in a modular fashion offsite, they require a smaller land area and, with reduced emissions, they 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, there is an expectation of extended life from the end-user. 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.

Because combined-cycle systems use a common lubricant-oil system, the oil has to handle high-temperature conditions and water. To match the varying speeds of the different turbines, gearboxes are increasingly being used. This means increased requirements for oils with EP properties, usually indicated by a minimum FZG rating. Due to some turbine failures in the 1980s, reportedly caused by deposit problems from hydrolytic breakdown when using zinc dialkyldithiophosphates (ZDDP), most turbine oils are zinc-free today.

Interest in oil conductivity due to sparking from static electricity 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

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 specification (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
- 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, very good 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 antiwear requirements can be low. However, some applications utilize gear drives that require antiwear 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 in terms of 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 recommended base stocks

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.

- Antiwear
- 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

Formulation	ISO VG 32	ISO VG 46	ISO VG 68
SpectraSyn™ 6	85	71	55
SpectraSyn™ 40	–	14	30
Synesstic™ 5	15	15	15

Table 7.3.B PAO-/ester-based formulations

Formulation	ISO VG 32	ISO VG 46	ISO VG 68
SpectraSyn™ 6	83	69	53
SpectraSyn™ 40	2	16	32
Esterex™ A51	15	15	15

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.

Since those times, 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 51 519) 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 most commonly used are the following:

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

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
  - FZG DIN 51 534 Parts 1 and 2
  - Timken OK load
  - 4 ball weld — ASTM D2783 or DIN 51 350 part 1
  - 4 ball wear — ASTM D4127 or DIN 51 350 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 is created, gear teeth require an oil film to be created with each tooth engagement. In high-speed gear sets, there is only a very short time for the lubricant film to be established. In the gear-tooth engagement, significant sliding occurs between the two gear surfaces, and only at the pitch point does rolling occur.

Gear applications are essentially governed by elasto-hydrodynamic lubrication.

Correct 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 due to the effects 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, 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 a number of 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 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
- 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 stock combinations (weight %)

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

- Antiwear*
- 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 its higher viscosity index, 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 the 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.

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

Formulation		Conventional PAO		SpectraSyn Elite™ 65 mPAO		SpectraSyn Elite™ 150 mPAO		SpectraSyn Elite™ 300 mPAO
		ISO VG 220	ISO VG 320	ISO VG 220	ISO VG 320	ISO VG 220	ISO VG 320	ISO VG 320
SpectraSyn™ 6		8.5		17.5		35.4		36.7%
SpectraSyn™ 8			28.2		7.2		29.4	
SpectraSyn™ 40		80						
SpectraSyn Elite™ 65				71	81.3			
SpectraSyn™ 100			60.3					
SpectraSyn Elite™ 150						53.1	59.1	
SpectraSyn Elite™ 300								51.8%
Synesstic™ 5		10	10	10	10	10	10	10.0%
Additive package*		1.5	1.5	1.5	1.5	1.5	1.5	1.5%
KV @40°C	**ASTM D445**	222.8	332.6	220.3	324.9	221.6	326.6	319.6
KV @100°C	**ASTM D445**	25.7	36.8	29.8	40.0	29.0	39.4	42.72
VI	**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	**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

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 usually carried out 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 calender 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. 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 antiwear (or mild EP) protection. Typically, the antiwear 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 PAO/AN base oil blends (% weight)

Formulation	ISO VG 68	ISO VG 100	ISO VG 150	ISO VG 220	ISO VG 320	ISO VG 460
SpectraSyn™ 6	58	48	37	26	16	6
SpectraSyn™ 100	22	32	43	54	64	74
Synesstic 5™	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:

- Antiwear
- Oxidation inhibitor
- Defoamant
- Demulsifier
- Rust and/or corrosion inhibitor
- EP dispersant and friction monitor (optional; application-dependent)

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 between bakery ovens and freezer operations. The same machinery is also subject to frequent washing down and cleaning, which means that water ingress and corrosion are serious threats.

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

Most food manufacturers now use what are commonly called "food-grade" lubricants. These lubricants are made from specially approved base oils and additives so that any incidental contact (see "NSF registration classifications" on page 85) between the oil and the foodstuff may help to reduce health risk to consumers.

Although the market for incidental-food-contact lubricants is growing, it is estimated that a high percentage of the food and beverage companies in the U.S. are not using lubricants specifically designed for incidental food contact.[1] The increasing demand for food, particularly in Asia, also increases the number of large mechanized food-processing plants, which replace local manual operations. Increasing legislation, global harmonization and demand for high-performance lubricants in these plants encourages the use of food-grade lubricants.

Modern incidental-food-contact lubricants, particularly those based on synthetic oils, offer performance that is comparable with conventional synthetic grades. An additional benefit of the good performance is that companies can opt to use the incidental-food-contact lubricants on a wider array of machinery than food-processing equipment. This minimizes the number of lubricants in stock and avoids the risk of cross-contamination.

With increasing demand for incidental-food-contact lubricants, more lubricant manufacturers are making these types of lubricants, and the selection of suitable additives and base stocks for the industry is also increasing.

Until 1998, the U.S. Department of Agriculture (USDA) had a program that reviewed and approved incidental-food-contact lubricants based on criteria set by the Food and Drug Administration (FDA). With the cancellation of the USDA program, companies had to check their products against the FDA regulations and effectively self-certify their food-machinery products.

In 1999, the activities of the USDA program were picked up by NSF International. NSF is an accredited third-party certification body that tests and certifies products to verify that they meet public health and safety standards. NSF administers a registration system for nonfood compounds, including lubricants for incidental food contact. Lubricant suppliers with products that meet the required FDA regulations register their products with the NSF and the products are subsequently listed in the NSF "White Book" (Nonfood Compound Listings). Products registered with NSF must use an official registration mark as well as carry a category and registration number on their labels to show compliance with the system. NSF registration is generally accepted as an industry standard across the world.

Definitions

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

Direct contact: the product is intended to become part of the food and may also impart a property to the food that would enhance it (e.g., flavoring agent or additive).

Indirect contact: the product will come in contact with the food and may become part of it, but will not impart any properties that would enhance the food (e.g., label adhesive).

Incidental contact: Not likely to come into contact with the food and will not impart properties that would enhance the food (e.g., anti-rust agent on food preparation surfaces that will be removed prior to food being prepared).

Lubricants and their individual components would, in general, only be approved for incidental contact.

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) which 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: soluble oils applied to equipment in contact with food to clean them and provide rust protection

Reference: [1] R. Profilet, Lubrizol Corporation, "Finding your way around the food grade lubricants maze," Tribology and Lubrication Technology, Nov 2007.

Lubricant requirements

Incidental-food-contact lubricants should have a light or transparent color with a neutral odor and taste. 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 antiwear properties.

Highly refined "white" 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.

As well as being more oxidatively stable when fully formulated, PAO-based formulations offer two additional advantages over mineral white 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

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

ExxonMobil Chemical Synesstic™ AN 5 and AN 12 and SpectraSyn Elite™ 65 and 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.

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	100	10		55	38	23	8	
SpectraSyn™ 8		90						
SpectraSyn™ 10			100					
SpectraSyn™ 40				45	62	77	92	88
SpectraSyn™ 100								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 passifier and antiwear
- A tackifier may be used to reduce dripping

Typical formulation

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 H1 hydraulic oil	%wt
SpectraSyn™ 6	84
SpectraSyn™ 100	11.5
Lubrizol® 4370FG	4.5
ISO VG 220 H1 gear oil	%wt
SpectraSyn™ 6	19.5
SpectraSyn™ 40	76
Lubrizol® 4370FG	4.5

Lubrizol® 4370FG is an ashless additive package that can be used to formulate hydraulic fluids, gear oils and other lubricants where incidental food contact with lubricants can occur.

Lubrizol® 4370FG meets the requirements for incidental food contact lubricants as per 21CFR 178.3570. It is NSF HX-1 registered (NSF# 138737).

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.

Table 7.6.C Incidental contact food grade lubricants
ISO VG 46 hydraulic oil using 4.5% Lubrizol® 4370FG

Test	Units	Method	Mineral base stocks*	PAO base stocks*	PAO/15% Synesstic™ 5†
Viscosity @40°C	cSt	D445	48.6	45.4	45.9
Viscosity @100°C	cSt	D445	7.2	7.6	8.0
RPVOT	minutes	D2272	571	1,063	1,218
Thermal stability		D2070			
CU/Steel appearance			8/7	10/10	8/8 ‡
Sludge	mg/100ml		34.1	43.6	15.5 ‡
Cincinnati Milacron		Procedure A			
Cu/Fe appearance			5/2	10/10	8/8
Cu/Fe wt 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, 1200rpm, 40kg)		D4172			
Scar diameter	mm		0.37	0.40	0.35

*Mineral and PAO data provided by The Lubrizol Corporation and used with permission (Datasheet for Lubrizol® 4370FG "Hydraulic fluid and gear oil concentrate for incidental food contact applications").

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

‡Average of two test results.

All methods are ASTM methods as denoted by the D and the test number except where indicated.

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 polyphenyls, 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 in order 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 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 requirements 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 could 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)

Formulation	ISO VG 10	ISO VG 15	ISO VG 22	ISO VG 32	ISO VG 46
SpectraSyn™ 2	50	20			
SpectraSyn™ 4	50	80	70		
SpectraSyn™ 6			30	100	90
SpectraSyn™ 8					10

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

Formulation	ISO VG 10	ISO VG 15	ISO VG 22	ISO VG 32	ISO VG 46
SpectraSyn™ 2	59	20			
SpectraSyn™ 4	21	60	60		
SpectraSyn™ 6			20	80	
SpectraSyn™ 8					80
Synesstic™ 5	20	20	20	20	20

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

Formulation	ISO VG 10	ISO VG 15	ISO VG 22	ISO VG 32	ISO VG 46
Synesstic™ 5	35	60	85	100	88
SpectraSyn™ 2	65	40	15		
SpectraSyn™ 100					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 Table 7.7.C:

- 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 are those involving 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. As a consequence, 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.

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™, 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

Formulation	ISO VG 68	ISO VG 100	ISO VG 150	ISO VG 150	ISO VG 220	ISO VG 320
Esterex™ TM111			87		52	
Esterex™ NP343	69	60		50		41
SpectraSyn™ 40			13		48	
SpectraSyn™ 100	31	40		50		59

Table 7.7.E base stock formulations with PAO/AN

Formulation	ISO VG 68	ISO VG 100	ISO VG 150	ISO VG 150	ISO VG 220	ISO VG 320
Synesstic™ 12	45	90	75	87	45	55
SpectraSyn™ 8	55	10				
SpectraSyn™ 40			25		55	
SpectraSyn™ 100				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 antiwear
- 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,"[1] a grease is traditionally described as a three-dimensional matrix of thickener particles with the spaces in the matrix filled with a lubricating oil — similar to a sponge. As the matrix is compressed under load, the oil is released to provide its lubricating function.

However, the reality is more complicated. Greases are actually "a complex, physical, multi-phase system."[2] 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 the majority of 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 as a result 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.

References: [1]T. F. Hoad. "grease." The Concise Oxford Dictionary of English Etymology. 1996. Retrieved March 19, 2010 from Encyclopedia.com: http://www.encyclopedia.com/doc/1O27-grease.html. [2]The Chemistry & Physics of Grease, Axel Christiernsson, Lubrisense white paper 04-01, www.axelch.com.

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 by the use of lubricating oils. It is, therefore, no surprise that between 80 and 90% of all rolling-element bearings are now grease-lubricated.[3]

Thickeners

The thickener is 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 elastoHydro-Dynamic (EHD) lubrication conditions[4]

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 for the electric-motor bearing market.

Although the majority of 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.[5]

References: [3] A. Begg, "SKF Lubricant grease knowledge and sustainability," Keynote speech, ELGI 2009. [4] P.M. Cann, "The influence of Temperature on the Lubrication Behaviour of Lithium Hydroxystearate Grease," 5th Annual ELGI Conference Budapest 1994. [5] A. Kemble, "Evaluation of Industrial Bearing Grease Performance," Eurogrease 1998, July/August. [6]"Grease Technology," Mobil Industrial Grease brochure.

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 in order 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 taken into account. 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.[6] 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. 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 for 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, through the use of higher vi base oil or oils with reduced traction
- Improved wear protection through thicker oil films or improved oil-film formation
- 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 (2-150 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 the use of 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 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.

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 Chemical 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 polyethers, 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 a broad range of operating temperatures, depending on grade. They are not only used in numerous industrial applications, but also find significant usage in 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 from the following combination of components:

- Base stock 75–95%
- Thickener 5–20%
- 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 antiwear, rust inhibitors and oxidation inhibitors. Depending on the application involved, metal passivators, polymers (viscosity modifier or tackifier) and extreme pressure additives may be used.

In reality, considerable formulation science is 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 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 SpectraSyn Elite™ mPAO grades offers improved low-temperature fluidity, especially for higher-viscosity grades. Table 8.0.B shows the benefits in low-temperature torque and USS steel mobility.

Table 8.0.A Comparison of high and low temperature properties between PAO and mineral-oil based greases

Blend base oil composition		Mineral grease	PAO grease
SpectraSyn™ 100			24.7
SpectraSyn™ 6			50.2
600N		82.2	
Generic grease additive package		Approximately 4%	
Target mineral oil viscosity, cSt @40°C		110	110
Lithium complex thickener content (calculated)		8.6	13.8
Test	Test method	**Results**	
Full scale penetration, unworked/worked, 0.1mm	**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
USS low-temperature mobility @-18°C(0°F), g/min	**USS Steel**	8.9	25.3
Oxidation resistance			
PDSC @180°C oxidation stability/life, minutes	**ASTM D5483**	56.5	96.1

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

Table 8.0.B Comparison of low-temperature properties between PAO- and mPAO-based greases

Blend base oil composition		PAO grease	mPAO grease	mPAO grease
SpectraSyn™ 100		75		
SpectraSyn™ 6		25	28	43
SpectraSyn Elite™ 150			72	
SpectraSyn Elite™ 300				57
Generic grease additive package		4% in base oil ratio above		3%
Target mineral oil viscosity, cSt @40°C		460	460	460
Lithium complex thickener content (calculated)		14.4	11.9	14
Test	Test method	**Results**		
Full scale penetration, unworked/worked, 0.1mm	**ASTM D217**	290/298	274/275	287/282
Dropping point, °C	**ASTM D2265**	334	322	271
Low-temperature performance				
Low-temperature torque, @-40°C	**ASTM D1478**			
Starting torque, g-cm		4,220	2,830	2,210
Running torque (after 1 hour), g-cm		1,330	552	531
USS low-temperature mobility @-18°C(0°F), g/min	**USS Steel**	10.7	13.2	12.6

Source: ExxonMobil data

API Group V synthetic-based greases

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

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 9.6) 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 antiwear and high-temperature properties between PAO- and AN-based greases

Blend base oil composition		AN grease	PAO grease
SpectraSyn™ 100			24.7
SpectraSyn™ 6			50.2
Synesstic™ 12		81.8	
Generic grease additive package		Approximately 4%	
Target mineral oil viscosity, cSt @40°C		110	110
Lithium complex thickener content (calculated)		9.3	13.8
Test	Units		
Full scale penetration, unworked/worked, ASTM D217	0.1 mm	280/282	269/276
Dropping point, ASTM D2265	°C	>308	>308
Antiwear/EP performance			
Four ball wear/EP testing			
Wear, ASTM D2266, 40kg, 120 rpm, 1 hr @75°C	mm	0.38	0.51
EP, ASTM D2596 load weld index	kg	39.4	44.1
EP, ASTM D2596, weld load	kg	250	315
Fretting wear, ASTM D4170	mg	9.2	20.3
Oxidation resistance			
PDSC @180°C oxidation stability/life, ASTM D5483	minutes	87.9	96.1
FE9 Bearing test (DIN 51821) @140°C, 6000rpm, 1.5kN			
L10 life	hours	180.5	36.6
L50 life	hours	488.5	62.7

ExxonMobil Chemical test results: All results are single-sample results unless indicated otherwise.
All methods are ASTM methods as denoted by the D and the test number except where indicated.

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

9.0 Appendices

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9.0 Appendices

9.1 Additive glossary

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

Adhesive agents

Tacky, stringy materials that help form and retain uniform oil films on metal surfaces, particularly under severe conditions such as water spray.

Antiwear 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 antiwear characteristics of petroleum oils to permit loadings of double or triple that which 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 also 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 overbased 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 products 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 antiwear agents and usually react with the metal surface at high temperatures to provide sufficient protection to carry even heavier loads than the antiwear agents. 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. They may be used to increase the lubricity or slipperiness where coefficient of friction may be important, or to improve fuel economy/energy conservation.

Metal passivators
These materials help to minimize the catalytic action of certain surfaces; for example, copper-based tubes may oxidize oil unless coated with a passive coating.

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. Metal deactivators 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.

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

Rust inhibitors
Most lubricating oils contain rust inhibitors to enhance their ability to minimize rusting. They typically are based on calcium sulfonate or alkylated succinic acids.

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 AN can be used in this role.

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 temperature while providing sufficient viscosity at high temperature. They can be subject to breakdown through thermal or mechanical stress.

9.2 Acronyms

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 of Iron and Aluminium Trades
AN Alkylated Naphthalene or Acid Number
AMT Automated manual transmission
API American Petroleum Institute
ASTM American Society for Testing and Materials
ATF Automatic Transmission Fluid
CEC The Co-ordinating European Council
CCR Conradson Carbon Residue
CCS Cold-Cranking Simulator
COC Cleveland Open Cup
cP Centipoise
cSt Centistoke
CVT Continuously variable transmission
DCT Dual clutch transmission
DIN Deutsche Institut für Normung (German national standards organization)
DPF Diesel Particulate Filter
EHD Elastohydrodynamic
EHL Elastohydrodynamic lubrication
EP Extreme Pressure
FDA Federal Drug Administration
FZG Forschungstelle für Zahnräder und Getriebebau (German Research Institute for Gears and Gearboxes)
hp Horsepower
HVI High Viscosity Index
HTHS High Temperature, High Shear
ILSAC International Lubricant Standardization and Approval Committee
in Inch
ISO International Standards Organization
JASO Japanese Automotive Standards Organization
kg Kilograms
KV Kinematic Viscosity
lbs Pounds
LSD Limited slip differential
MRV Minirotary Viscometer
MSDS Material Safety Data Sheet
MW Molecular Weight
NLGI National Lubricating Grease Institute
NMMA National Marine Manufacturers Association
NSF National Sanitation Foundation
OD Outer diameter
OECD Organization for Economic Co-operation and Development
OEM Original Equipment Manufacturer
Pa Pascal
PAG Polyalkylglycol
PAO Polyalphaolefins
PIB Polyisobutylene
POE Polyol ester
ppm Parts per million
pt Point
R&O Rust & Oxidation inhibited
SAE Society of Automotive Engineers
SAPS Sulfated Ash & Phosphorous
SCR Selective Catalytic Reduction
SG Specific Gravity
SH&E Safety, Health & Environment
SSI Shear Stability Index
SUS (or SSU) Saybolt Second Universal
TC-W3 Two-Cycle Water-Cooled engine oil specification
TAN Total Acid Number
TISI Thai Industrial Standards Institute
TMP Trimethylolpropane (type of ester)
TÜV Technischer Überwachungsverein (Technical Inspection Association)
USDA United Stated Department of Agriculture
VG Viscosity Grade
VI Viscosity Index

9.3 Lubricant grade classifications

9.3.1 SAE automotive lubricant viscosity grades

SAE J300 engine oils

SAE viscosity grade	Low-temperature cranking viscosity[1] (cP) max @temp °C	Low-temperature pumping viscosity[2] (cP) max @temp °C	Kinematic viscosity[3] (cSt) @100°C	Kinematic viscosity[3] (cSt) @100°C	High shear rate viscosity[4] (cP) @150°C
			Minimum	Maximum	Minimum
0W	6,200 @-35	60,000 @-40	3.8		
5W	6,600 @-30	60,000 @-35	3.8		
10W	7,000 @-25	60,000 @-30	4.1		
15W	7,000 @-20	60,000 @-25	5.6		
20W	9,500 @-15	60,000 @-20	5.6		
25W	13,000 @-10	60,000 @-15	9.3		
8			4.0	<6.1	1.70
12			5.0	<7.1	2.0
16			6.1	<8.2	2.3
20			5.6	<9.3	2.6
30			9.3	<12.5	2.9
40			12.5	<16.3	2.9[5]
40			12.5	<16.3	3.7[6]
50			16.3	<21.9	3.7
60			21.9	<26.1	3.7

References: [1]ASTM D5293. [2]ASTM D4684 (no yield stress). [3]ASTM D445. [4]ASTM D4683, CEC-L-36-A-90 (ASTM D4741) or ASTM D5481. [5]0W-40, 5W-40 and 10W-40. [6]15W-40, 20W-20, 25W-40 and 40.

SAE J306 automotive gear oils

SAE grade	Maximum temperature for a viscosity of 150,000 cP[7]	Kinematic viscosity @100°C, minimum	
		Min[8]	Max
70W	-55°C	4.1	
75W	-40°C	4.1	
80W	-26°C	7.0	
85W	-12°C	11.0	
80		7.0	<11.0
85		11.0	<13.5
90		13.5	<18.5
110		18.5	<24.0
140		24	<32.5
190		32.5	<41.0
250		41.0	

References: [7]ASTM 2983 Brookfield viscosity. [8]Limits must also be met after testing in CEC L-45-T-93 Method C (20 hours).

9.3.2 ISO viscosity classification (ISO 3448)

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

The system defines 20 grades 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.

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

SUS @100°F ÷ 5 = cSt @40°C

ISO viscosity grade	Midpoint kinematic viscosity, cSt @40°C	Kinematic viscosity, cSt @40°C	
		Minimum	Maximum
ISO VG 2	2.2	2.0	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	29.8	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: ISO

9.3.3 Former AGMA viscosity classification for gear oils

Former AGMA lubricant #	Kinematic viscosity cSt @40°C		Equivalent ISO VG
	Min	Max	
0	28.8	35.2	32
1	41.4	50.6	46
2	61.2	74.8	68
3	90	110	100
4	135	165	150
5	198	242	220
6	288	352	320
7	414	506	460
8	612	748	680
8A	900	1,100	1,000
9	1,350	1,650	1,500
10	1,980	2,420	2,200
11	2,880	3,250	3,200

EP, R&O inhibited and C (compound) designations are no longer used with switch to ISO viscosity grade classifications.

Source: AGMA 9005-E02 (Used with permission from the American Gear Manufacturers Association, 1001 N. Fairfax Street - 5th Floor, Alexandria VA 22314).

Source: ExxonMobil data

9.3.4 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

9.3.5 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			

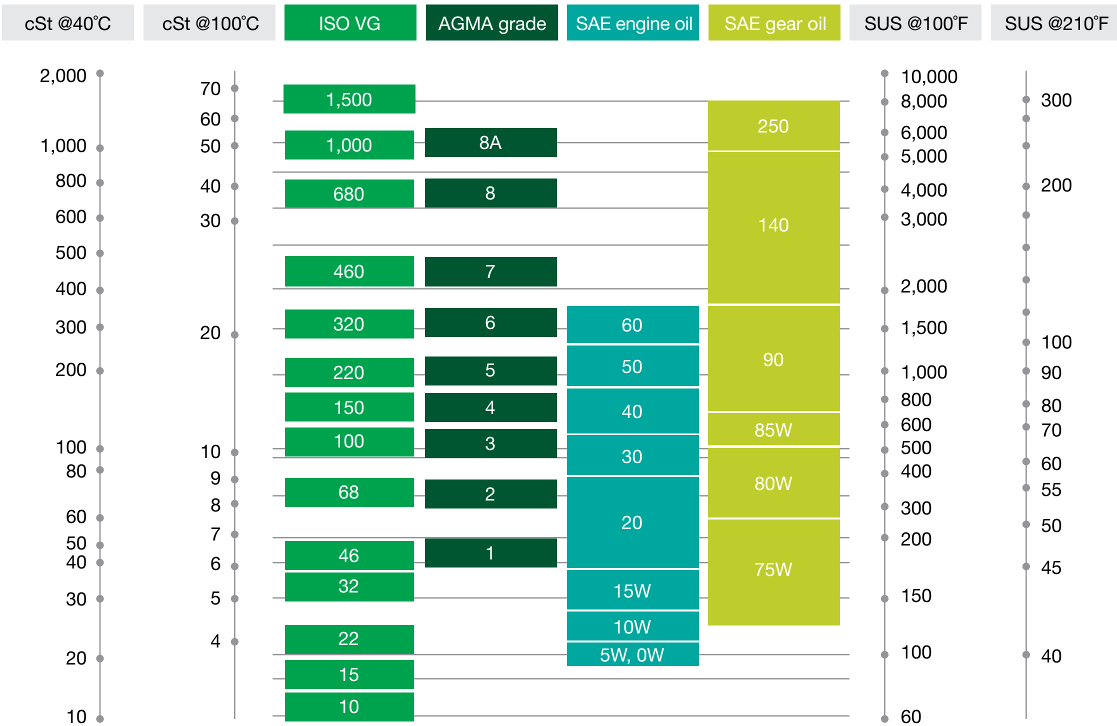
Source: API Base Oil Interchangability Guidelines for Passenger Car Motor Oils and Diesel Engine Oils, API 1509, Appendix E. Reproduced courtesy of the American Petroleum Institute.

Visit API.org Appendix-E-REV-09-01-11

9.4 Viscosity conversion table

Kinematic viscosity	SUS	Engler	Redwood no.1 sec.	Kinematic viscosity	SUS	Engler	Redwood no.1 sec.
2	32.6	1.1	30.8	110	511	14.5	450
3	36.0	1.2	33.2	120	558	15.8	490
4	39.1	1.3	35.8	130	605	17.1	530
5	42.5	1.4	38.4	140	649	18.4	570
6	45.7	1.5	41	150	695	19.7	620
7	49.0	1.6	43.7	160	742	21.0	660
8	52.0	1.7	46.5	170	788	22.5	700
9	55.7	1.7	49.2	180	834	24.0	740
10	59.0	1.8	52.1	190	881	25.0	780
11	62.5	1.9	55.2	200	927	26.0	820
12	66.2	2.0	58.4	210	973	28.0	860
13	70.0	2.1	61.6	220	1,020	29.0	900
15	77.5	2.3	68.2	230	1,066	30.0	940
17	85.5	2.6	75.2	240	1,112	32	990
19	94	2.8	82.8	250	1,159	33	1,030
21	100	3.0	90.4	260	1,205	34	1,070
23	111	3.2	98	270	1,251	36	1,110
25	120	3.5	106	280	1,297	37	1,150
28	133	3.8	117	290	1,344	38	1,190
30	142	4.1	125	300	1,390	40	1,230
33	155	4.5	137	315	1,460	41	1,300
35	164	4.7	145	330	1,529	43	1,350
38	178	5.1	157	350	1,622	46	1,440
40	187	5.4	166	370	1,715	49	1,520
43	200	5.8	178	390	1,807	51	1,600
46	214	6.2	190	410	1,900	54	1,690
50	233	6.7	207	430	1,990	57	1,770
55	256	7.3	228	450	2,090	59	1,850
60	279	7.9	248	470	2,180	62	1,930
65	302	8.6	268	490	2,270	64	2,010
70	325	9.3	286	500	2,320	66	2,050
75	349	9.9	307	550	2,540	72	2,260
80	372	10.5	329	600	2,780	79	2,460
85	395	11.2	349	650	3,010	86	2,670
90	418	11.8	370	700	3,240	92	2,880
95	442	12.5	390	750	3,470	99	3,080
100	465	12.3	410	800	3,700	1,105	3,280

9.5 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

9.6 Biodegradability data

Product	% Biodegradability in 28 days		Assessment
	OECD 301F	OECD 301B	
Esterex™ A32	70	-	Readily biodegradable
Esterex™ A34	78	-	Readily biodegradable
Esterex™ A41	76	-	Readily biodegradable
Esterex™ A51	58	-	Inherently biodegradable
Esterex™ P61	71	-	Readily biodegradable
Esterex™ P81	55	-	Inherently biodegradable
Esterex™ TM111	<1	-	Not inherently biodegradable
Esterex™ NP343	-	76	Inherently biodegradable
Esterex™ NP451	84	-	Readily biodegradable
Synesstic™ 5	46.4	-	Inherently biodegradable
Synesstic™ 12	24	-	Inherently biodegradable
PAO	• In general, lower viscosity PAO products undergo more biodegradation than higher viscosity PAO products. • No PAO products meet the OECD readily biodegradable classification. • Low viscosity PAOs (2 to 8 cSt @100˚C) are inherently biodegradable. • Higher viscosity PAOs (>10cSt @100˚C) are not inherently biodegradable.		

Source: ExxonMobil data

OECD classification

Readily biodegradable

In order to be classified as "readily biodegradable," a test material must meet two OECD requirements: It must achieve greater than 60% biodegradation in 28 days and 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.

Inherently biodegradable

In order to be classified as "inherently biodegradable," the test material must meet the following OECD requirement: greater than 20% biodegradation.

For more information visit:
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