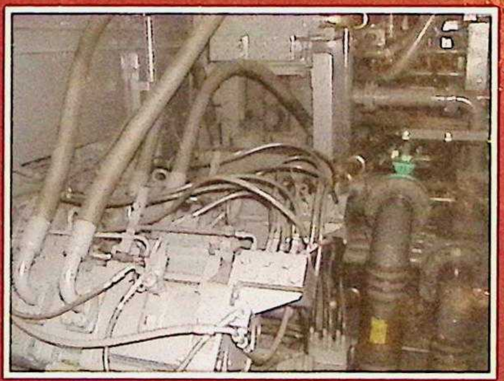
LUBRICATION *and* MAINTENANCE *of* INDUSTRIAL MACHINERY

Best Practices and Reliability



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Conservation of Lubricants and Energy

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8.1 Introduction

Many of the materials essential to global industrial markets have been identified as being in potential short supply. A substantial number of those materials originate from regions of the world where interrupted supply is a real and present risk. Petroleum is a finite world resource with continuing supply and economic problems, with more special concerns for fuels than for petroleum-based lubricants.

It is the objective of this chapter to present specific conservation practices for lubricants and functional (hydraulics, coolants, etc.) fluids used in tribological components and for energy. The treatment will necessarily be brief, but references will point to more detail information.

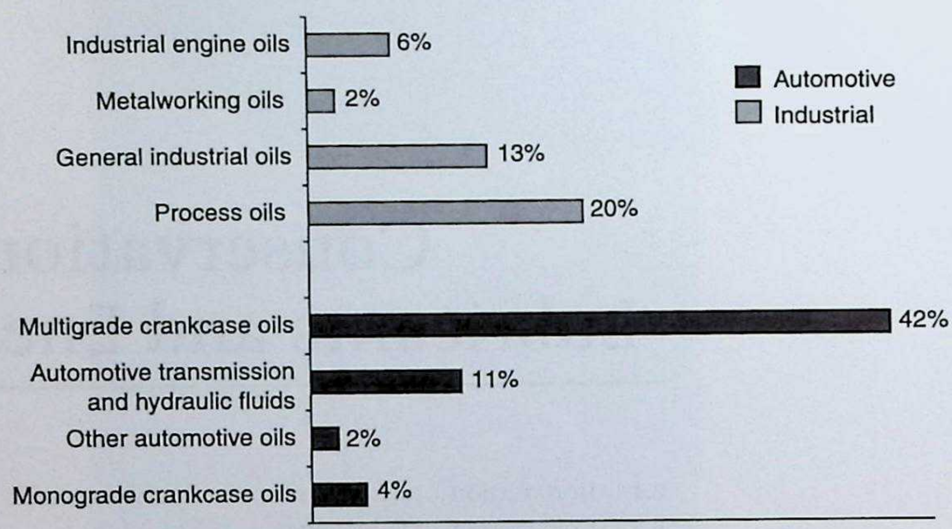


FIGURE 8.1 2002 sales of lubricants (total: 2.4 billion gal). (Taken from NPRA, Lubes'n'Greases Magazine. With permission.)

8.2 Conservation of Lubricants

8.2.1 Trends

Lubricants and hydraulic fluids are most commonly derived from petroleum sources. Petroleum serves as the base-stock in the majority of liquid lubricants and greases and very often is a raw material in the synthesis of unique lubricants (typically referred to as synthetics). Details of the distribution of the industrial and automotive lubricant markets in the United States are shown in Figure 8.1. A five-year trend of industrial and automotive lubricants sales is shown in Figure 8.2.

8.2.2 Improved Manufacturing and Formulation

The manufacturing methods used in refining lubricants are significant to material conservation and energy. Modern hydrogen processed bases oils (API Groups II and III) are popular because they

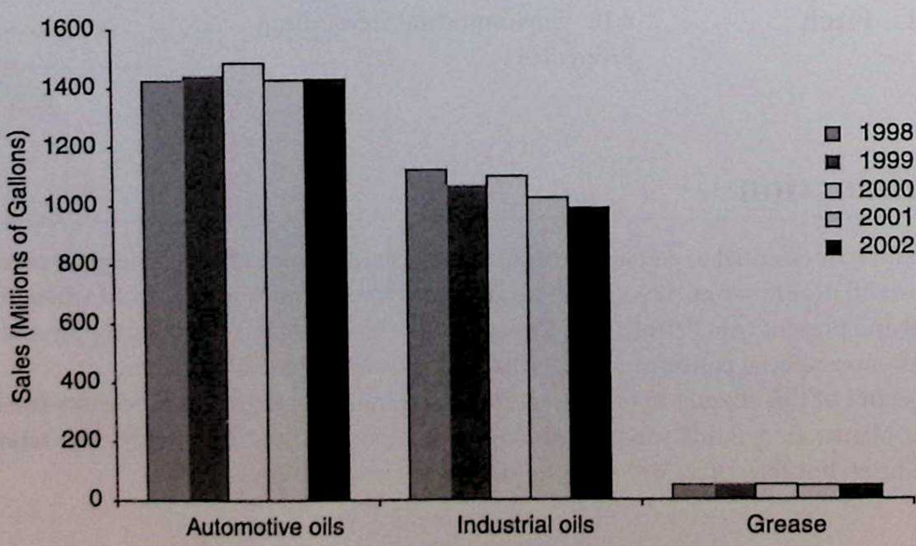


FIGURE 8.2 Five-year trend of total reported sales of lubricants. (Taken from NPRA, Lubes'n'Greases Magazine. With permission.)

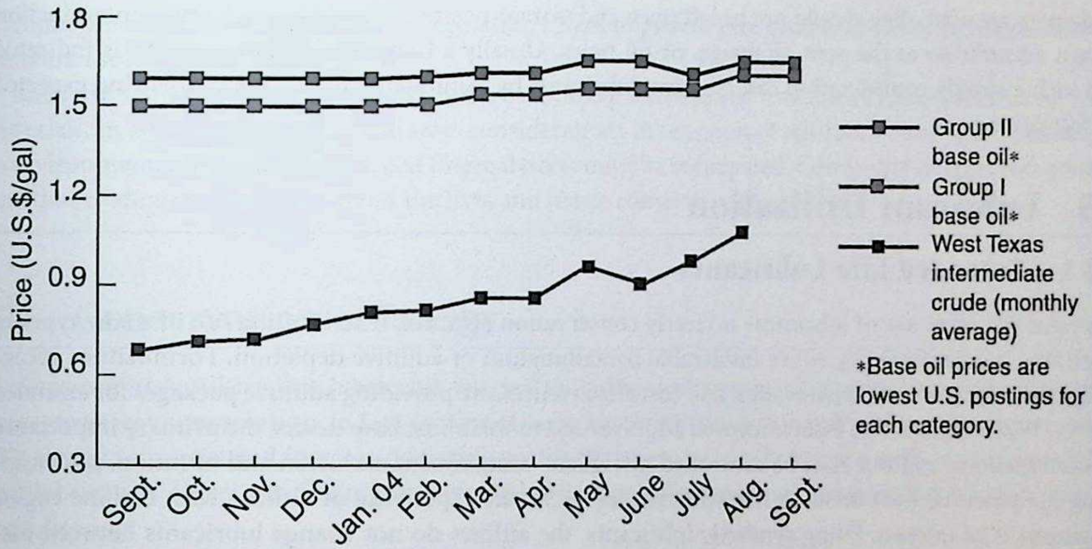


FIGURE 8.3 Base oil and crude prices. (Copyright 2004, Lubes'n'Greases Magazine. With permission.)

(1) minimize solvent, acid, and clay, (2) reduce by-product disposal problems, (3) increase yield, (4) lower costs, (5) permit use of wide range of crudes, (6) improve color, and (7) give higher viscosity index (VI). Figure 8.3 shows a 12-year base oil production trend for paraffinic and naphthenic stocks. Pricing trends in 2003–2004 for Group I mineral oils and Group II hydroprocessed oils are shown in Figure 8.4.

8.2.3 Packaging and Handling

Packaging and handling practices have a significant contribution to conservation of lubricants. Contamination commonly occurs when containers are left open in point-of-use and storage areas. The presence of moisture and particulates degrade the effectiveness of all types of lubricants, in many cases requiring that the lubricants be discarded. Recommended practice often requires packaging in sealed containers of the size, or fraction thereof, usually needed for the system. Where drum-sized or tote-bin

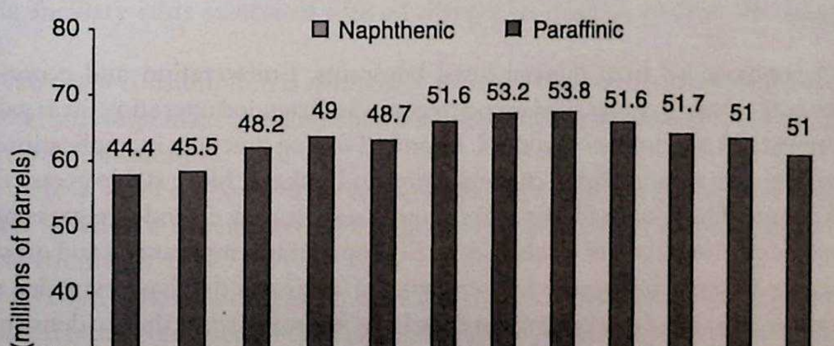


FIGURE 8.4 United States refinery production volumes. (Taken from NPRA, Lubes'n'Greases Magazine. With permission.)

containers are used, they should not be left open and storage position should be such that contamination cannot accumulate at the vent, drainage, or fill holes. Usually a horizontal drum position is indicated and such a simple consideration can conserve lubricants by minimizing discards and assuring expected performance.

8.3 Lubricant Utilization

8.3.1 Extended Life Lubricants

Extended life cycle use of lubricants is clearly conservation effective. The limiting life of many types of lubricants is determined by either intolerable contamination or additive depletion. Formulators, recognizing the importance of conservation and cost effectiveness, are providing additive packages for extended service. With sufficient life from improved additives and more robust base stocks, the primary importance is contamination and that may be controlled by vigilant contaminant exclusion and filtration. In considering the potential for extending the lubricant life cycle, the experience of airlines with turbine engine lubricants is of interest. Using synthetic lubricants, the airlines do not change lubricants between major engine maintenance events; for several thousand hours operation only minor makeup oil is added to compensate for leakage and consumption. That is the equivalent of millions of miles per oil change. Another illustration of extended life cycle lubrication is in hermetically sealed household refrigerators where continuous operation for over two decades is common. Such hermetically sealed systems are ideal for extended lubricant service life, emphasizing again the importance of contamination control.

8.3.2 Synthetic Lubricants and Functional Fluids

Conservation practices important to petroleum lubricants are also generally relevant to synthetic lubricants and functional fluids. Because synthetics can have greater oxidation stability than mineral-based lubricants, the possibilities for extended service life have even greater potential. The cost of synthetics is higher than refined petroleum products and the applications are more specialized and controlled than for petroleum lubricants. Airlines have used reprocessed phosphate ester hydraulic fluids; polyphenyl ether lubricants have also been recycled for some military use. In those cases, low initial cost as well as favorable collection and processing circumstances allowed recycling to be cost effective.

8.3.3 Greases

Most greases are compounded from mineral-based lubricants. Conservation and economics can be achieved by many of the same measures cited for petroleum oils. Extended operating life is gained through product improvement and contamination control. Improved sealing practices in applications offer major gains in conserving greases by minimizing contamination and leakage. More stable grease thickeners, as well as new and improved lubricant additives, have allowed significantly extended regreasing periods for mechanical components. Products with capabilities for high operating temperatures and others with resistance to displacement by water impingement are examples of lubricants that have extended relubrication intervals. For example, wear life of components have markedly improved while the incidence of mechanical failures have markedly decreased by modern thickeners, base oils, and additives.

8.3.4 Solid Lubricants

Solid lubricants are often used in greases, in slurries with liquid carriers, in bonded surface films, and in self-lubricating composite materials. Optimum concentrations have been determined in each application system. The extended use of solid lubricants in many applications has significant impacts on reliability and energy uses. Although the total volume of solid lubricants is less than one might consider in view of the many applications, even lesser quantities can often be used. The usual thickness of bonded films is in the range of 0.0002 to 0.0005 in., a thickness dictated by production control limitations of the coating processes.

Vacuum processes such as sputter-ion deposition allows improved film uniformity and, therefore, thinner films are used.

Similarly, with self-lubricating bulk solids, optimizing the required functions can conserve lubricating materials. In addition to friction and wear considerations in selection of self-lubricating solids, resistance to environment, mechanical stress, and thermal stress must be anticipated. Composite systems and specific function coatings can greatly extend the lives and hence conserve such materials.

8.4 Conservation of Energy

It seems counterintuitive that lubricants selected to optimize wear control may not be optimum when it comes to energy conservation. In fact, in view of today's growing pressure to reduce demand on nonrenewable energy resources and increase operating profits, we are increasingly facing a shift of emphases from past lubrication objectives. Energy-conserving lubrication offers motivation on several fronts. Consider the following:

1. When energy consumption is economized, equipment operating costs come down, translating to a boost in business profits, regardless of whether the energy source is renewable (hydro, solar, wind) or nonrenewable (coal or petroleum). For many industries, the cost of energy far exceeds the cost of maintenance, machine repair, and even downtime. A small percentage of reduction in energy consumption can translate into large returns.
2. Reduced demand on nonrenewable fossil fuels means cleaner air, reduced greenhouse gas emissions, and a healthier environment (of growing political and social importance in view of the Kyoto Protocol on global warming, ISO 14001, Clear Air Act, etc.). When fuels do not burn, there is no waste stream (smoke stack, tail pipe, etc.) and the risk of pollutants from emissions such as nitrogen oxides (the principle component of smog), sulfates, CO_2, and unburned hydrocarbons is reduced proportionally.
3. With few exceptions, lubricants and lubrication methods that reduce energy consumption will also reduce heat and wear debris generation; however, the reverse may not hold true. When heat and wear debris are reduced, less stress is imposed on additives and the base oil. The result will be longer thermal and oxidative stability, and in turn, longer oil drains, lower oil consumption, and the ancillary costs associated with oil changes (as much as 40 times the cost of the lubricant itself!).
4. When lubricant consumption is reduced, so too is the disposal of environmentally polluting waste oil and certain suspended contaminants, some of which may be hazardous and toxic; ethylene glycol (antifreeze), for example.
5. When there is better economy in the consumption of both petroleum fuels and mineral-based lube oil, there is reduced dependence on foreign sources of crude oil, including those from politically unstable countries.
6. In certain countries, including European Union nations, reductions in the consumption of nonrenewable fuels can avert energy tax penalties such as the Climate Change Levy in the United Kingdom.

In recent years, there has been growing interest in energy-conserving lubricants and energy-conserving lubrication. Note, energy-conserving lubricants relate to formulation (base stocks and additives) and their selection for machine application. In contrast, energy-conserving lubrication includes the use and application of lubricants (change intervals, delivery methods, lube volume, etc.). Both can have a marked impact on energy conservation.

Energy economy and wear control do not necessarily go hand-in-hand. In certain cases, they may be conflicting objectives. For many organizations, environmental factors and energy costs fall low on the list of priorities compared to productivity and machine reliability. In such cases, the principle objective of the practice of lubrication is to reduce wear and maximize reliability.

8.5 Energy-Conserving Fluid Properties

When formulating or selecting lubricants, the following properties are important in reducing friction and energy consumption.

8.5.1 Kinematic Viscosity

When it comes to energy economy, viscosity can be both an inhibitor and an enabler. Recalling the well-known Stribeck curve, the oil film produced by hydrodynamic lubrication is directly influenced by viscosity. However, too much viscosity causes churning losses (excessive internal oil friction) and heat production, especially in engines, gears, bearings, and hydraulics. In addition to energy losses, this increased heat can more rapidly break down the oil and its additives.

8.5.2 Viscosity Index

Kinematic viscosity by itself defines an oil's resistance only to flow and shear at a single temperature, typically 40 or 100°C. However, in normal operation, lubricating oils transition through a wide range of temperatures. As such, it is the oil's VI combined with kinematic viscosity that defines what the viscosity will be at a specific operating temperature. Will it be too high when ambient start-up temperatures are low and too low when operating temperatures are high? Likewise, what will be the time-weighted average viscosity of the lubricating oil during the machine's service life? It is this average viscosity that defines energy consumption, not the occasional temperature-based viscosity excursions that may have a greater impact on wear (cold starts for instance). In general, the significance of VI on energy conservation and wear is often sharply underestimated.

8.5.3 Non-Newtonian Properties

Fluids that exhibit shear-dependent viscosity changes (known as the non-Newtonian fluids) are known to reduce energy consumption in many machines. Good examples are VI-improved motor oils (multigrades) and many all-season hydraulic fluids. As fluid movement increases (shearing) during service, the oil's effective viscosity self-regulates slightly downward, along with energy consumption. This, in part, explains why high-VI, multigrade motor oils are generally those that are designated energy-conserving by the API.

8.5.4 High-Temperature Shear Stability

Synthetics and other high-VI base oils perform best here, as do multigrade formulations with low-VI concentrations. Temperature and viscosity shear-back at high temperatures can lead to loss of critical lubricant film strength, leading to power losses and wear. However, temporary shear thinning can also reduce parasitic viscous drag in crankshaft bearings.

8.5.5 Pressure—Viscosity Coefficient

The role of pressure–viscosity (PV) coefficient on energy consumption is not well defined in the literature. However, it is widely understood that many base oils exhibit a sharp increase in viscosity as pressure rises; a necessary quality of lubricants in achieving effective elastohydrodynamic lubrication (EHD). Some oils, such as mineral oils and PAOs (polyalphaolefins), have higher PV coefficients than others, such as ester-based synthetics and water-based fluids. While high PV coefficients may be important at reducing contact fatigue wear, in some cases, this property may contribute to lower fuel economy. The high pressure-induced viscosity in sliding frictional zones and in hydraulic systems could result in exceedingly high viscous drag energy losses.

8.5.6 Bulk Modulus

A fluid that is sponge-like and easily compressed has low bulk modulus of elasticity. The more compressible a lubricant is, the more potential for lost energy and heat production. This is especially true in hydraulic and lube oil circulating systems.

8.5.7 Boundary Film-Strength Properties

Many lubricants and hydraulic fluids can gain considerable film strength under boundary and mixed-film lubrication from the base oil, without the need for additives. A phosphate ester synthetic is an example of a fluid with intrinsic lubricity. Most other lubricants rely on additives such as friction modifiers, antiwear agents, extreme pressure (antiscuff), solid lubricants, and fatty acids. The effectiveness of these additives at reducing wear, friction, and energy consumption can vary considerably between the different additive types employed. The performance of these additives also varies by machine and application (load, speed, metallurgy, temperature, and contact geometry).

8.5.8 Grease Consistency

The consistency of grease can have an impact on energy consumption in ways similar to viscosity. The energy needed to move grease in frictional zones and in adjacent cavities by moving machine elements is affected by its consistency and shear rate (grease is non-Newtonian). So, too, energy is required in some applications to pump grease to bearings and gears. Pumping energy losses is influenced, in part, by grease consistency and thickener type.

8.5.9 Grease-Channeling Properties

A grease that has good channeling characteristics helps keep the bulk lubricant away from moving elements, avoiding excessive churning and drag losses. Poor channeling characteristics may lead to increased energy consumption, heat production, and base oil oxidation.

8.6 Wear

Wear from boundary friction can have a near-term adverse effect on fuel economy and can generate heat. Wear is often the result of such things as lubricant starvation, low viscosity, poor or degraded antiwear additive performance, dirt and other contaminants, deposits (e.g., ring grooves), etc. One researcher identified an 8°C (14.4°F) increase in bearing oil temperature, which he attributed to solid contamination of the oil.

However, there is also a long-term effect especially in engines. Over a period of time, an engine loses so much metal (rings, cylinder walls, cam follower, cam lobe, etc.) that combustion efficiency is severely impaired. (This is discussed in greater detail in the next section.) Loss of combustion efficiency directly impacts fuel economy and tailpipe emissions. In this respect, the average fuel economy performance of a motor oil over a period of 100,000 miles or more is a better assessment of its life-cycle performance as opposed to snapshot energy consumption assessments of new engines and new oils.

8.7 The Surprising Role of Particle Contamination on Fuel Economy

When a lubricant degrades, it forms reaction products that become insoluble and corrosive. So, too, the original properties of lubricity and dispersancy can become impaired as the lubricant ages and additives deplete. Much has been published about the risks associated with overextended oil drains and the buildup of carbon insolubles from combustion blow-by, especially in diesel engines.

There have been surprisingly few studies published on the impact of fine abrasives in a motor oil as it relates to fuel economy over the engine's life. Yet, it is not hard to imagine numerous scenarios in which solid abrasives suspended in the oil could diminish optimum energy performance. Below is a list of several scenarios.

8.7.1 Antiwear Additive Depletion

High soot load of crankcase lubricants has been reported to induce abrasive wear and impair the performance of zinc dialkyldithiophosphate (ZDDP) antiwear additives. The problem is more pronounced in diesel engines. Some researchers believe that soot and dust particles exhibit polar absorbencies, and as such, can tie-up the antiwear additive and diminish its ability to control friction in boundary contacts (cam nose, ring/cylinder walls, etc.). However, there appears to be greater evidence that soot itself is highly abrasive in frictional zones where dynamic clearances are 1 μm. These include cam/follower and ring reversal areas on cylinder walls.

8.7.2 Combustion Efficiency Losses

Sooner or later, wear from abrasive particles and deposits from carbon and oxide insolubles will interfere with efficient combustion in an engine. Valve train wear (cams, valve guides, etc.) can impact timing and valve movement. Wear of rings, pistons, and cylinder walls influences volumetric compression efficiency and combustion blow-by resulting in power loss. Particle-induced wear is greatest when the particle sizes are in the same range as the oil film thickness (Figure 8.5). For diesel and gasoline engines, there are a surprising number of laboratories and field studies that report the need to control particles below 10 μm. One such study by General Motors concluded that, "controlling particles in the 3 μm to 10 μm range had the greatest impact on wear rates and that engine wear rates correlated directly to the dust concentration levels in the sump [14]."

8.7.3 Frictional Losses

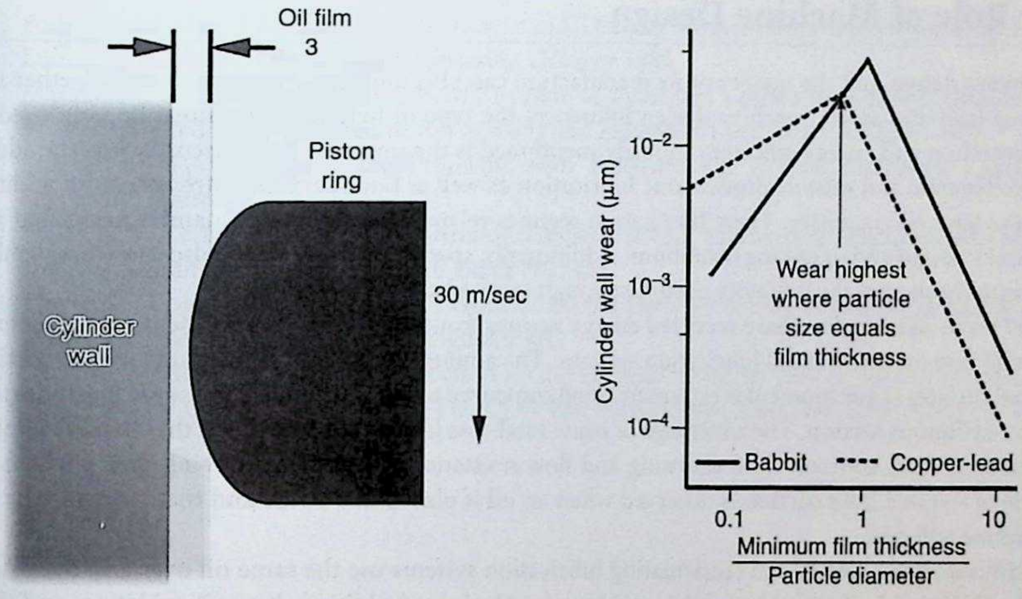
When hard clearance-size particles disrupt oil films, including boundary chemical films, increased friction and wear will occur. One researcher reports that 40 to 50% of the friction losses of an engine are attributable to the ring/cylinder contacts, with two-thirds of the loss assigned to the upper compression ring. It has been documented that there is an extremely high level of sensitivity at the ring-to-cylinder zone of the engine to both oil- and air-borne contaminants. Hence, abrasive wear in an engine's ring/cylinder area translates directly to increased friction, blow-by, compression losses, and reduced fuel economy.

8.7.4 Viscosity Churning Losses

Wear particles accelerate the oxidative thickening of aged oil. High soot load and lack of soot dispersancy can also have a large impact on oil viscosity increases. Viscosity-related internal fluid friction not only increases fuel consumption, but also generates more heat, which can lead to premature degradation of additives and base oil oxidation.

8.7.5 Stiction Losses

Deposits in the combustion chamber and valve train can lead to restricted movements in rings and valve control. When hard particle contamination agglomerates with soot and sludge to form adherent deposits between valves and guides, a tenacious interference, called stiction, results. Stiction causes power loss and engine knock. It causes the timing of the port openings and closings to vary, leading to incomplete combustion and risk of backfiring. Advanced phases of this problem can lead to a burned valve seat.



Diesel engine oil film thickness

Component	Oil film thickness (ζm)
Ring-to-cylinder	3.0–7
Rod bearings	0.5–20
Main shaft bearings	0.8–50
Turbocharger bearings	0.5–20
Piston pin bushing	0.5–15
Valve train	0–1.0
Gearing	0–1.5

FIGURE 8.5 Common oil film thickness. (From Noria Corporation. With permission.)

8.8 Role of Lubrication Practices

While lubricant formulation and selection are important, energy conservation is also influenced by machine design and lubricant application factors. A superior lubricant cannot offer redemptive relief for poor lubrication practices and machine design. Even the very best lubricants cannot protect against destruction caused by dirt and water contamination. Overgreasing of bearings is known to increase frictional losses and raise bearing temperature. The same is true for bearings that are underlubricated. For bath lubricated bearings and splash lubricated gears, a change in oil level by as little as 1/2 in. (1.3 cm) can increase temperature by more than 10°C. This, of course, translates to greater energy consumption, shorter oil life, and increased wear.

Excessively aerated oils due to worn seals and wrong oil levels can have similar effects (loss of bulk modulus). There have also been studies showing the negative effects of overextended oil change interval on fuel economy in diesel engines. Additionally, overextended filter changes cause excessive flow resistance and fluid bypass. Both can often be corrected by the frequent and proper use of oil analysis in selecting the optimum oil and filter change interval, tailored to equipment type and its application.

8.9 Role of Machine Design

A machine's design and the quality of its manufacture can also impact energy economy. Together with operating load and speed, machine design influences the type of lubricant that must be employed for wear protection and energy efficiency. Already mentioned is the importance of viscosity films produced by hydrodynamic and elastohydrodynamic lubrication as well as boundary film strength from additives and polar base oil chemistry. These lubrication regimes relate to the contact dynamics associated with a machine's design and operating conditions. Additionally, specific film thickness, also known as lambda, brings into the picture the influence of surface roughness and shaft alignment.

Many users and suppliers have reported energy savings from total-loss lubricant delivery technologies such as oil mist and centralized lubrication systems. The amount of fluid that a machine uses to lubricate frictional surfaces at any moment is extremely small compared to the amount of fluid some machines must keep in continuous motion. The advantage of some total-loss lubrication systems is that there is minimal loss of energy from constant fluid churning and flow resistance of lubricants moving through lines. An example of internal fluid friction is observed when an oil is placed in a bottle and then shaken. The oil's temperature will rise.

In addition, bath, splash, and recalculating lubrication systems use the same oil over and over. As we all know, this reused oil over time can become impaired by loss of additives, base oil oxidation, and rising concentrations of contaminants. In contrast, when well engineered and in the right application, oil mist and other certain total-loss systems can provide a continuous supply of fresh, clean, and dry new oil. Energy consumption is also influenced by the size and type of fittings, oil lines, and filters.

8.10 Environmental Stewardship

In summary, lubricants, lubrication, and contamination play no small role in reducing energy consumption and the general wasteful use of petroleum products, including lubricants. Increasingly the selection and use of lubricants is going to stress greater importance on energy and environmental impact. At the same time, we will not lose sight of other vital objectives including machine reliability and safety.

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