

Physical and Chemical Properties of Engine Oils—SAE J357a

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1. Introduction—This SAE Information Report discusses a number of the physical and chemical properties of new and used engine oils. Where appropriate, standardized methods of test for these properties are listed. This report was prepared to provide those concerned with the design and maintenance of internal combustion engines with information relative to the terms used to describe engine lubricants.

The lubricants used in modern engines must be multifunctional. In addition to the basic function of lubricating (reducing friction and wear between moving parts), the oil must also provide a seal between cylinder walls and pistons, it must carry heat away from critical areas, and it must help keep the engine clean by dispersion of contaminants. Protection against rust and corrosion on internal engine parts is also an important function of the lubricant. In performing these functions, it is subjected to extreme environmental conditions. Engine component temperatures can range from below zero during shutdown periods to 200°C or higher while the engine is in operation. An oxidizing atmosphere is usually present in the engine. A wide variety of contaminants is introduced into the engine oil system. Some are inert; others either are chemically active, or they catalyze undesirable chemical reactions.

2. General Description of Engine Oil Components—Fully formulated lubricants consist of (1) base stocks and (2) the additives that are necessary to produce the required performance in the finished product. Base stocks are of two general types; petroleum and synthetic. The additives used to enhance performance consist of many types of chemicals. These engine oil components will be described in the following sections.

2.1 Petroleum Base Stocks—Crude petroleum oils have as principal components three basic types of hydrocarbon molecules; that is, paraffinic, naphthenic, and aromatic. The type or types of molecules that predominate are a basis for classifying crude oils as follows:

Crude Oil Type	Predominant Hydrocarbon
Paraffinic	Paraffinic
Naphthenic	Naphthenic
Asphaltic	Naphthenic/Aromatic
Mixed Base	Paraffinic/Naphthenic/Aromatic

Crude oils as they come from the ground can be a mixture of the following: gaseous products, gasoline, diesel fuel, lubricating oil stocks, asphalt, etc. The various classes of products are separated initially through vacuum and/or atmospheric distillation. Precipitation of the heaviest, most viscous fractions using a solvent such as propane can also be practiced. The lubricating oil fractions resulting therefrom provide a series of base stocks of various volatilities and viscosities that are referred to as neutral fractions and bright stock. Generally speaking, the viscosities for the neutral fractions range from about 13–130 cSt at 40°C. The bright stock fraction will have a viscosity of from 500–1100 cSt at 40°C. These fractions generally require further refining to make them suitable for engine oil applications.

Where wax is present in the lubricant fraction, a process such as methylethyl ketone solvent dewaxing or propane solvent dewaxing is used to remove some waxy materials which crystallize and/or congeal at low temperatures and thereby impede low temperature flow. Also found in the as-distilled base stock fractions will be unstable components such as nitrogen and sulfur-containing compounds, metal-containing compounds, and aromatic hydrocarbons of varying structures. Many of these compounds can have an adverse effect on the efficiency of the additives used in engine oil applications, and they should be removed through extraction processes using solvents such as phenol or furfural, or modified by hydrotreating or hydrocracking.

Normally, wax is removed after solvent refining (furfural, phenol). Thus, in a simplified description, the refining process consists of (1) fractionation of the crude oil into neutrals and bright stocks suitable for blending to

various viscosities, (2) removal of unstable components to enhance base oil stability and additive response and, (3) removal of some waxy hydrocarbons to improve low temperature fluidity characteristics.

The physical and chemical properties of the finished base stocks will not be solely a function of crude source but will also be dependent upon the processes employed and the degree of refining severity employed. The engine oil compounder blends the various components to achieve the viscometric properties required and adds additive agents to achieve the performance levels that are desired for a given application.

2.2 Synthetic Base Stocks—A number of chemical compounds also have been found to be suitable as base stocks for engine oils. These base stocks are manufactured by organic reactions such as alkylation, condensation, esterification, polymerization, etc. The starting material(s) may be one or more relatively pure organic compounds, generally of a simple composition, which are usually obtained by processing fractions from petroleum, vegetable, and animal sources.

Classes of chemical compounds which might be used as a source of synthetic base stocks are shown in the following table. Those marked with an asterisk are of greatest current interest for technical and economic reasons.

(a) Synthetic hydrocarbons such as:	Alkylated Aromatics* Polyalphaolefins* Polybutenes*
(b) Organic Esters such as:	Dibasic Acid Esters* Polyol Esters* Polyesters
(c) Others such as:	Halogenated Hydrocarbons Phosphate Esters Polyglycols* Polyphenyl Esters Silicate Esters Silicones

A synthetic lubricant base stock may consist of any of the above or any mixture of the above which are compatible with each other.

The additive agents necessary in both petroleum base stock and synthetic base stock engine oils are also synthesized materials. However, even though these materials are synthesized they should be referred to as additives and not included in the base stock description.

Some synthetic base stocks are compatible with petroleum base stocks and the two types may be blended together to obtain desired physical and chemical properties. Such combinations should be identified as blends of synthetic and petroleum base stocks.

2.3 Additive Agents—A lubricant additive agent is defined as a material designed to enhance the performance properties of the base oil. These additive agents are used at concentration levels ranging from several parts per million to greater than 10 volume percent. Generally these are materials which have been chemically synthesized to supply the desired performance features, and they frequently contain an oil-solubilizing hydrocarbon as part of the molecule. Some additive agents are naturally occurring materials which have undergone only minor modifications to obtain the desired property. The various types of additives are classified according to their primary functions as follows: antifoam agent, antirust agent, antiwear agent, corrosion inhibitor, detergent, dispersant, extreme pressure agent, friction reducer, oxidation inhibitor, pour point depressant, and viscosity index improver. Some additives possess multifunctional properties.

The unique performance features contributed by additives are required to satisfy the lubrication needs of today's engines, oil change intervals, and service conditions. Some additives may either enhance or interfere with the function of another. Therefore, the finished engine oil is formulated to achieve a balanced performance through combined properties attributable to both the base oil and the additives.

The Ø symbol is for the convenience of the user in locating areas where technical revisions have been made to the previous issue of the report. If the symbol is next to the report title, it indicates a complete revision of the report.

3. Physical and Chemical Properties—A tabulation of the physical and chemical properties of an oil can assist the user and the oil refiner in defining a consistently uniform product. However, these properties cannot be used to establish oil performance which is related to the requirements of the engine as defined by design parameters and the service in which it is used. Some of the performance characteristics of engine oils are discussed in SAE J304 and SAE J183.

While the physical and chemical properties of an oil do not generally define oil performance, these individual properties are meaningful and are related to the oil's ability to fulfill its function as a lubricant. The following sections discuss these properties and their lubrication function.

3.1 Tests Pertinent to Both New and Used Oils

3.1.1 Viscosity and Viscosity Index—The viscosity of an oil is a measure of its resistance to flow. The viscosity of an oil decreases with increasing temperature and vice versa. Newtonian oils do not experience a viscosity change with change in shear rate at a given temperature; whereas non-Newtonian oils, such as engine oils compounded with viscosity index improvers or oils with some wax particles present, do show a decrease in viscosity when the shear rate is increased. Since some of the viscosity decrease encountered at high shear rate will be regained when the shear stress is removed, this decrease is referred to as a temporary shear loss. That viscosity which is not regained is referred to as a permanent shear loss. Therefore, non-Newtonian oil may exhibit several different *temporary* or apparent viscosities at various locations within an engine due to differences in shear rates. The magnitude of the temporary and permanent loss of viscosity depends upon the nature of the viscosity index improver and the conditions under which it is used. Furthermore, the oil viscosity also varies with pressure. Oil viscosity will change in service through shearing, dilution by fuel fractions, oxidation, volatilization, contamination by combustion by-products, etc. To be considered pertinent, the viscosity of an engine oil must be determined using procedures which have been shown to give results which correlate with those found in engines.

Low shear rate measurement of viscosity is usually made using ASTM Method D445 and reported in centistokes. The test temperatures most commonly used are 40°C and 100°C. Several special methods are in use to measure oil viscosity at high shear rates. Results obtained from ASTM Method D2602, using a high shear rate instrument known as the Cold Cranking Simulator, have been correlated with the low temperature cranking performance of engine oils. It is the method adopted for classifying oils according to viscosity at -18°C in SAE J300.

The viscosity-temperature relationship of an oil depends primarily on the nature or composition of the oil. A minimum change in viscosity with temperature is desirable. ASTM Method D341, Standard Viscosity-Temperature Charts, provides a series of six charts so constructed that for any given oil, the viscosity-temperature values can be approximated by a straight line over the temperature range in which the oil is a Newtonian liquid. ASTM Method D2270, Viscosity Index, provides a means for calculating an empirical number that yields a relative evaluation of the viscosity-temperature characteristics of the fluid in question when compared to two reference oils having the same viscosity at 100°C. The higher the viscosity index, the smaller will be the change in viscosity with change in temperature.

The relationship of viscosity and temperature defined by Viscosity Index is not affected by shear rate for Newtonian oils. However, the physical properties of non-Newtonian oils (such as those containing polymers) are not fully described by the Viscosity Index derived from low shear rate viscosity measurements only. The viscosity-temperature relationship of polymer thickened oils is a function of the shear rate applied in measuring viscosity. At high shear rates, the improvement in viscosity-temperature relationship imparted by the polymer may be reduced relative to the data found at low shear rates.

The viscosity of an oil at low temperature is important in cold starting due to the effect on cranking speed as well as the power required to accelerate the engine to sustained operating speed. Viscosity is also a factor in the time required to develop the necessary oil pressure and lubrication throughout the engine after cold starting. A relatively low viscosity oil, defined by low temperature measurement techniques, is desirable to aid in both cold starting ability and lubrication. The viscosity, as measured at low temperature with the Cold Cranking Simulator, correlates with engine cold cranking performance. However, low viscosity at

low temperature as measured by the Cold Cranking Simulator, a high shear rate device, does not assure prompt development of engine oil pressure and flow from the pump to remote areas of the engine. Low shear rate viscosity is critical in determining flow to the pump inlet and throughout the oil system.

The viscosity of engine oils decreases as temperature increases. An oil with proper high temperature viscosity characteristics must be selected for the high temperature operation associated with continuous running of an engine. Increasing the high temperature viscosity of the oil in use will generally reduce oil consumption, leakage, blowby, and wear. Alternatively, both the oil pressure and friction associated with oil film shearing are increased with the use of higher viscosity oils.

The Fuels and Lubricants Technical Committee is currently evaluating new methods of test for viscosity which may lead to a revision of the SAE Engine Oil Viscosity Classification System.

3.1.2 Cloud Point and Pour Point—The cloud point of an oil is defined as the temperature at which a cloud or haze appears at the bottom of a test jar when testing a moisture-free oil by ASTM Method D2500. The haze indicates the presence of some insoluble fractions, such as wax, at the temperature noted. In most applications this haze will have little practical significance.

The pour point of an oil is defined as the lowest temperature at which it can be poured when tested by ASTM Method D97. The pour point has some relationship to the rate at which oil will be supplied to the suction side of the oil pump. However, more precise and correlatable viscometric methods are being developed which will predict the ability of an oil flow to the oil pump and throughout the system at low temperature. In actual practice, the oil in the crankcase will be a mixture of oil and small amounts of fuel fractions, the composition depending on several factors. (See paragraph on Fuel Dilution).

Some oils display an increase in pour point when exposed to a repeated temperature variation. Federal Test Method, Standard No. 791a, Method 203 of January 15, 1969 describes a procedure for evaluating the tendency of the pour point to increase as follows: "This method is used for determining the pour stability of blends of winter grade (regular, heavy duty, and diluted heavy duty) motor oil, and certain types of hydraulic fluids. It consists of subjecting the sample to specified temperature changes for six days, and determining the lowest temperature at which the oil will remain fluid."

The cloud and pour points of engine oils do not have a direct relationship with the cranking or starting of engines.

3.1.3 Flash and Fire Point—The flash point of a petroleum product is the temperature to which the product must be heated under specific conditions to give off sufficient vapor to form a mixture with air that can be ignited momentarily by a specified flame.

Fire point is the temperature to which the product must be heated under prescribed conditions to burn continuously when the mixture of vapor and air is ignited by a specified flame.

Flash and fire points are significant from the viewpoint of safety and should be related to the temperatures to which petroleum products will be subjected in storage, transportation, and use. Normally, engine oils will present no hazards in this respect. For engine oil, relatively low flash and fire points are indications of oil volatility, and thus may be related to oil consumption at high temperature. The minimum flash point that can be tolerated must be determined in each application. Flash point is also used to indicate contamination by a volatile product such as gasoline. ASTM Method D56, Flash Point by Tag Closed Tester, ASTM Method D93, Flash Point by Pensky-Martens Closed Tester, ASTM Method D92, Flash and Fire Points by Cleveland Open Cup, and ASTM Method D1310, Flash Point by Tag Open Cup Tester, are all methods of obtaining the above type of information. ASTM Method D92 is the preferred method for engine oils.

3.1.4 Distillation Data—The volatility characteristics of engine oils can be defined by distillation procedures outlined in the ASTM Methods. ASTM Method D1160 is a reduced pressure (vacuum) distillation method. This is needed with engine oils since the components generally used in such product require distillation at reduced pressure (hence lower temperature) to prevent cracking.

ASTM Method D2887, which gives boiling range distribution data by gas chromatography, is gaining acceptance and is increasingly used instead of

ASTM Method D1160. Correlations between performance characteristics, such as oil consumption and the volatility characteristics of the oil in use must be developed with actual engine test data.

3.1.5 Alkalinity-Acidity—The alkalinity or acidity characteristics of petroleum products are defined by the neutralization number, the acid number, or the base number obtained by one of several standardized methods. Methods currently used include ASTM Method D664, Neutralization Value by Potentiometric Titration, ASTM Method D974, Neutralization Value by Color-Indicator Titration, and ASTM Method D2896, Total Base Number of Petroleum Products by Potentiometric Perchloric Acid Titration. By ASTM Method D664, engine oils may have both acidic and alkaline characteristics, depending upon the nature of the additives used. Certain salts which are commonly used as engine oil additives, such as zinc dithiophosphates, will undergo exchange reactions with the standard titrant KOH and thereby produce false acid values. Changes in alkalinity or acidity with use give some indication of the nature of the changes taking place in the engine oil. For instance, a reduction in alkalinity can be ascribed to depletion of additive components. An increase in acidity may be ascribed to oxidation and/or contamination by products of combustion. No general relationship between bearing corrosion and acid or base number is known. None of the aforementioned methods is intended to be used to predict performance of an oil under service conditions. They can be used to follow general deterioration rates of oils in service.

3.1.6 Carbon Residue—The base stock components of engine oils are mixtures of many compounds which differ widely in their physical and chemical properties. Some vaporize at atmospheric pressure without leaving an appreciable residue. When destructively distilled, the non-volatile compounds may leave a carbonaceous material known as carbon residue. Two ASTM Methods are used for evaluating base stocks in this respect. These are ASTM Method D189, Conradson Carbon Residue, and ASTM Method D524, Ramsbottom Carbon Residue of Petroleum Products. Engine oils which contain ash-forming constituents, such as the additives commonly used in formulating oils, may have misleadingly high carbon residues by either method. Carbon residue has little value as a guide for predicting deposit-forming tendencies in engines.

3.1.7 Ash Content—The amount of ash formed from burning engine oils may be obtained by ASTM Method D482, Ash from Petroleum Products, but, ASTM Method D874, Sulfated Ash from Lubricating Oils and Additives, is the method currently and most commonly used. The ash produced from burning new engine oils is principally related to the quantity of ash-producing additive contained therein. The ash produced by used oils will be a function, not only of the amount of ash-producing additive agents in the original oil, but also of the amount of contaminants such as lead compounds present in the engine oil if the engine is operated on a leaded fuel. High values can also result from other contaminants such as dirt, iron oxide, wear metals, and corrosion products. The ash from an oil will contribute to deposits on combustion chamber surfaces, spark plugs, and exhaust valves. However, the mechanism for the buildup of deposit in these areas is very complex and depends upon many variables in addition to the ash content of the oil.

3.1.8 Compatibility—Engine oils are expected to be homogeneous and completely miscible with all types of engine oils with which they might be mixed in service. When oils are mixed in any proportion, there should be no evidence of separation either of the components or of the oils when the mixed oils are heated to a temperature as high as 225°C and cooled to a temperature as low as the pour point of the mixture. The homogeneity and miscibility test currently used to evaluate automotive engine oils is Standard No. 791B, Federal Test Method 3470.

3.1.9 Foaming—Antifoam quality is a performance characteristic which can be and has been evaluated by specially developed engine tests. A bench test for determining this quality is ASTM Method D892, Foaming Characteristics of Lubricating Oils. As with any bench test, the degree of correlation with actual service should be determined before applying ASTM D892 results to specifications, etc.

3.1.10 Gravity, Color, Odor—The gravity (density) and color of engine oils may frequently be used in specifying engine oils. ASTM Method D287, API Gravity of Crude Petroleum Products (Hydrometer Method), ASTM Method D1298, Density, Specific Gravity or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method, and ASTM

Method D941, Density and Specific Gravity by Lipkin Bicapillary Pycnometer, may be used to determine the gravity and density characteristics of oils. The color of engine oils may be specified by using ASTM Method D156, Saybolt Color of Petroleum Products or ASTM Method D1500, ASTM Color of Petroleum Products (ASTM Color Scale). These factors are generally associated with the quality control of manufactured products rather than with performance characteristics.

It is expected that engine oils will not produce offensive odors due to the nature of the base oils or the additive agents with which the oil is compounded. Offensive odors should not be generated during either use or prolonged storage of an engine oil. There are no standardized odor tests available.

3.1.11 Elemental Analysis—Elemental analysis of engine oils is often used as a means of quality control. Instrumental analytical techniques such as emission spectrography, atomic absorption spectrometry, x-ray diffraction, etc. are useful in this respect. Similar analysis of used oils will provide information relative to the changes in the chemical content of the engine oil. These data can also give a measure of contamination by materials such as products of combustion, particularly with engines using leaded gasoline. They can also provide information relative to the extent of wear in the engine. Concentrations of the following elements are commonly determined.

1. Additive elements such as barium, calcium, zinc, phosphorus, sulfur, and magnesium.
2. Contaminants such as lead, silica, etc.
3. Wear metals such as iron, copper, lead, tin, aluminum, etc.

3.1.12 Hydrocarbon Structure—Infrared spectrophotometry techniques are valuable in determining the hydrocarbon structures found in lubricant stocks and additives. Changes in these structures can be determined by analysis of used oil samples. It is also possible to identify the presence of hydrocarbon contaminants, water, glycol, and similar materials in used oil samples.

3.2 Tests Pertinent to Used Oils

3.2.1 Used Oil Properties—The analysis of used engine oils may be of value in establishing the condition of the oil with respect to its useful life, and may be helpful in estimating the condition of the engine. To be of most value, used oil analyses must be compared with similar analyses of the new oil. The conditions of usage must also be considered in evaluating used oil analyses.

3.2.2 Insoluble Content—Insoluble materials found in both new and used engine oils may be determined using ASTM Method D91, Precipitation Number of Lubricating Oils, or the more frequently used ASTM Method D893, Insolubles in Used Lubricating Oils. Use of these methods permits an evaluation of the contaminant content and buildup of insoluble materials through oxidation, etc. However, the results must be judged with care, because minor changes in the analytical procedure can produce different results. For example, the age and purity of the coagulant solutions specified in ASTM Method D893 can affect the results obtained.

With modern, highly dispersant oils, insoluble determinations become exceedingly difficult. Because of the extremely small particle size generally found in these oils, coagulants, super centrifuges, ultrafine filters, and other procedural and equipment refinements may be required in order to make accurate determinations. ASTM Committee RDD-VI-B is investigating means of accurately and reproducibly determining the insoluble content of highly dispersant oils.

3.2.3 Coolant (Moisture) Content—Small quantities of water will frequently be found in used engine oil as contamination from products of combustion, leakage from the cooling system, or condensation from atmospheric moisture. ASTM Method D95, Water in Petroleum Products and Bituminous Materials by Distillation, defines a procedure for determination of the water content of used oil. For a qualitative determination, a commonly used simple test is to heat a drop of oil on aluminum foil. A snapping or crackling sound indicates free or suspended water in the oil. Cooling system leakage can be suspected when water is found in the oil on cooldown after operation for several hours under high temperature conditions such as interstate highway driving. The presence of glycol can be a more definite indication of leakage. It is detected best by