The World of Engine Oils - Comparison of Physical and Chemical Properties of 4000 Oils Collected from the Market

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SUMMARY

As engines are rapidly changing in design so, too, are engine oils. The demands placed on today's oils far surpass the demands of little more than a decade ago. In many cases, oil manufacturers rise to meet the challenge of evolving technology, providing the motorized world with products of engineering ingenuity. In other cases, oils fall short of expectations and requirements. This paper presents a study of oils collected over several years from three industrialized regions of the world -- North America, Europe, and Japan. Characteristics and performance capabilities are compared among regions and over time. The reader is left with a interesting overview of the engine oil industry.

INTRODUCTION

Industry Trends for Engines and Oils

The increasingly rapid pace with which engines are being modified and redesigned to meet power, emission, economy, performance, and durability demands is echoed by the rate of change in engine oils which must lubricate these machines. Manufacturers have also expressed a greater concern that oils be consistently blended and marketed for these engines to agreed standards.

The consequence has been several years of effort and compromise among the automotive, petroleum, and additive industries to reach agreement on definitions of the quality and performance of engine oils for engines expected to maintain emission control and freedom from repair over considerably more than one hundred thousand kilometers.

IOM - The Source for Lubricant Information

The data used for this paper was generated from the Institute of Materials (IOM) Engine Oil Databases. Three databases were used -- the *North American Database* consisting of over 3,200 engine oils analyzed over the last 12 years, the *Japanese Database* consisting of over 400 engine oils collected over the last four years, and the *European Database* also consisting of over 400 engine oils collected over the last four years.

Engine oils were collected from retail markets throughout the world using IOM's experienced network of collectors. Collection of oils was carefully planned to obtain a cross-section of samples which would simulate the market as closely as possible. Testing was conducted by closely monitored independent laboratories using blind-coded samples. Data accuracy was verified by interspersing blind-coded reference oils with the oil samples at a rate of one reference oil to every fifteen oil samples. An electronic error-detection program was also used to flag test values which fell outside established parameters. Suspicious data was rerun for confirmation before reporting. Finally all test results were reviewed by the IOM Technical Advisory Board, consisting of industry professionals with an average of 40 years of lubrication experience.

It is important to note that the histograms and averages presented throughout this paper reflect 3000+ North American oils collected over 12 years, compared to 400+ oils each for Europe and Japan collected over four years. This difference in sample time and quantity should be taken into consideration when applying the data.

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I. HIGH TEMPERATURE VISCOSITY

High Temperature, Low Shear Viscosity
Two methods of measuring low shear viscosity at higher temperatures are presented and discussed here.

Kinematic viscosity (viscosity divided by density) has long been used as a standard viscometric measurement technique, inherently giving it historical value as a reference point. The relevance of this test to the industry is primarily that it determines an oil's conformity to the SAE J300 Viscosity Classification System. It has been related to certain forms of oil consumption and only recently (when high temperature high shear viscometry supplanted it) was used as a guide for selecting an appropriate viscosity of oil.

Figures 1 through 3 on Page 3 compare the kinematic viscosities of oils from North America, Europe, and Japan. Control lines are included, denoting acceptable limits for each grade, as specified by SAE J300. As is evident, higher viscosity oils, such as 15W50s and 20W50s fall within SAE specifications more often than lower viscosity grades, such as 5W30s, 10W30s, and 10W40s. North American oils fall outside SAE guidelines more often than European and Japanese oils. This may be because the North American market tends to favor lower viscosity oils.

After determining how well the oils meet SAE viscosity grade specifications as fresh oils, the question of how well they stay in grade when exposed to shear degradation comes to mind? ***Figures 4 through 6*** on Page 3 compare the kinematic viscosities of the same oils after 20 cycles of shear degradation using the Fuel Injection Shear Stability Test (FISST).

Although the European oils faired the best, multigrade oils in all three regions experienced considerable difficulty staying in grade after degradation. Higher viscosity oils, such as the 15W50s and 20W50s, experienced the most viscosity loss across the board; more than half fell out of grade.

Dynamic viscosity (or pure viscosity) measurements eliminated the confusion of density differences. The low shear viscometric device used for these measurements is the Tannas Basic Rotary (TBR) Viscometer. The TBR is a rotational viscometer measuring oil viscosity at 150 °C and shear rates of 1 to 200 reciprocal seconds. Since viscosity measurements are taken in centipoise, they can be directly compared to viscosity measurements generated on other instruments. This is an important benefit if one is interested in determining permanent and temporary viscosity loss levels of oils or characterizing the molecular weight and distribution of VI Improvers.

Figure 7 shown below compares the high temperature, low shear dynamic viscosity of oils from the three world regions. It is interesting to note that North American and Japanese oils share similar low shear viscometric properties, with bi-modal peaks at approximately 3.4 cP and 4.5 cP. Oils from both regions also cover about the same viscosity range, from a low of around 2.7 cP to a high of approximately 6.5 cP. European oils, on the other hand, exhibit greater low shear viscometric properties, with bi-modal peaks at about 4.5 cP and 5.1 cP. There also tends to be less variation among European oils. Viscosity values fall within a tighter range, from 3.5 cP to 6.5 cP.

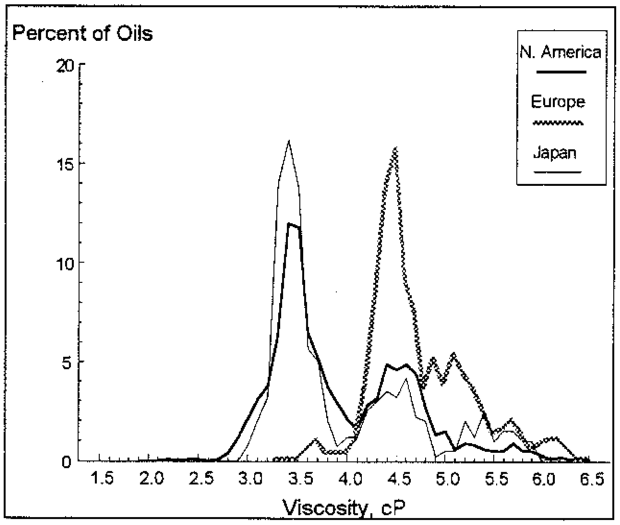

Figure 7 - High temperature, low shear dynamic viscosity, all regions

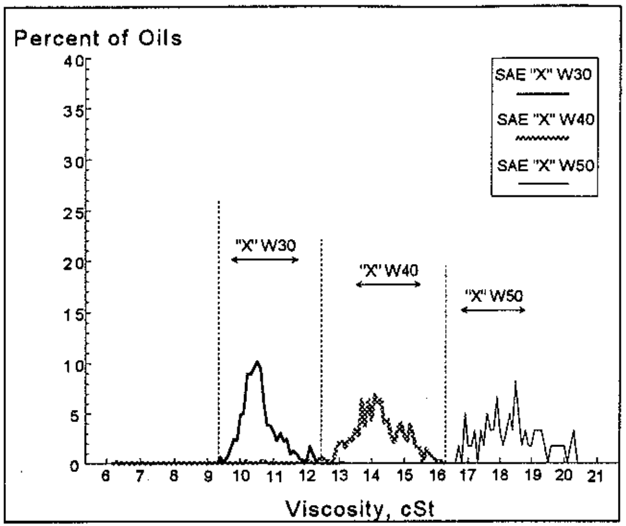

Figure 1 - Kinematic viscosity at 100 °C, North American oils

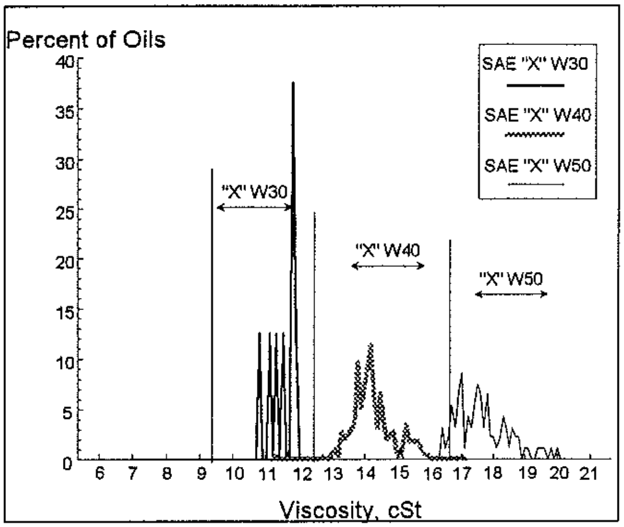

Figure 2 - Kinematic viscosity at 100 °C, European oils

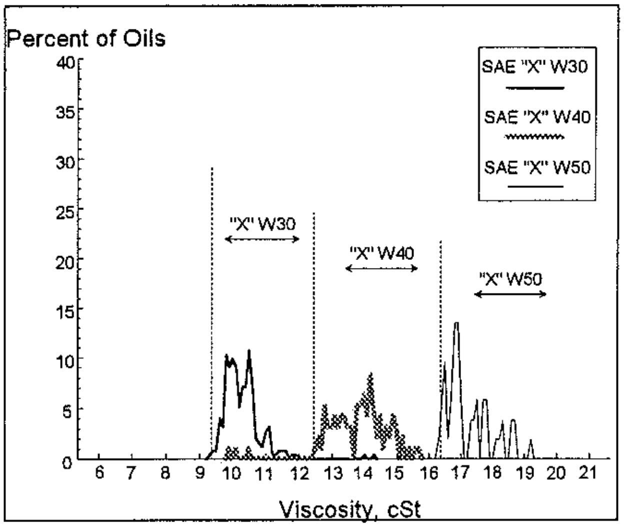

Figure 3 - Kinematic viscosity at 100 °C , Japanese oils

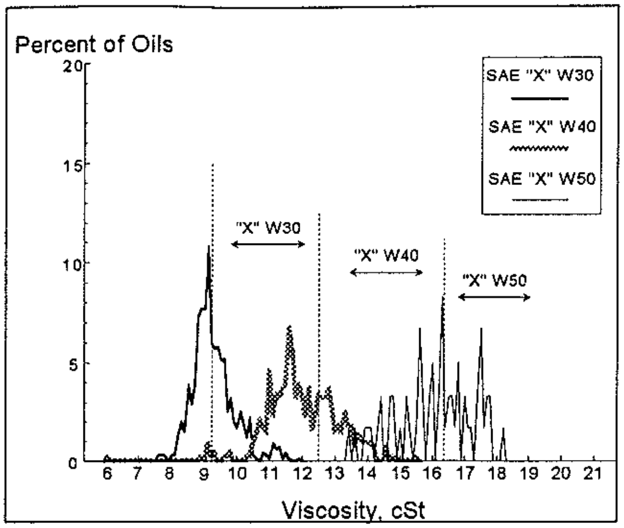

Figure 4 - Degraded kinematic viscosity at 100 °C, North American oils

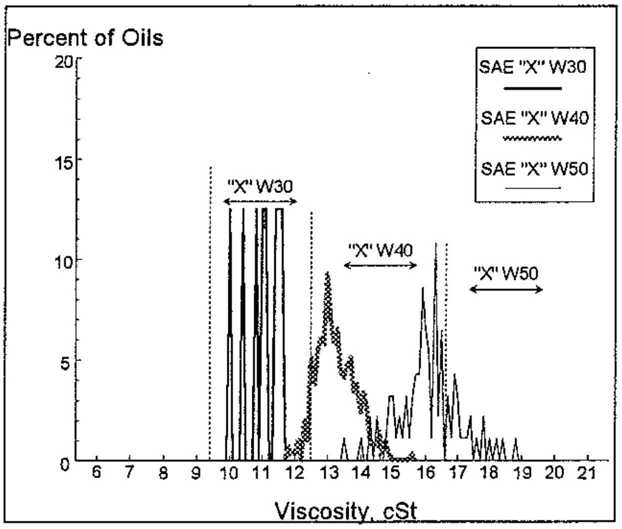

Figure 5 - Degraded kinematic viscosity at 100 °C, European oils

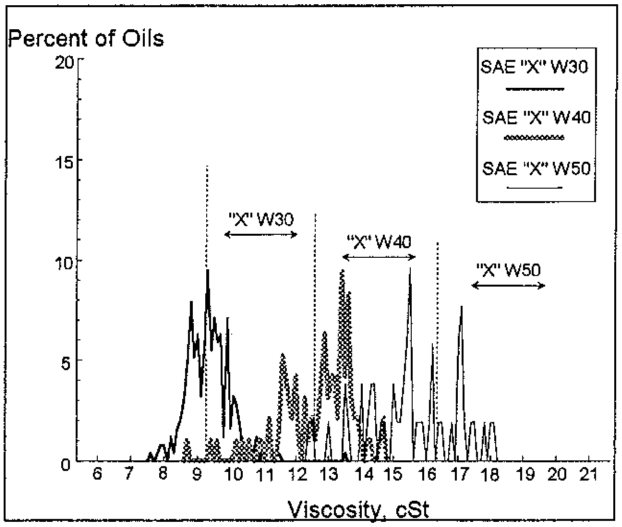

Figure 6 - Degraded kinematic viscosity at 100 °C, Japanese oils

High Temperature, High Shear Viscosity

With modern engines and multigrade oils, low shear measurements are often supplemented with other, more severe, viscosity measuring techniques which more closely simulate the engine stress in high load, high speed areas.

In an effort to simulate the ability of an oil to meet the hydrodynamic needs of the engine under operating conditions, high temperature/high shear viscosity is measured using the Tapered Bearing Simulator-Viscometer (TBS). This device determines viscosity at 150 °C and shear rates of at least to one million reciprocal seconds, simulating the stress placed on an oil in the journal bearings and on the cylinder walls during engine operation. Within limits, the higher the TBS viscosity value, especially after degrading the oil using a shear stability test, the more bearing protection can be expected. However, it should be noted that higher operating viscosities can reduce fuel efficiency to some degree.

Figures 8 through 11 present comparisons of average high temperature, high shear viscosity values over the years and across the regions for SAE 10W30, 10W40, 15W40, and 20W50 grade oils. As with low shear viscosity, European oils tend to have higher values and less diversification across SAE grades.

For 10W30 oils, North America and Japan share similar viscosity characteristics. Both regions have remained fairly constant over the years, with values hovering around 3.13 cP. Although there are only two years of 10W30 data for Europe, oils from that region have higher viscometric properties and values are increasing.

For 10W40 oils, European oils have the highest values again and have remained constant over the years. Japan started out with higher viscosity values, similar to European oils, but has been trending down. North American oils have been exhibiting a slight increase in viscosity over the years.

SAE 15W40 and 20W50 oils present interesting differences. Japan maintains a higher level of viscosity for 15W40 oils, even surpassing Europe, but drops back down for 20W50 oils. North America and Europe share similar, consistent properties for 15W40 and 20W50 oils.

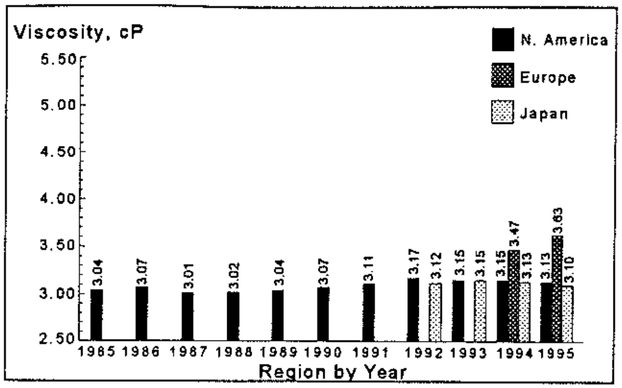

Figure 8 - Average high temperature, high shear values, 10W30 oils

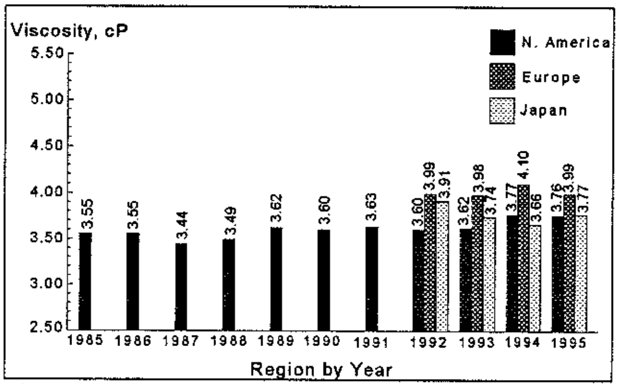

Figure 9 - Average high temperature, high shear values, 10W40 oils

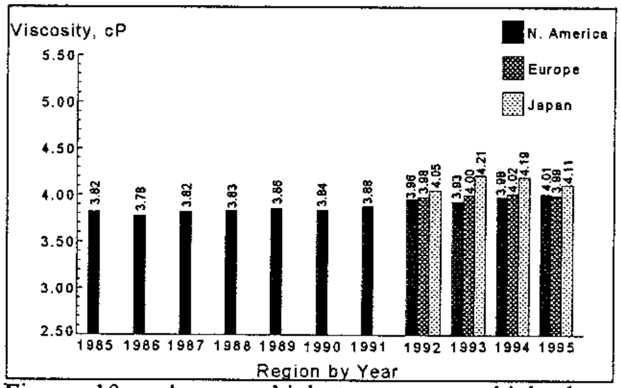

Figure 10 - Average high temperature, high shear values, 15W40 oils

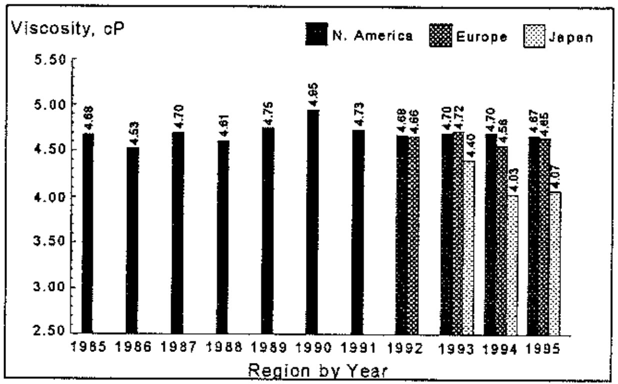

Figure 11 - Average high temperature, high shear values, 20W50 oils

Of further interest may be a comparison of the differences between low shear and high shear viscosities among regions to determine the effect of increasing shear rates on the VI polymers used in multigrade oils. One would predict that viscosity differences would not be noticeable in single grade oils.

To demonstrate this, ***Figure 12*** below presents a comparison of low shear and high shear viscosity values for North American single grade oils. As expected, there is very little difference overall. However, one interesting peak emerges in the high shear curve, depicting oils that are marketed as single grade oils, yet contain VI polymers susceptible to shearing like multigrade oils. ***Figure 13*** to the right presents the same comparison, only with multigrade North American oils. Note the shearing effect on the polymers as the oils go from low shear to high shear.

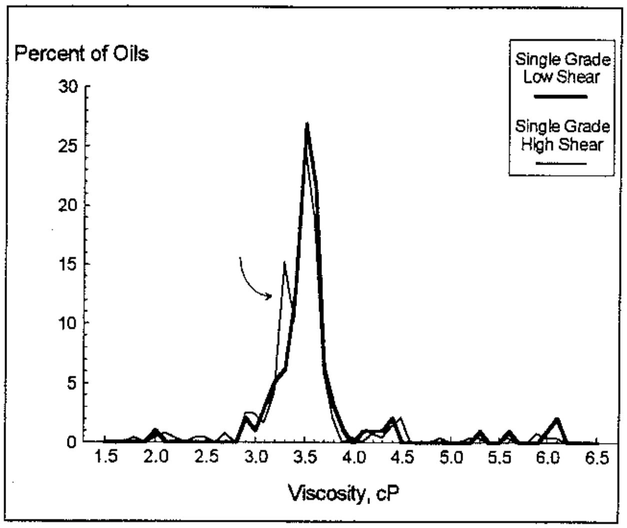

Figure 12 - Low shear viscosity vs. high shear viscosity, North American single grade oils

Figures 14 and 15 to the right present the differences between low shear and high shear viscosity for European and Japanese oils. As discussed earlier, European oils tend to have higher viscosity values and a narrower viscosity range. Japanese oils cluster more distinctly into three viscosity grade zones and are spread over a wider range. North American multigrade oils also cover a wider viscosity range but are spread out more evenly than European and Japanese oils. All three regions experience a similar amount of decrease in viscosity when moving from low shear to high shear rates. This will be discussed more in the next section.

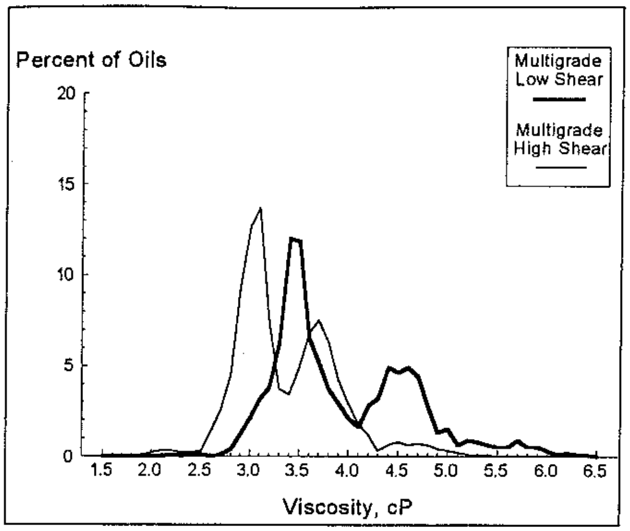

Figure 13 - Low shear viscosity vs. high shear viscosity, North American multigrade oils

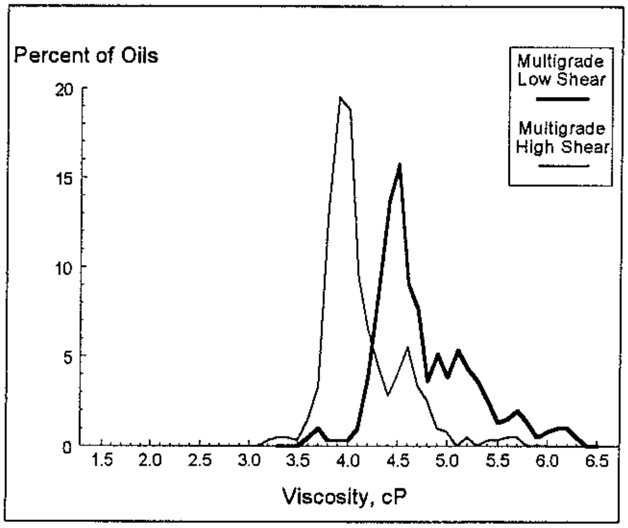

Figure 14 - Low shear viscosity vs. high shear viscosity, European multigrade oils

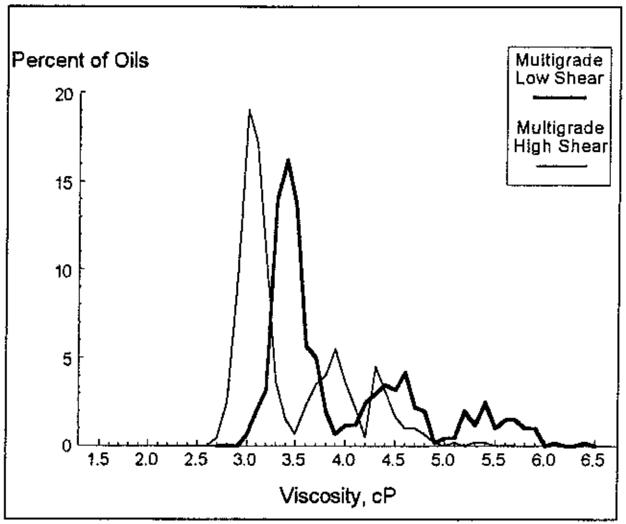

Figure 15 - Low shear viscosity vs. high shear viscosity, Japanese multigrade oils

Temporary Viscosity Loss (TVL)
The change in the viscosity of an oil as a result of orientation of the polymeric molecule due to increasing shear rates is its temporary viscosity loss. The level of temporary viscosity loss experienced with an oil is dependent on the concentration of the VI Improver, the size and structure of the polymeric molecule, and the molecular weight distribution.

The difference between the low shear and high shear viscosities presented on the previous page is the temporary viscosity loss experienced by oils from the three regions and is shown graphically in ***Figure 16***. The curves depict similar temporary viscosity loss characteristics among oils from each of the three regions.

Permanent Viscosity Loss (PVL)
In contrast to temporary viscosity loss, permanent viscosity loss is a rupturing of the polymeric chain as a result of destructive shearing conditions experienced during the process of lubrication. Permanent viscosity loss values provide a measure of the ability of the VI Improver to resist forces of degradation. Permanent viscosity loss varies from oil to oil because of the concentration of the VI Improver, the molecular weight and distribution of the polymeric chemistry, the VI Improver chemistry and molecular arrangement, the VI Improver solvency in the base fluid, and the degradation device used.

Figure 17 shows the permanent viscosity loss experienced by the oils from all three regions. Although temporary viscosity loss was similar among regions, quite distinct differences between the polymeric additives become clear when comparing permanent viscosity loss.

European oils experience the lowest permanent viscosity loss overall, with values clustering between 2 % and 10 % loss. Japanese oils fall over a slightly wider range but still group primarily around 2 % to 10 % loss with a substantial secondary peak between 10 % and 16 %. North American oils are also spread over a wider range, however the values tend to be higher, falling primarily between 6 % and 19 %.

A ratio of temporary to permanent viscosity loss is presented in ***Figure 18***. For most European and Japanese oils, the temporary viscosity loss is twice as large as the permanent viscosity loss, whereas most North American oils experience the same amount of temporary viscosity loss as permanent viscosity loss.

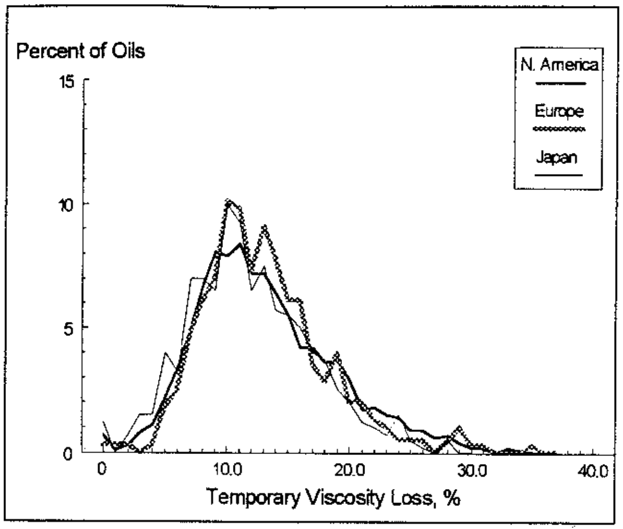

Figure 16 - Temporary viscosity loss, all regions

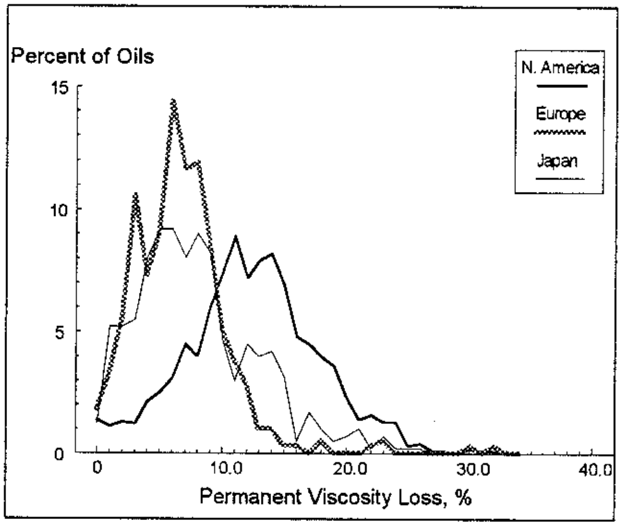

Figure 17 - Permanent viscosity loss, all regions

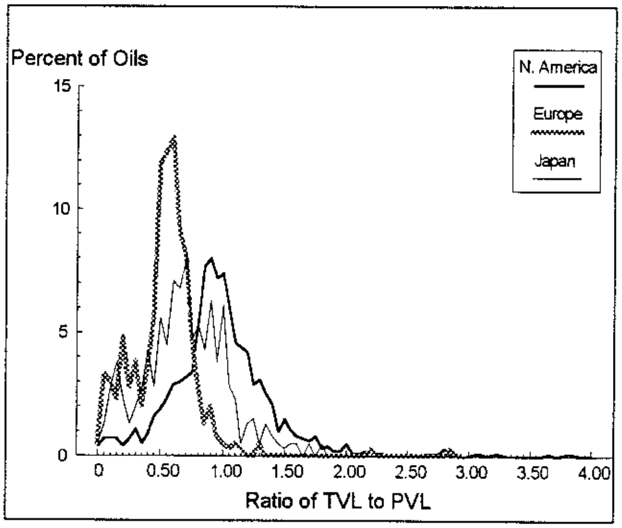

Figure 18 - Ratio of temporary viscosity loss to permanent viscosity loss, all regions

II. LOW TEMPERATURE VISCOSITY

Startability

The ability of an oil to permit a cold engine to start is determined by measuring its viscosity using the cold cranking simulator (CCS). ***Figures 19 through 21*** present CCS values for each of the three regions. Oils are graphed separately by grade with control limits identified. North American oils met SAE specifications more often than European and Japanese oils, although several fell outside specification limits.

It is interesting to note that Japanese oils have distinctly different starting viscosity histograms. Both 20W-"X" and 5W-"X" oils are bi-modal. A high concentration, more than 50 %, of the oils classified as 15W-"X" are clustered around 2800 cP, with a small secondary group clustered around 3800 cP.

Starting viscosity is one part of the cold temperature equation. Pumping viscosity is another crucial part. In fact, greater ease in starting engines at low temperatures as a consequence of lower friction, electronic timing, and fuel injection has resulted in higher starting viscosities, placing even more importance on the ability of an oil to permit satisfactory flow to the engine parts needing lubrication once the engine has been started.

Pumpability

Two methods for measuring pumpability are presented and discussed in this paper.

The Mini-Rotary Viscometer TP1 (MRV TP1) method is based on cooling the oil very slowly down to -20 °C, a temperature range thought to be important in developing gelation, then fast-cooling to the temperature of test critical to the SAE viscosity grade.

Although the test has shown reasonable precision, depending on the test temperature, the method has inherent weakness' in that gelation forming below -20 °C may not be detected. In fact, some questions have been raised regarding the ability of the test to determine gelation in some oils at any temperature. Additionally, a means for determining the severity of gelation is not provided in the test method.

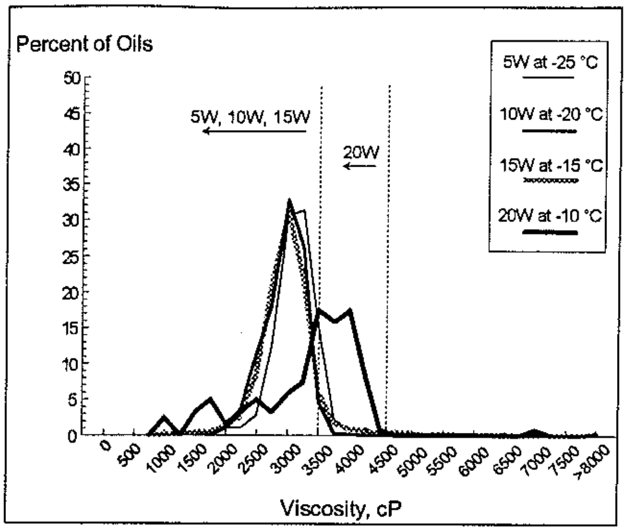

Figure 19 - Cold cranking simulator, North American oils

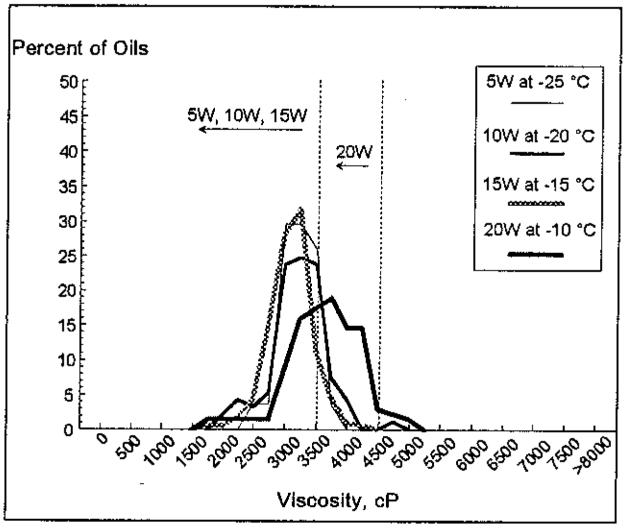

Figure 20 - Cold cranking simulator, European oils

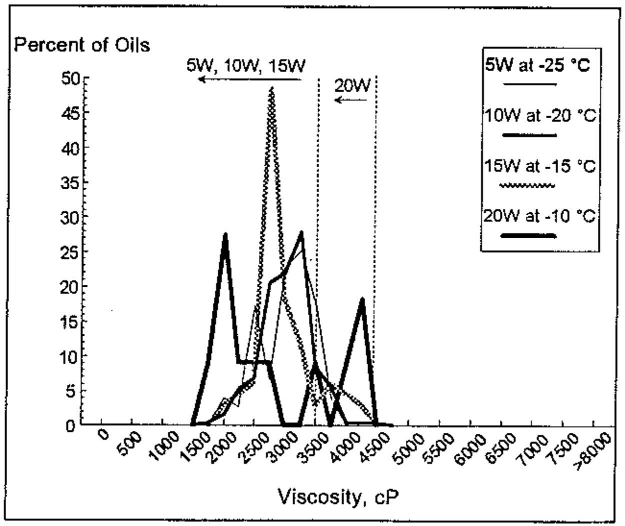

Figure 21 - Cold cranking simulator, Japanese oils

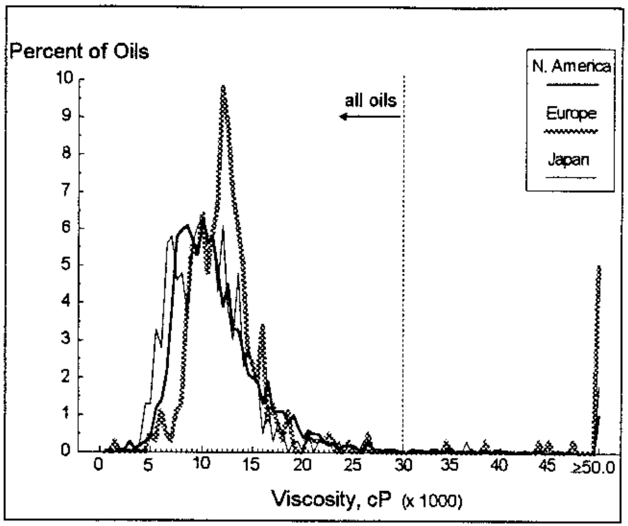

Figure 22 - MRV TP1 low temperature pumping, all regions

Figure 22 above presents the low temperature pumping viscosity of oils from the three regions. Although SAE specifies a maximum viscosity limit of 30,000 cP, a number of oils are well above 50,000 cP. European oils concentrate heavily around 14,000 cP. North American and Japanese oils spread over a wider range but tend to concentrate around 10,000 cP.

The Scanning Brookfield Technique provides an alternative to the MRV TP1 test by measuring the viscosity of an oil over a temperature range of -5 °C to -40 °C using a slow-cooling curve of 1 °C/hour. In addition to reporting the viscosity over the temperature range, the temperature at which a critical viscosity of 40,000 cP is reached is reported. Sensitivity to gelation is greater, with a unique ability to report both the presence and severity of gelation.

Figure 23 above presents the temperature at which oils from the three regions reached the critical viscosity of 40,000 cP. North American and Japanese oils are similar in pumping viscosity characteristics, with peaks at approximately -34 °C. European oils are spread over a wider range with a major peak at approximately -28 °C.

Cross-plots of the MRV TP1 viscosity and Scanning Brookfield temperature at 40,000 cP are shown in ***Figures 24 through 26*** to the right. Note how few Japanese oils fall outside the acceptable SAE viscosity limit of 30,000 cP. North American and European oils, on the other hand, demonstrate a greater number of oils falling outside of the viscosity limits.

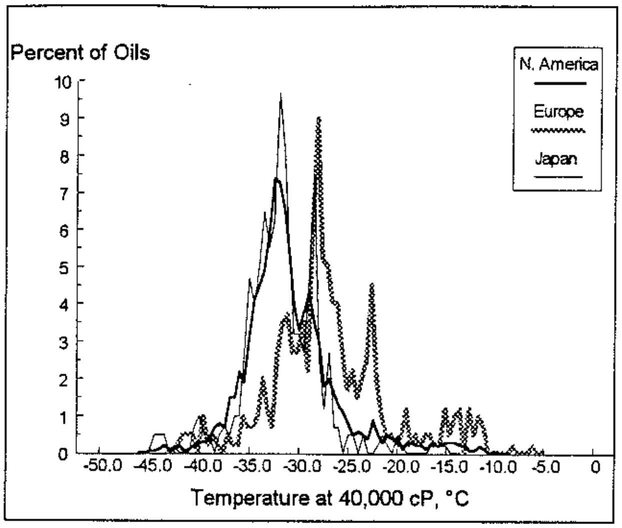

Figure 23 - Scanning Brookfield temperature at 40,000 cP, all regions

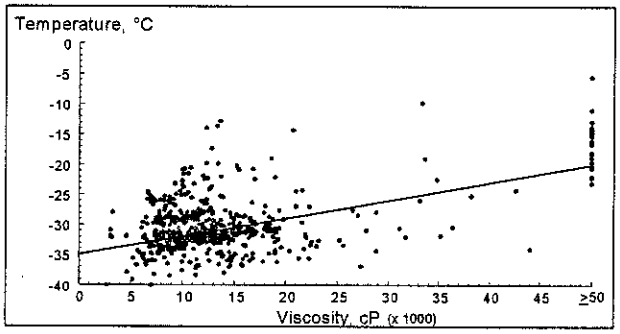

Figure 24 - MRV TP1 vs. Scanning Brookfield, North American oils

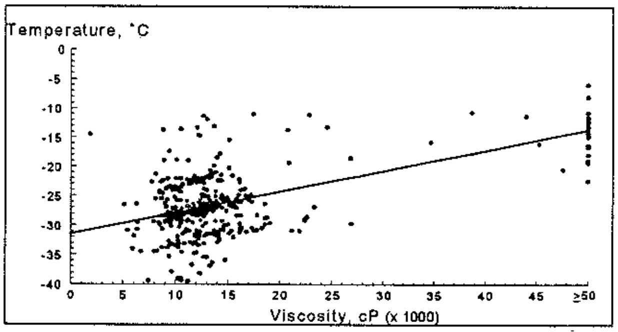

Figure 25 - MRV TP1 vs. Scanning Brookfield, European oils

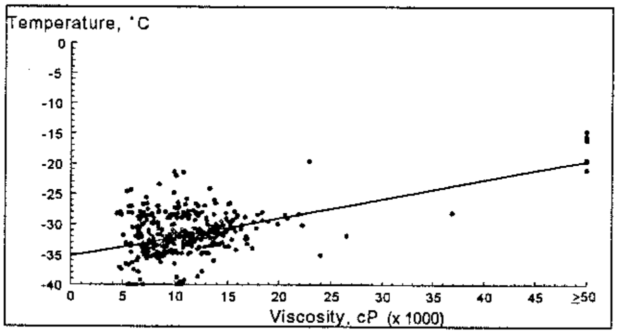

Figure 26 - MRV TP1 vs. Scanning Brookfield, Japanese oils

Gelation

The possibility of an oil blend developing an air-binding or gelated structure under certain cooling conditions determines its gelation tendency. Interrelationships of basestocks, wax levels, VI improvers, pour-point depressants, and dispersant-inhibitor packages all play an important role in gelation and should be carefully considered. This is particularly the case with the availability of so many basestocks from around the world as well as the virtually continuous development of new additive chemistries to enhance the formulated engine oil.

The tendency for gelation in an oil is measured by its Gelation Index. Gelation-prone oils are most likely to permit the engine to start but not pump, thus having the most potential for engine damage.

An overview of the gelation tendencies of oils from the three regions is presented in ***Figure 27*** below. Gelation indices above 16 have been known to cause field failures. For the most part, the oils shown here remain below this critical point. There are several, though, which demonstrate severe gelling tendencies, with index values above 50.

Japanese oils have the least tendency for gelling. Europe has the greatest number of oils with gelation tendencies, several of them quite severe. Cross-plots of the Gelation Index and Gelation Temperature for each region are given in ***Figures 28 through 30***, allowing closer inspection. Note that oils which have high gelation indices tend to have low Gelation Temperatures

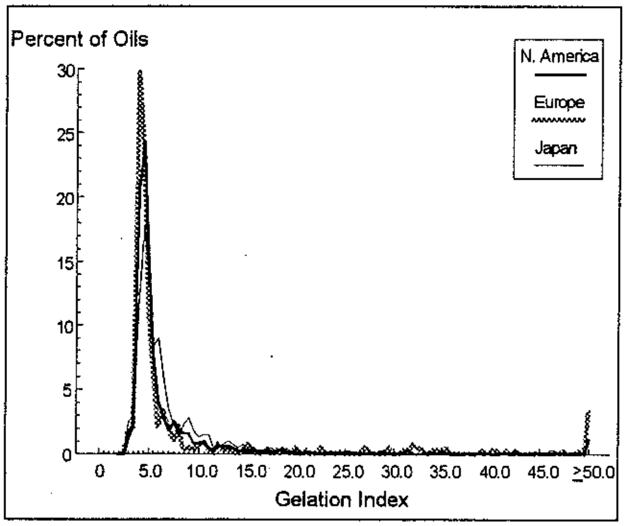

Figure 27 - Gelation Index values, all regions

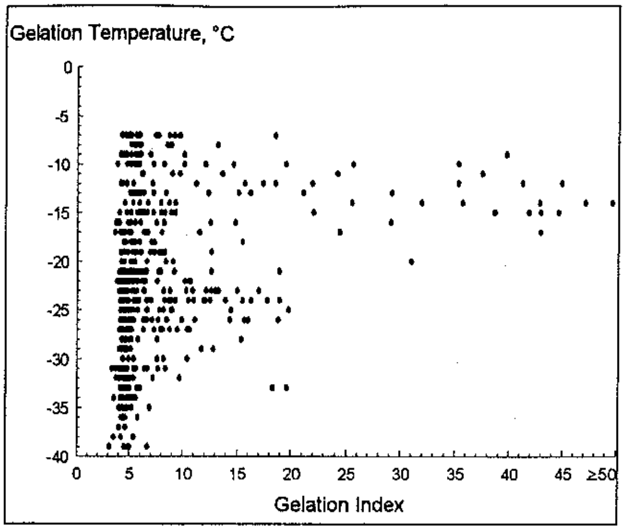

Figure 28 - Gelation Temperature vs. Gelation Index, North American oils

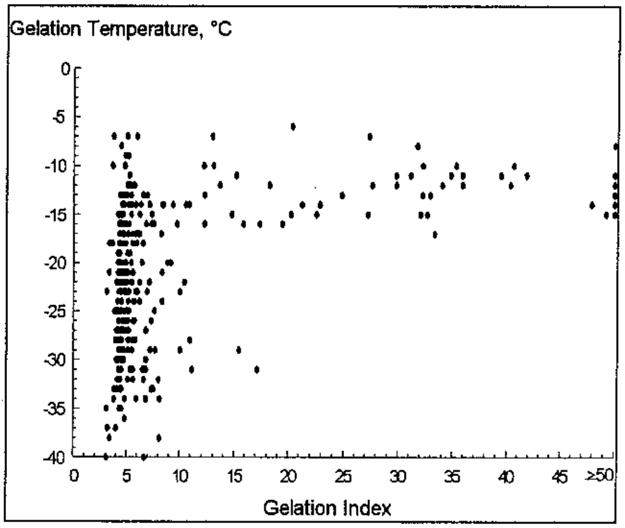

Figure 29 - Gelation Temperature vs. Gelation Index, European oils

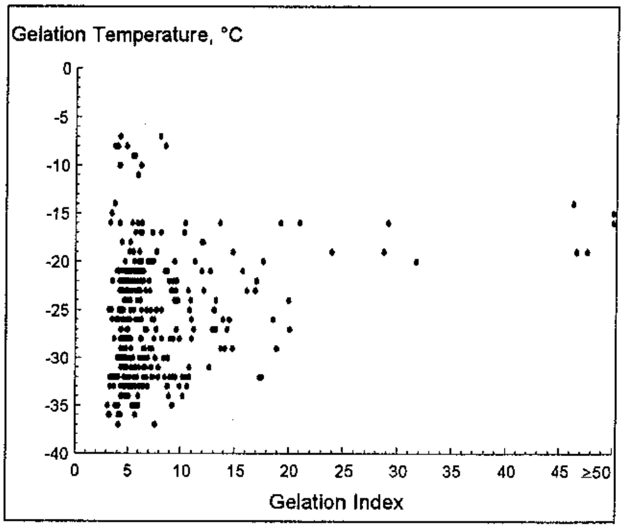

Figure 30 - Gelation Temperature vs. Gelation Index, Japanese oils

III. ELEMENTAL PROPERTIES

Zinc

Zinc is an anti-wear agent and oxidation inhibitor which is added to oils to improve their lubricating performance and life. To a certain extent, higher zinc levels are good.

Average zinc values over the years for each region are shown in ***Figure 31 to*** the right. Japan has traditionally carried lower amounts of zinc in their oils. North American oils contained substantially high amounts in the past but have come down in recent years. European oils carry the same level as current North American oils.

Phosphorus

The reason for lower zinc levels could be explained by its relationship with phosphorus. In many cases, zinc is added to engine oil as ZDDP, zinc dialkyldithiophosphate. There is concern that high levels of phosphorus in engine oil may contribute to catalyst contamination of the exhaust system and increased emissions.

Average phosphorus values over the years for each region are shown in ***Figure 32*** to the right. As expected, they follow the same trends as zinc.

Nitrogen

Nitrogen is an ashless dispersant and detergent. It is usually associated with higher quality oils because of its price. ***Figure 33*** demonstrates the use of nitrogen over the years. Japanese oils have been found to contain 50 % to 100 % more than the other regions.

Sulfur

Sulfur acts as an anti-wear and anti-oxidant agent. Its use is shown in ***Figure 34***. European oils have been found to contain very high amounts of sulfur.

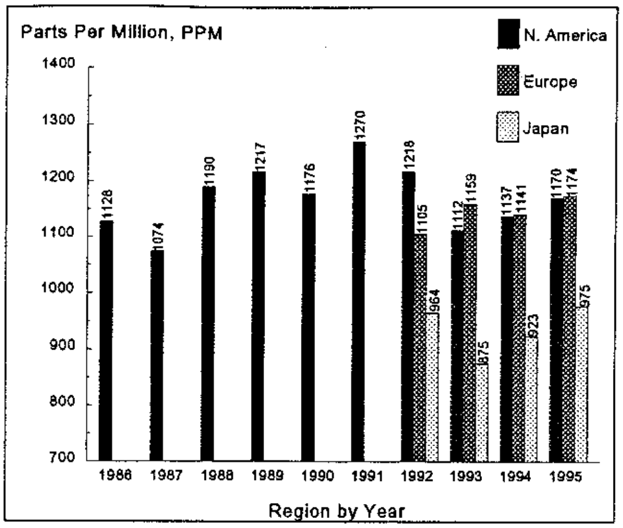

Figure 31 - Average zinc values, all regions

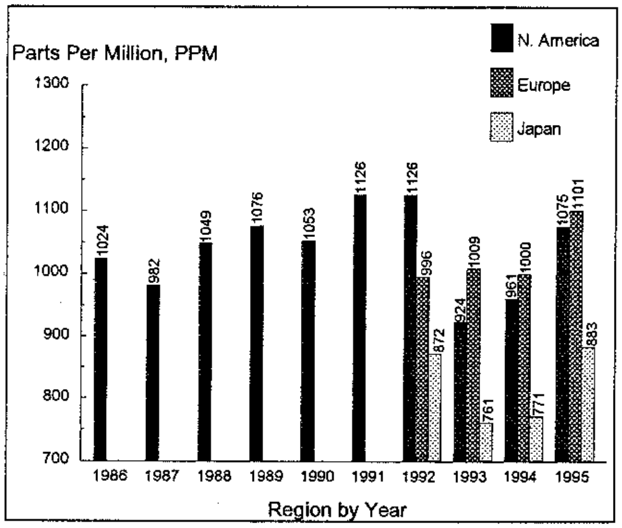

Figure 32 - Average phosphorus values, all regions

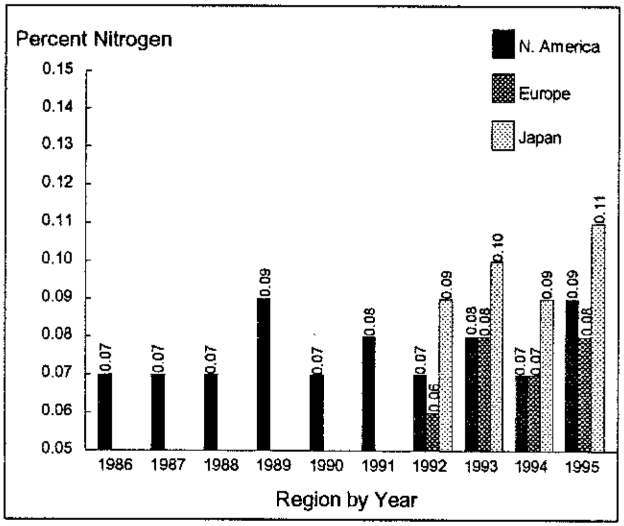

Figure 33 - Average nitrogen values, all regions

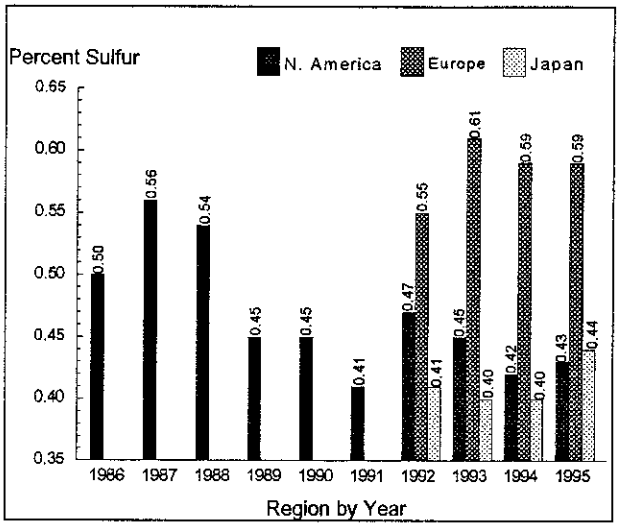

Figure 34 - Average sulfur values, all regions

IV. OXIDATION RESISTANCE

One of the most important base oil properties is its tendency to oxidize when exposed to higher temperatures in the presence of air. Oxidation can have serious effects on the ability of the oil to flow properly. Moreover, oxidation of the oil produces certain chemicals which cause deposits to form in critical areas of the engine such as on the pistons and in the ring grooves.

The ability of an oil to resist oxidation is measured using the Thin Film Oxygen Uptake Test or TFOUT, which measures the time, in minutes, before an oil succumbs to oxidation.

Figure 35 compares the oxidation time of oils from the three regions. North American oils and European oils appear to have similar oxidation resistance properties, although European oils trend slightly higher. Japanese oils cover a wider temperature range and are somewhat less oxidation resistant. There are a handful of oils in all three regions which demonstrate excellent properties for oxidation resistance.

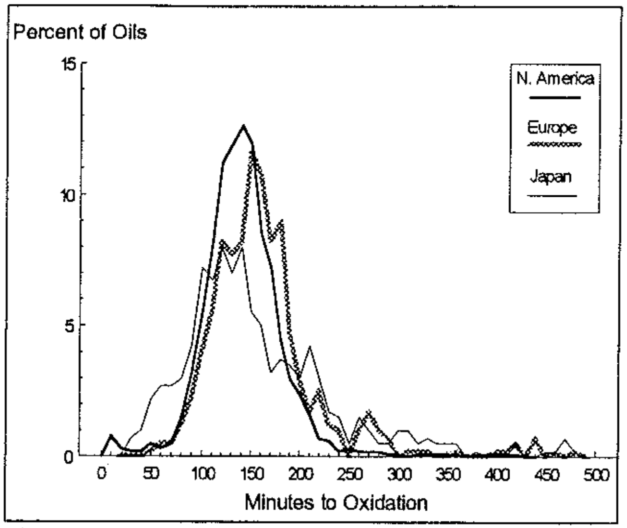

Figure 35 - Oxidation resistance, all regions

V. TOTAL BASE NUMBER

The total base number (TBN) of an oil measures its ability to tolerate and resist the corrosive activity of acids which are formed during engine operation by fuel combustion and oil oxidation. Some engines, including some heavy duty and diesel engines, produce higher levels of these harmful acids, thereby requiring oils which contain a higher base number.

The TBN test measures the reserve alkalinity left in an oil in milligrams per gram. To a certain extent, the higher the TBN value, the better. ***Figure 36*** compares the TBN values of the three regions.

It is very interesting to observe the regional differences. European oils have decidedly higher total base numbers, with a large concentration of values ranging from about 9.0 mg/g to 11.0 mg/g and a secondary group in the 5.0 mg/g to 8.0 mg/g region. In contrast North American and Japanese oils tend to concentrate around 5.5 to 8.5 mg/g. Japanese oils have a secondary group of oils in the 9.0 mg/g to 11.0 mg/g region. Europe's preference for diesel engines may account for the importance placed on oils containing high TBN values.

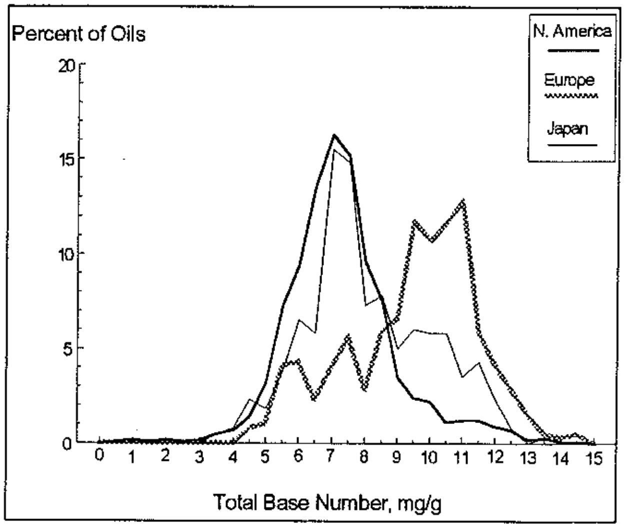

Figure 36 - Total base number, all regions

VI. VOLATILITY

Engine oil volatility is defined as the characteristic of an oil becoming a vapor when heat is applied. Oils with low base oil viscosities tend to be more volatile than high viscosity oils. Volatility can lead to several problems. Oil consumption results in higher engine temperatures, which lead to greater evaporation, more oxidation, more deposits, and shorter engine life. Engine manufacturers are also concerned with the volatility level of engine oils because of concern with exhaust system catalyst contamination by volatilized oil containing phosphorus compounds.

The percent of oil volatilized is measured using the Noack test and the Gas Chromatograph test. This paper presents results from both tests. ***Figure 37*** below portrays the tendency toward volatility for oils from the three regions using the Noack test. European and Japanese oils have similar volatility characteristics with the exception that European oils tend to have about 5 % less volatility than Japanese oils. North American oils are distributed quite widely and tend to have higher volatility levels. The same tendencies are seen with the Gas Chromatograph results in ***Figure 38*** below, only now all the volatility levels have shifted down about 10 %.

A comparison of the two methods is shown by region in ***Figures 39 through 41*** to the right. Correlation between the two methods appears fairly low and decreases as volatility increases. European oils again appear to have low volatility levels and tight dispersion. North American oils are widely dispersed with higher volatility levels.

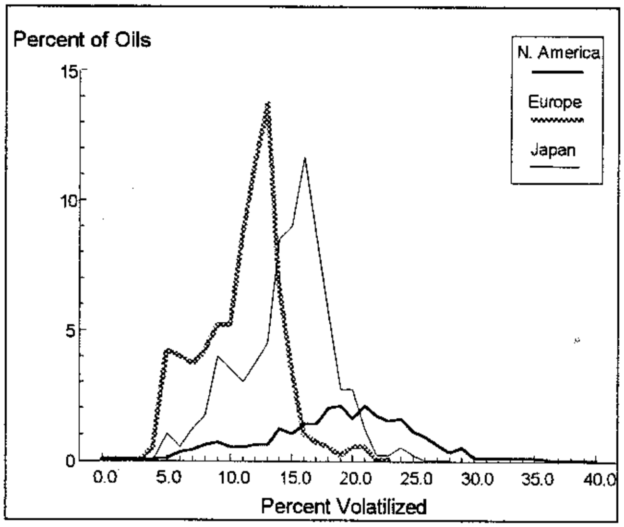

Figure 37 - Noack Volatility, all regions

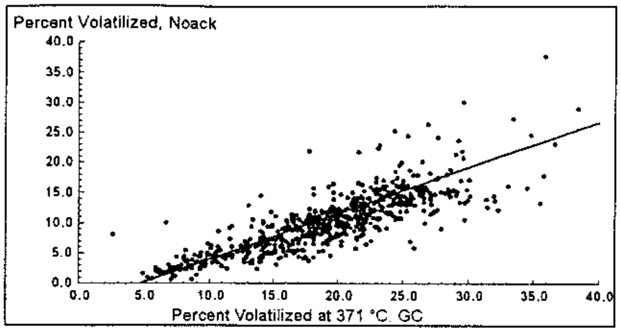

Figure 39 - Noack Volatility vs. Gas Chromatograph Volatility, North American oils

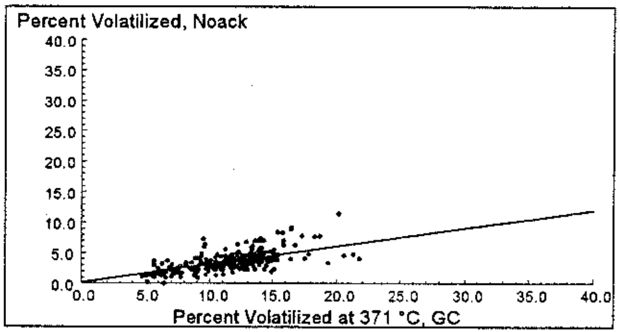

Figure 40 - Noack Volatility vs. Gas Chromatograph Volatility, European oils

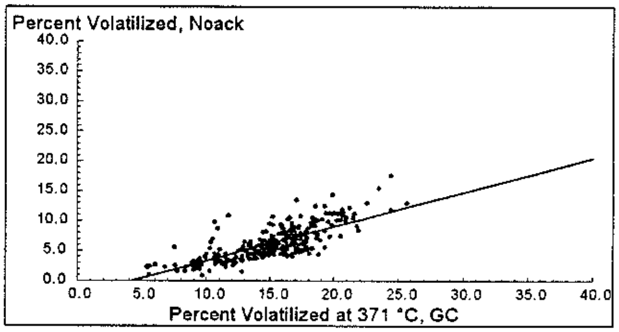

Figure 41 - Noack Volatility vs. Gas Chromatograph Volatility, Japanese oils

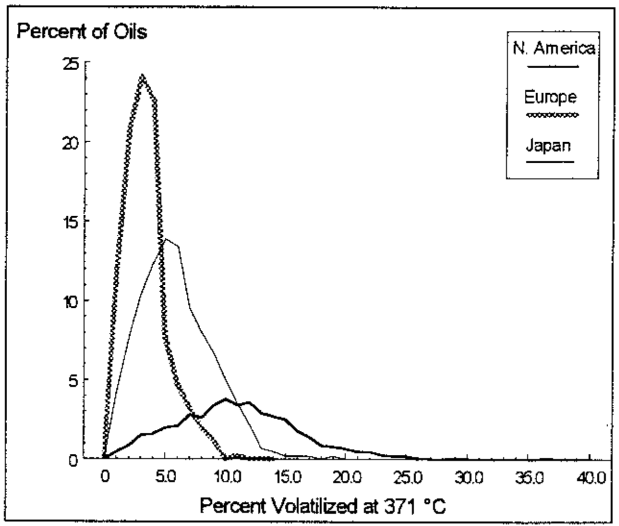

Figure 38 - Gas Chromatograph Volatility, all regions

SUMMARY

This paper presents an interesting and realistic overview of the engine oil industry. A wide range of products were independently purchased from retail markets of three regions of the industrialized world -- North America, Europe, and Japan. Wide scale bench testing was conducted on each oil to identify its physical and chemical characteristics. Several interesting differences emerge from this analysis, such as:

- Europeans tend to favor oils with greater dynamic viscosity and less variation at high temperatures.
- North American oils indicate good cold temperature starting properties.
- Very few Japanese oils exhibit cold temperature pumpability and gelation problems.
- European oils have high levels of sulfur compared to North American and Japanese oils.
- Japanese oils contain high levels of nitrogen.
- European oils indicate high Total Base Number values.
- North American oils have higher levels of volatility.

Results have been compiled and reported in such a manner as to allow the reader to make engine oil comparisons between regions, among viscosity grades, and over time.

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