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Global Monitoring and Examination of Engine Oil Properties – Harnessing the Power of Bench Test Data

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Summary

The operation of the automobile is dependent on its engine which, over time, is primarily dependent on the properties of its engine oil. Quality levels of engine oils have become more and more important as engine designs have increasingly emphasized power, performance, smaller size and greater fuel efficiency. Engine oils must meet increasingly higher standards of performance to serve these engines – standards driven by a variety of factors including government regulations. Fortunately, these standards are increasingly applied through relatively inexpensive bench tests based on good correlation with engine test data obtained on the dynamometer or from field experience.

However, of the many hundreds of engine oils that are placed on the worlds marketplaces claiming certain levels of performance, a number do not meet their claims – some by a wide margin. In view of the impact that the engine oil has on the operation and longevity of the engine, it is reasonable and prudent to determine whether engine oils meet the standards they claim and there is a source of such information. The Institute of Materials (IOM) has annually collected hundreds of oils from the world's marketplaces for over 30 years. These oils are subjected to a number of bench tests that characterize their quality levels and these data are objectively published. A number of bench test results define the properties and performance required of these oils to meet critical standards and specifications as well as other needed measures of quality.

This paper uses the data from the IOM Engine Oil Database of engine oils collected over the last six years to appraise and compare the more recent quality and performance levels of marketed oils to meet the rapidly growing needs of modern engines based on the important areas of oxidation resistance, fuel efficiency, low-temperature pumpability, and phosphorous content. Other important factors, such as engine oil phosphorus emissions and related properties will be presented in a future publication.

Zusammenfassung

Die Funktion eines Kraftfahrzeuges wird wesentlich vom Motor bestimmt, dessen Lebensdauer signifikant von den Eigenschaften des Motorenöles abhängt. Durch neue Motorentechnologien, wie zum Beispiel das Downsizing, ist die Qualität der Motorenöle kontinuierlich gestiegen. Für moderne Motoren und wegen der gesetzlichen Regularien hinsichtlich der Abgasgesetzgebung müssen die Öle heute deutlich höhere Anforderungen erfüllen. Für die Entwicklung und den Nachweis, dass die Anforderungen der jeweiligen Spezifikation erfüllt werden, werden verstärkt relativ günstige Prüfstandstests, die eine gute Korrelation zum realen Fahrbetrieb zeigen, herangezogen.

Allerdings erfüllen nicht alle der vielzähligen Motorenöle die auf den Markt gebracht werden immer das ausgelobte Leistungsvermögen. Im Hinblick auf die aufgeführte Bedeutung der Motorenölqualität für die Dauerhaltbarkeit der Motoren ist es angemessen zu überprüfen, welche Öle die ausgelobten Leistungskriterien erfüllen, und es ist wichtig, dass solche Informationen zugänglich sind. Seit über 30ig Jahren hat das Institute of Materials (IOM) weltweit hunderte von Motorenölproben aus dem Markt genommen.

Das Leistungsvermögen und die Daten dieser Proben wird in einer Reihe von Prüfstandstests ermittelt und objektiv veröffentlicht, so dass ersichtlich wird ob die Öle die angegeben Standards und Spezifikationen einhalten.

Diese Veröffentlichung beruht auf Daten des IOM von Motorenölen die in den letzten 6 Jahren gesammelt worden sind und vergleicht das Leistungsspektrum mit den heutigen Anforderungen moderner Motoren hinsichtlich Oxidationsbeständigkeit, Kraftstoffverbrauch, Tieftemperaturverhalten und Phosphorgehalt. Andere wichtige Parameter werden in einer zukünftigen Veröffentlichung vorgelegt.

1. Introduction

1.1 The Automobile and Society

Over the last hundred years, the automobile has become a highly desired and even essential mode of human transportation throughout the world. In some areas such as North America and Europe, this dependence has been sharply evident for decades. In other areas, such as portions of Asia and the Pacific, this relationship is more recent. However, no matter where it is used, the automobile is only as dependable as its engine and the engine oil carefully made for its continued operation.

1.2 The Critical Role of the Engine Oil

With today's increasingly demanding needs for the difficult combination of performance, protection and fuel efficiency with smaller, more powerful engines, there is a rapidly growing need to assure that wherever an automobile is used there is engine oil of sufficient quality to protect it in the environment of its use. This requires carefully formulated engine oils based on deeper understanding of the physics and chemistry of engine lubrication. More critically, greater attention is needed to be given to the actual (versus the claimed) quality of the engine oils being put on the world's markets for use.

1.3 Engine Oil Specifications

Since the beginning of the automobile, the need for information and understanding of the relationship between its engine and its lubricant has existed. However, the automobile has long passed from being an expensive hobby to being a necessity for most owners. As use of the costly automobile grew, its owner's expectations of reliability also grew. With those growths and the accompanying warranty responsibilities for engine manufacturers, specification of minimum engine oil performance levels and specification also grew with time and understanding of engine needs.

1.4 Engine Oil Sources and Acceptability

As the automobile became common in various societies around the world, sources of engine oil have also multiplied rapidly in those regions in response to the need. As would be expected, these marketed engine oils carried various claims of good performance and similarly raised questions of such claims.

Without objective supporting data, the actual level of knowledge and skill applied in manufacturing an engine oil is not apparent to the customer on purchase. However as this paper will show, objective data on the engine oils of the world is available from the Institute of Materials.

2. The Institute of Materials

The Institute of Materials (IOM) was formed to meet the needs of the automotive, petroleum and lubricant additive industries. These became evident in a 1983 study presented by one large automobile manufacturer to the Society of Automotive Engineers (SAE) Fuels and Lubricants Sub-Committee. The data presented strongly indicated the need to effectively obtain, evaluate and communicate the properties of engine oils actually reaching the marketplace for use by automobile owners. While the SAE took a non-public, direct-to-the-manufacturer path to attempt to stop the marketing of oils of questionable quality, the Institute of Materials was formed in 1984 to directly gather many engine oils from the market, analyze them by well-recognized bench tests and publicly publish the resulting data for anyone interested. This information included the local geographical location of purchase of the oil and information on the container including claims. The first major geographic region selected for collection of engine oils and subsequent analysis of quality was North America.

Over the ensuing years, the scope of engine oil collection was extended in the early 1990's from North America to the marketplaces of Europe and Asia and has been expanded further since that time. Each year, several hundred engine oils on the retail market have been purchased during IOM's 30-year history. Each of these oils is subjected to over 30 bench tests by selected laboratories to determine and compare their properties and test responses as engine lubricants.

To date, over 14,000 engine oils have been tested. This database is the world's largest collection of such data. The data has been made available to those interested by both subscription or by individual reports as well as on the Internet.

Since the engine oils collected by IOM actually indicate the quality of formulation and manufacture of the product reaching the market, the IOM Engine Oil Database has been used for a number of purposes by Subscribers including those Subscribers monitoring manufacturing consistency and competitive products. A number of papers have been published using IOM data with the stipulation that 1) the data be identified as being from IOM and 2) that the IOM data may not be adulterated with non-IOM data.

This paper shows how the Engine Oil Database reveals the engine-protective benefits of careful, well-informed engine oil formulation and distribution as well as the presence on the market of less knowledgeable or concerned formulations. Moreover, despite best practices, it has happened that an otherwise well-formulated engine oil has been driven into weather conditions or used in engines for which the particular engine oil had not been formulated.

3. Analysis of Five Engine Oil Properties

Of the more than 30 bench tests used to evaluate the marketed engine oils, five were chosen to show the variation among these marketed products.

Variation of other equally important bench tests of engine oil properties and performance could have been chosen but these five were thought particularly interesting given some of today's engine operation concerns.

For those interested in other aspects provided by the IOM Engine Oil Database, several previously published papers have shown the depth of understanding and range of information available regarding engine lubricants and a list will be sent from IOM to any inquiry.

The areas chosen for discussion in this paper are:

- Oxidation resistance in the turbocharger
- Oxidation resistance in the engine,
- Low-Temperature engine oil pumpability (a newly resurgent concern from recent winter field failures in Europe)
- Fuel efficiency improvement by choice of the high shear rate viscosity of the engine oil
- Phosphorous content as a source of engine wear protection and exhaust pollutant.

4. Oxidation Resistance in the Turbocharger

Turbochargers have been used for years on more costly automobiles in different parts of the world to improve power and fuel efficiency of the automotive engine. Europe, however, has set the pace by incorporating the turbocharger in commonly-used vehicles and, in today's strong efforts to generally improve fuel efficiency, use of turbochargers is rapidly becoming more common everywhere.

With the integration of the engine and turbocharger, they share the same engine oil. However, it has been shown [1,2] that the turbocharger and engine present two different oxidation environments. The engine presents its environment while operating whereas the turbocharger often primarily affects the stagnant engine oil after the engine has been shut off. The very hot (often greater than 1000°C) turbocharger rotor forces high temperatures down the turbocharger shaft thus progressively baking the oil and additives into a 'coke' during which the later lubrication of the operating turbocharger is more and more restricted until failure occurs.

In the late 1980's, the Thermo-oxidation Engine Oil Simulation Test, TEOST 33C was developed by an automobile manufacturer [3,4] using as standards of correlation several European engine oils which performed well or poorly in the field in resisting turbocharger deposit formation. Subsequently, the test was incorporated into North American and Japanese engine oil specifications and was formalized into ASTM Test Method D6335 in 1998 [5].

4.1 Comparison of Marketed Engine Oils in the Turbocharger Oxidation Test TEOST 33C, ASTM D6335

To provide a comparative view of engine oil response to the ASTM D6335 turbocharger oxidation tendency test, it was thought to be most informative to first give an overall view of the distribution of test values over a period of six years from 2008 to 2013 in Europe, Asia (including the Pacific rim) and the Americas.

Specifically, a special plotting format was developed which permitted comparing a chosen property or response of oils marketed in different areas of the world in the six progressive years. This had the advantage of visualizing whether or not marketed oils were generally progressively improving or not and how their formulary compositions compared from one area of the world to another.

Figure 1 uses this plotting technique to make a comparison of the oils collected by the Institute of Materials in Europe, Asia Pacific and the Americas regarding the tendency to form turbocharger deposits. On the ordinate (Y-axis) is given milligrams of deposit formed while the abscissa (X-axis) showed the percentage of the oils collected each year giving the associated deposit level.

It will be noted that it appears that the engine oils from Asia are superior in turbocharger deposit resistance to the engine oils from Europe and the Americas. This is correct, however as mentioned earlier (and later discussed further), the causes of deposit formation in the turbocharger and the engine are different. As will be shown, when these same Asian oils are compared in engine deposit

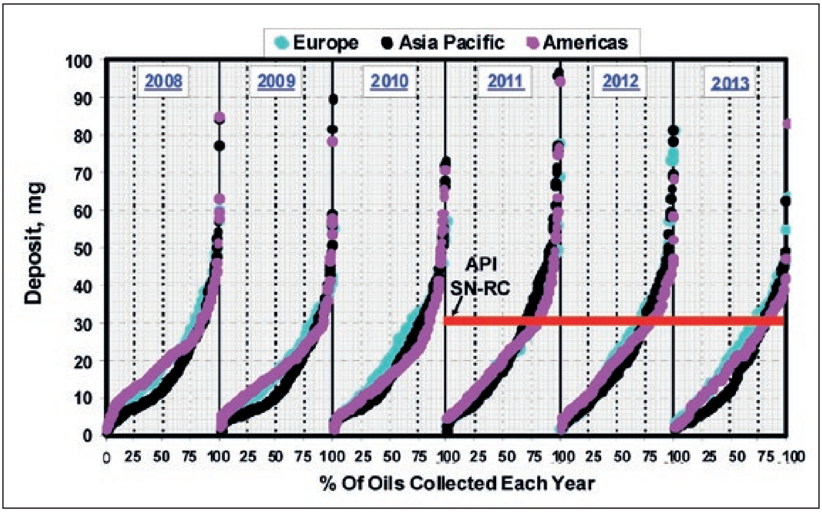

Fig. 1: Turbocharger Deposit Formation Tendency (ASTM Test Method D6335)

resistance, the Asian oils' overall superiority in the turbocharger is reversed. Careful formulations of engine oils can assure that both turbocharger and engine deposits are controlled. Accordingly, only Europe and the Americas – two areas of the world having long formulating familiarity – will be compared at this time.

In regard to *Figure 1*, it is interesting that, near the end of 2010, the American Petroleum Institute (API) issued the latest Standard SN-RC (Resource-Conserving) for automotive engine oils and that this API SN-RC standard included the ASTM D6335 TEOST 33C turbocharger deposit tendency bench test. The new API SN-RC was an upgrade of the previous API Standard SM. To meet the API SN-RC standard, it was necessary for an engine oil to have a turbocharger deposit tendency of 30 mg or less in the ASTM D6335 test. (This new requirement is also shown in *Figure 1* as a horizontal red line.)

Using *Figure 1*, several observations can be made comparing the data of both Europe and the Americas. First of all, over the years from 2008 to 2013 considerably more than 50% of the oils collected in either area met the requirement of SN. However, it is also evident that in both areas a number of engine oils have deposit tendencies well over 60 mg and even 80 mg. These are levels of deposit that – on the basis of the field oils used to develop the TEOST 33C bench test – are prejudicial to the continued operability of the turbocharger.

Figure 2 shows this comparison explicitly. It is particularly evident that in 2010 the Americas showed an increase in unacceptable oils for turbocharger use. Moreover, this increased somewhat in 2011 in the Americas and even in Europe.

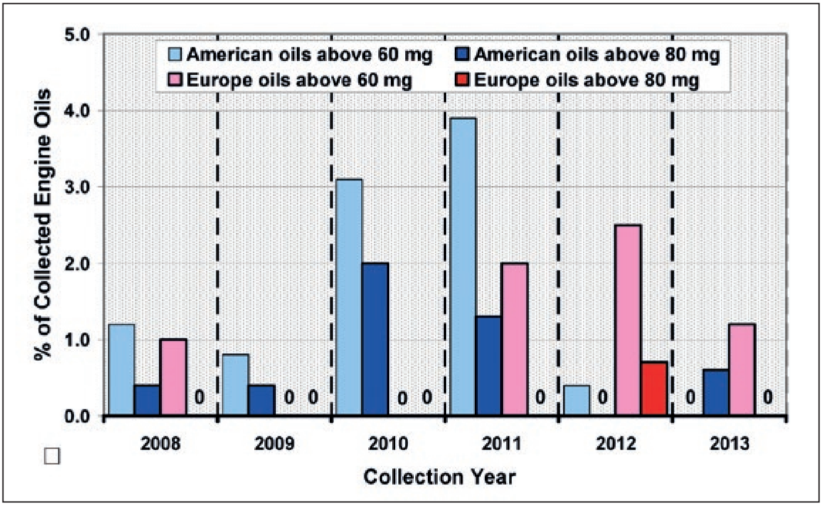

Fig. 2: Percentage of Engine Oils Collected in Europe and Americas Showing High Turbo-Deposit Tendencies

However, the inclusion of the TEOST 33C, ASTM D6335 bench test in the requirement for API SN-RC at the end of 2010 may be reasonably responsible for the evident improvement shown in 2012 and 2013 for the oils marketed in the Americas. This is in contrast to Europe where this turbocharger bench test may not be considered as important in controlling turbocharger deposits and 60 to 80 mg deposits are once more present.

Overall, considerably fewer questionable oils were found in Europe than in the Americas from 2008 to 2011. However, after the promulgation of API SN-RC in 2011, a significant decrease in turbocharger deposit tendency in 2012 and 2013 was seen in the Americas. Interestingly, beginning in 2011, a marked increase is evident in Europe. It will be noteworthy to find if this contrast continues in 2014.

One aspect of the oxidative mechanism of ASTM Test Method D6335 should be noted. A low level of some additives improves this test's response since some additives have been implicated in deposit formation from stagnant oil at these temperatures. Thus, low additive containing oil that would be inadequate for engine lubrication may be acceptable in resisting turbocharger deposit formation. Accordingly, passing D6335 does not imply that a given engine oil is suitably formulated for engine service and deposit formation tendencies in the turbocharger and/or engine are not equivalent.

5. Oxidation Resistance in the Ring Belt Area of the Engine Piston

Of the various areas of the engine being lubricated, the piston ring belt is probably the most important and demanding of oil's deposit formation resistance. As a consequence, the need for a bench test rather than expensive and variable engine tests is clear. In 1996, an effort to provide such a bench test was begun by an automobile manufacturer [6].

The approach of the prior TEOST 33C in controlled resistive heating of a carefully dimensioned steel rod was utilized to provide the basis of the deposit test. However, the temperature applied (285°C), time of test exposure (24 hours), and amount of circulated sample (approximately 8 grams), were all significantly different. The new bench test was developed and correlated closely (R^2 = 0.9+) with the well-known and relatively precise Peugeot TU3MH piston deposit rating engine test.

The new test, TEOST MHT, became ASTM Test Method D7097 in 2005 [7] and was incorporated into the API Standard SM and the International Standardization and Approval Committee's (ILSAC) GF-4 when those specifications were introduced in 2004 and later included in the present API SN-RC/GF-5.

5.1 Comparison of Marketed Engine Oils in the TEOST MHT Oxidation Test, D7097

Considering the importance of piston deposits, it is of interest to compare such deposit tendency in the engine oils marketed world-wide. This is shown in *Figure 3* where the red horizontal line at 35 mg deposit shows the maximum acceptable deposit level in the specifications for API SM and SN-RC.

There are two important aspects of the data shown in *Figure 3* on piston deposit tendencies. One is the percentage of engine oils meeting the standards established by ILSAC and the API. The other is the severity of piston deposit tendency of those engine oils not meeting these standards.

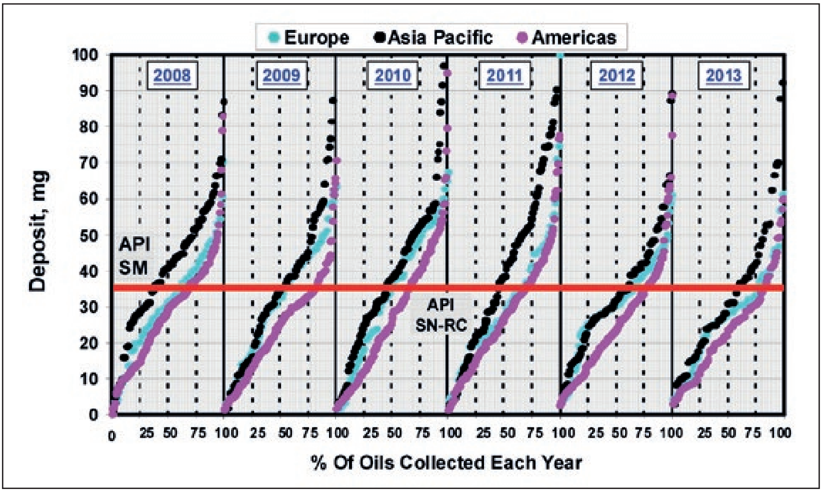

Fig. 3: Piston Ring-Belt Deposit-Forming Tendency (ASTM Test Method D7097)

Figure 4 shows the first aspect for the marketed engine oils presented in *Figure 3*. Two factors are evident. The first is that the percentage of engine oils available on the markets in Europe and the Americas favor the customer more than in Asia (with the exception of Japan). The second aspect is that in all three areas of the world, the availability of engine oils having acceptably good piston deposit resistance is tending to increase over the period from 2010 to 2013.

5.2 Marketed Engine Oils of Questionable Oxidation Resistance

However, considering the importance of reducing piston deposit formation, particularly with the increasing performance of modern and forthcoming engines,

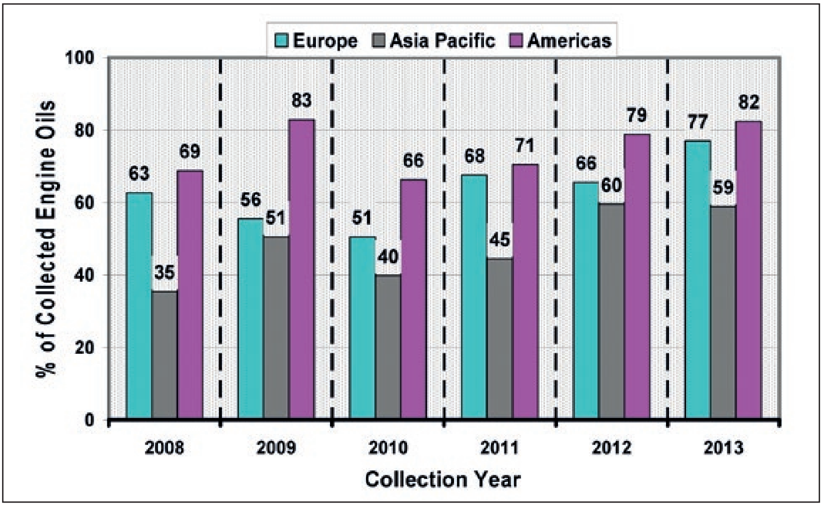

Fig. 4: Engine Oils Collected Meeting ASTM D7097, 35 mg Maximum of API SM (2004) and SN-RC (2010)

attention is growing regarding the frequency with which lower quality engine oils enter the world's markets. This is of particular importance to the warranty-vulnerable automobile industry. *Figure 5a* shows how the market presence of lower quality engine oils has changed with time. Of obviously

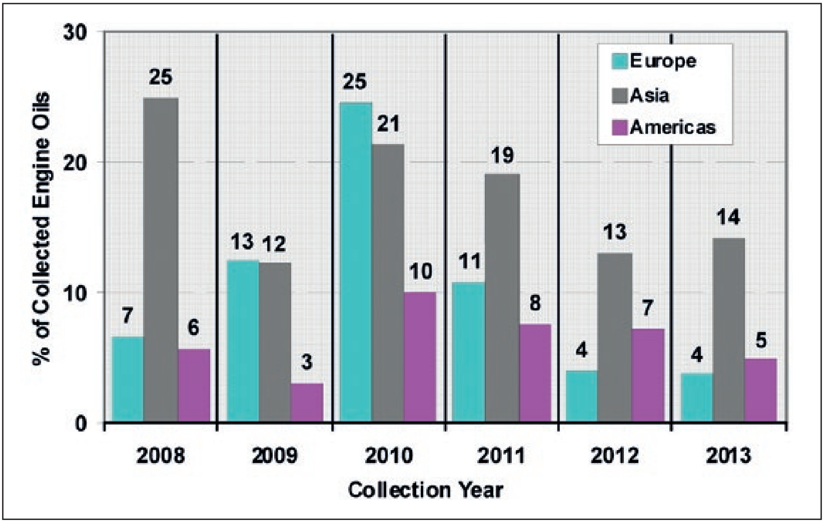

Fig. 5a: Collected Engine Oils with Piston Deposit Tendencies. Between 50 and 70 mg in the ASTM D7097 Bench Test

greater importance and concern are piston deposit levels of 70 mg and greater and this is shown in *Figure 5b*. The data show that Europe and the Americas have very low levels of such high deposit-forming tendency engine oils in contrast to Asia (excluding Japan). The level of poor quality oils in Asia is very evident.

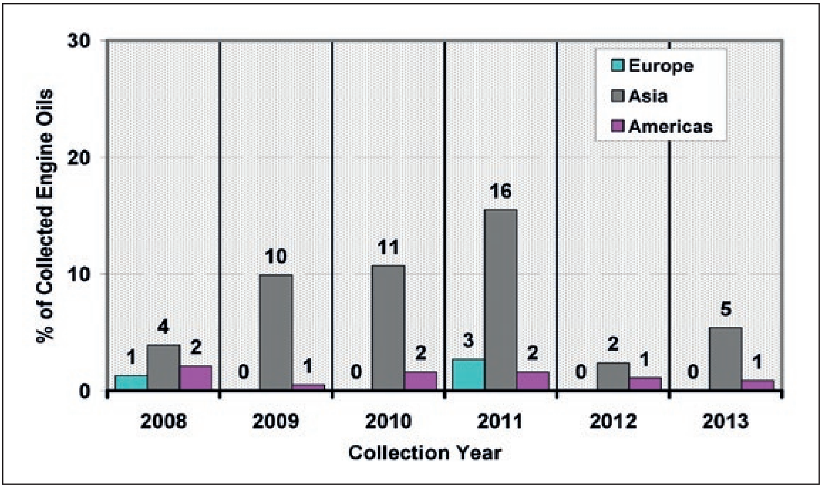

Fig. 5b: Collected Engine Oils with Piston Deposit Tendencies of 70 mg and Higher in the ASTM D7097 Bench Test

6. Comparison of Deposit Formation Tendencies of the TEOST MHT and TEOST 33C Bench Tests

In regard to previous comments concerning *Figure 1* on the apparently good performance of the Asian engine oil regarding turbocharger deposit tendency, it is now evident in *Figures 3, 5a and 5b* that this previously indicated good response in turbocharger deposit-forming tendency is not supported by deposit-forming tendency on the engine piston.

In fact, other information in the Institute of Materials Engine Oil Database indicates that the good responses of a number of Asian engine oils are a consequence of inadequate choice of additive levels or type in formulation. This, of course, would cause the evident contradiction of the turbocharger and engine deposit formation tendencies shown.

7. Low-Temperature Lubricant Supply to the Engine – Pumpability and Gelation

A half-century ago, the primary difficulty in operating the vehicle at low ambient temperatures was starting the engine. With considerably improved starting systems, a quarter-century ago the low-temperature problem changed to one of having adequate oil pumpability after starting. Such easier engine starting uncovered a more serious problem which revealed that at low-temperatures, some engine oils have gelation (semi-solidification) tendencies under certain cooling conditions.

7.1 The Crucial Problem of Engine Oil Gelation

The occurrence of the gelation problem was not simply a matter of the slower flow of thickened oil at lower starting temperatures (although that, too, can be a different problem). Rather, the condition occurs when, exposed to a particular cooling pattern, components of the engine oil are induced to form a matrix or structure. Thus, what can be termed a ‘gel’ develops in the engine crankcase which enmeshes the remaining oil so that the gelated mass cannot be readily pumped – if it can be pumped at all (a condition called “air-binding” the oil pump).

The consequence is an engine that can be readily started but will quickly and catastrophically fail during operation because of lack of engine oil lubrication of the critical engine components. Such incidents usually involve a number of vehicles in the same weather zone. This occurred in Sioux Falls, South Dakota [8,9] and colder climates of Europe in 1980 and was reported in 2008-9 again in Europe.

7.2 The Scanning Brookfield Technique (SBT)

The Sioux Falls incident led to the development of the Scanning Brookfield Technique (SBT) in 1985 [9,10] which responded to any appearance of gelation and became ASTM D5133 [11] in 1990. This rotational viscometric technique uses a very slow rotor motion of 0.3 RPM to measures viscosity continuously over a broad and slowly decreasing range of temperatures (normally from -5° to -40°C) at a rate of -1°C per hour.

The slow rotor motion during the continuous measurement of viscosity by the SBT also induces the engine oil to gelate – if it has that tendency – and reveals the onset and degree of gelation by the viscous contribution of such gelation to oils’ normal exponential increase in viscosity with decreasing temperature. When the additional viscosity increase of gelation is analyzed, the data produce a peak value of gelation strength called the Gelation Index as well as the relatively precise Gelation Index Temperature at which this peak occurs. Both the Gelation Index and its Gelation Temperature are the important variables determined by ASTM D5133.

When Gelation Index and ASTM D5133 were applied in ILSAC/API specifications in the late 1980s, a Gelation Index greater than 12 was considered undesirable (the Sioux Falls oils gave GIs of 16).

7.2.1 Comparison of Low-Temperature Pumpability Susceptibility Using the SBT

Figure 6 compares the pumpability of SAE W-grade engine oils using the temperature-scanning technique of ASTM D5133.Considering the destructive effects of gelated engine oil at low temperatures, the data shown in *Figure 6* is of particular interest. In the Americas where the Sioux Falls incident left a lasting imprint on formulation practices, the engine oils collected show a high level of passing the quality level of a maximum of 12 Gelation Index.

In comparison, considerably lower passing levels are shown by the oils from Europe and Asia (with the exception of Japan). Obviously, a rational for this could be that low temperatures are not as common in these areas. However the risk of failure was still present and in the years 2008 and 2009 – which in Europe had unusually cold weather – a number of pumpability failures have been reported there.

On the basis of the SBT data of *Figures 6 and 7* (following), formulation practices in Europe and Asia seem to have subsequently changed for the years after 2009.

7.2.2 Low-Temperature Pumpability Failure Susceptibility and Likelihood Using the SBT

The question of how oil gelation severity would impact engine failure is of interest. Viewed from the perspective of how many of the oils failing the D5133 SBT pumpability test were potentially marginal failures (oils showing

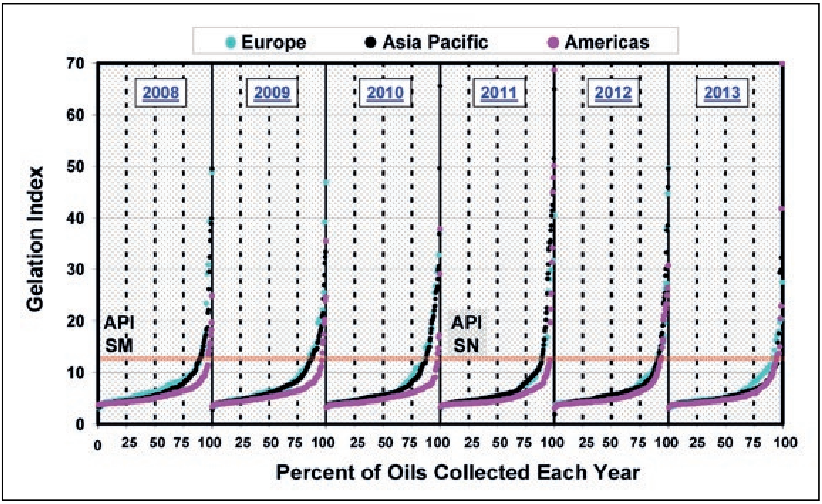

Fig. 6: Gelation Tendency at Low Temperatures (ASTM Test Method D5133)

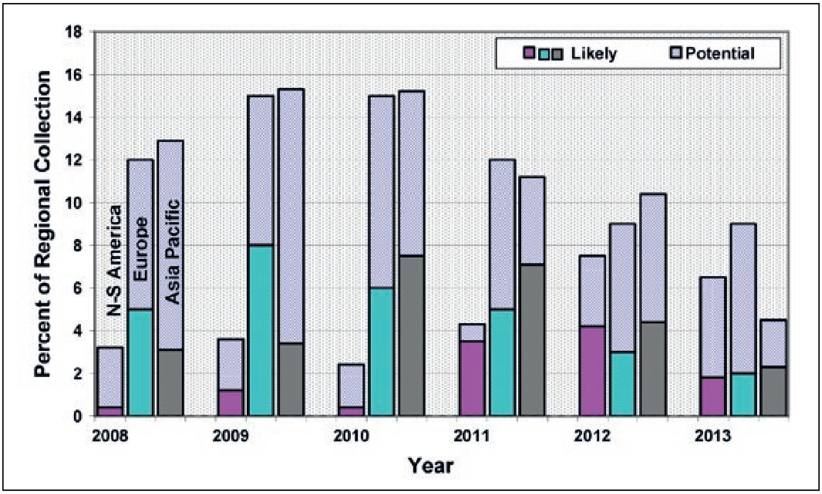

Fig. 7: Predicted Likelihood of Pumpabily Failure Damage. At Low-Temperatures by ASTM Method D5133

Gelation Index values from 12 to less than 20), and how many were likely failures (oils showing Gelation Index values above 20), the bar-graph of *Figure 7* is more explicit.In explanation of *Figure 7*, each area of the world is shown by a bar divided to indicate:

1. The percent of oils collected from the markets of each geographic area that are above a value of 12 Gelation Index and thus have either a potential or a likely susceptibility to failure in the engine at low temperatures.
2. The percent of the oils from each region that have Gelation Indices of 20 or higher and are likely to fail under low-temperature conditions.

Interestingly, as previously mentioned, the data seem to explain the recent pumpability failures in Europe in 2008-2009. In these years, the IOM oils collected from the European market showed Gelation Indices of 20 and above account for as much as eight percent of these oils. The adverse weather conditions reported during that time would be likely to cause the damage that was reported from pumpability failure.

The data of *Figure 7* are encouraging in showing that since the European experience; susceptibility to pumpability failure in both Europe and Asia has decreased significantly until in 2013 the levels are commensurate to those in the Americas where gelation has always had attention since the Sioux Falls incident.

7.3 Use of the TP-1 MiniRotary Viscometer Method

Development of the SBT was followed by an effort to regain use of the MiniRotary Viscometer (MRV, ASTM D3829 [12]), a pumpability test that had been developed earlier on the basis of correlation with cold-room engine tests [13] but later found inadequate in the face of Nature's more complex cooling pattern in the Sioux Falls incident [14]. A redeveloped MRV test technique was called TP-1 [15] and later became ASTM D4684 [16] replacing D3829 in test specifications.

The TP-1 approach cools the sample at -1/3°C/hour from -8° to -20°C after which the cooling rate is increased to -2.5°C/hour to the desired test temperature (although gelation does begin to occur at lower temperatures). After cooling, the test procedure consists of first gradually increasing the force applied to turn the rotor in the stator in a series of 10-gram increments to determine if the oil has gelated during the 36-hour cooling interval from -8° to -20°C. If so, the level of weight needed to overcome the resistance of the gelated structure is recorded. This load is called the 'Yield Stress'.

Whether or not a Yield Stress is encountered, following the Yield Stress test portion of the procedure, a 150 gram weight is then applied to turn the rotor for three revolutions and, if the rotor will turn, this information is used to calculate the viscosity of the sample at that temperature.

7.3.1 Comparison of Low-Temperature Pumpability Susceptibility Using the MRV TP-1

As in the previous SBT analysis of measuring the susceptibility of engine oils to pumpability failure, *Figure 8* shows the overall pattern of response to measurement by TP-1, using ASTM Test Method D4684.

The SAE J-300 Engine Oil Viscosity Classification requirement of a viscosity level no greater than 60,000 mPa•s (cP) at a test temperature chosen for the SAE Viscosity Grade is also shown as a red horizontal line. Using this criterion of acceptability, the Americas show considerably better response to the test in the years 2008 to 2011. However, by 2013 Europe and Asia have improved to become essentially equivalent to the Americas. Again, it is likely that this pattern of change reflects both the long North American concern with pumpability failure since Sioux Falls and also the recent adverse European experiences with pumpability failure reported in 2008-2009.

It is also of interest to appraise the second criterion of TP-1, that of the Yield Stress. *Figure 9* is a comparative analysis of Europe, the Americas and the Asia Pacific, showing the form and frequency of the failing oils.

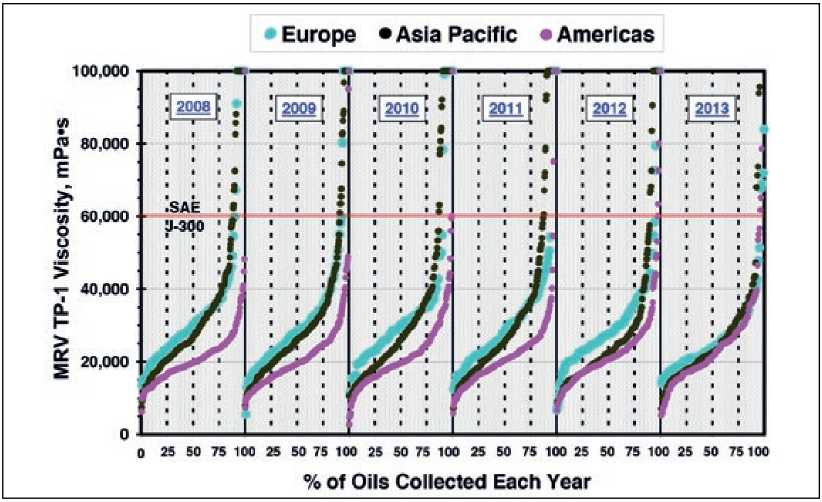

Fig. 8: MRV TP-1 Low-Temp. Pumping Resistance Bench Test (ASTM Test Method D4684)

The data of *Figure 9* are also quite revealing in showing that essentially all failure by the TP-1 bench test is by gelation indicated by the Yield Stress. Moreover, the data of 2008 to 2012 also show the higher frequency of gelated oils marketed in Europe and Asia Pacific in comparison to those marketed in the Americas. However, the data also show that the occurrence of oils prone to Yield Stress in the Americas is increasing from 2009 to 2013 while Yield Stress prone oils in Europe and Asia are generally diminishing. The next years of collection will be interesting in regard to continuation of such changes.

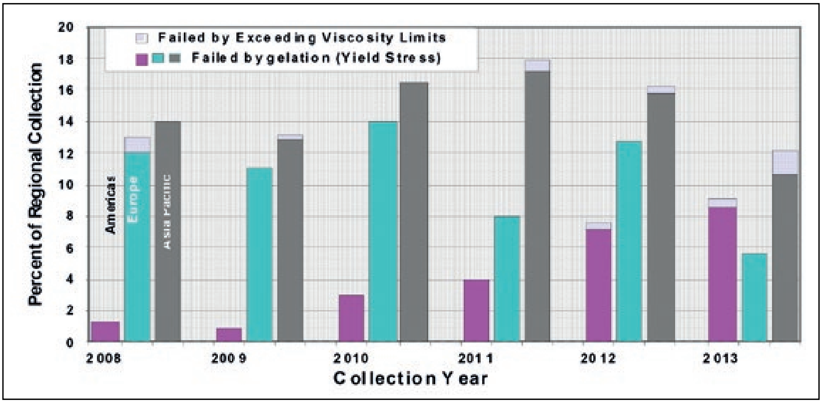

Fig. 9: MRV TP-1 Likelihood of Damage under Low Temperature Exposure Predicted by ASTM Method D4684

8. Comparison of the Fuel Efficiency Effects of Marketed Engine Oils

As was briefly noted early in this paper, the difficult combination of performance, protection and fuel efficiency of smaller, more stressed engines is a rapidly growing challenge.

From this viewpoint, perhaps the most important aspect of the viscosity of engine oil – beyond that of protecting the engine through hydrodynamic lubrication – is the energy the oil viscosity requires from the engine in order to provide such wear protection. The fact is that the engine oil has a strong influence on the engine's fuel efficiency. These considerations lead to another factor concerning the level of viscosity needed at an engine's operating temperatures to provide wear protection in concert with the various anti-wear additives which also play a critical role in the engine oil's anti-wear function.

Supporting this viewpoint are very recent requests to the SAE Engine Oil Viscosity Classification Task Force (EOVC) for the need for new, lower viscosity grades for modern automotive engines. As a consequence one new grade (i.e.: SAE 16) has been specified by the SAE EOVC and still lower grades are under consideration.

From these perspectives, it was thought to be of interest in this paper to evaluate the Viscosity-Dependent Fuel Efficiency Improvement Index (FEII-V) – a method developed [17] to permit comparison of the energy required by various engine oils which analytical data are included in the IOM Engine Oil Database. Increasing numerical value of the FEII-V indicates increasing fuel efficiency of the oil. A value of 100 FEII-V is not possible but would indicate engine oil absorbing no energy from the operating engine.

Figure 10 shows the distribution of FEII-V of engine oils collected from the markets of Europe and the Americas by the Institute of Materials over the selected years of 2008 to 2013.

The comparison shows surprising and unexpected differences between the regions. Since the FEII-V is directly related to the high shear rate viscosity of the engine oil, the evident fuel efficiency superiority of the oils from the Americas versus Europe and Asia deserves further study of the IOM Engine Oil Database.

It is evident that, on average, each year the oils selected arbitrarily from those readily available are considerably less fuel efficient in Europe and Asia than the Americas although the differences are less in 2013. This may reflect a more conservative balance in Europe between the benefits of viscosity in reducing wear versus reducing viscosity-related fuel expenditure. There are other ways of improving fuel efficiency rather than reducing operating viscosity.

Another and perhaps more likely scenario is that the lower viscosity Multigrade oils of SAE 5W and 0W classification may be more acceptable in the harsher winters of the North American continent. It will be of interest to note the values of FEII-V of the new lower viscosity SAE 0W-16 engine oils being brought to the market.

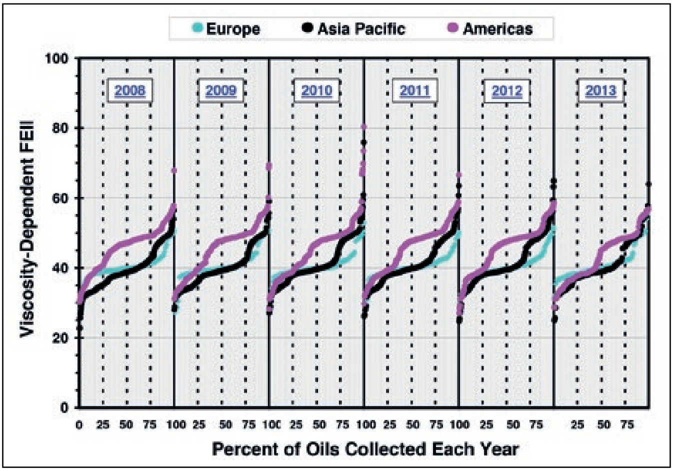

Fig. 10: Viscosity-Dependent Fuel Efficiency Improvement Index of Engine Oils Collected

9. Comparison of the Phosphorous Content of Marketed Engine Oils

For many years, the role of engine oil viscosity in reducing wear has been strongly improved by soluble organic zinc phosphates additives. These additives have been crucial in markedly improving wear protection and, in addition, to significantly counteract engine oil oxidation.

However, in fairly recent times – as automotive air pollution control became more important and expensive exhaust catalysts were required – these catalysts were found poisoned by volatile forms of phosphorus entering the exhaust gas from the engine's combustion chambers. As a consequence, an upper limit of phosphorus in modern engine oils is now required and a lower limit considered prudent.

Figure 11 shows the overall pattern of the phosphorous content in parts per million (ppm) of the engine oils collected from 2008 to 2013 using ASTM Test Method D4951 by inductively coupled plasma spectrometry. It is important to note the API SM requirements for phosphorous included a minimum level of 600 ppm and a maximum level of 800 ppm for the 0W20, 5W20, 0W30, 5W30, and the 10W30 oils. The ILSAC GF-5 and API SN-RC (Resource Conserving) specifications again require the same levels.

As is evident from *Figure 11*, considerably more engine oils in Europe and Asia exceed the 800 ppm level of phosphorus content limited by ILSAC and API in SM and SN-RC. Considered from the viewpoint of engine wear protection and oxidation inhibition of the engine oil, this higher phosphorus level formulation can be considered an advantage. However, from the viewpoint of exhaust gas pollution control, particularly in large cities, air pollution is a decidedly negative aspect of automobile use – as is evident in reports from Beijing and Shanghai in China.

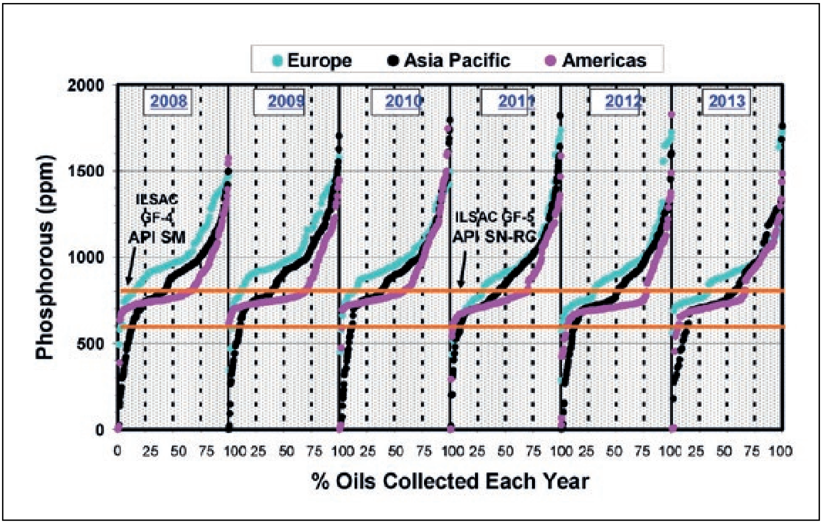

Fig. 11: Phosphorous Content of Engine Oils Collected (ASTM Test Method 4951)

There is another aspect of phosphorus volatility. Not all phosphorus additives have the same tendency to volatilize. Considering the importance of phosphorus compounds in the engine oil, the Institute of Materials Engine Oil Database includes data on the tendency for the phosphorus additives in engine oil to volatilize. This important relationship will be covered in a later paper specifically on this subject.

10. Discussion and Conclusion

The Institute of Materials information presented in this paper for five important properties of engine oils has shown strong differences of these properties in the oils available on the markets of Asia, Europe and the Americas. It has also shown the similarities and differences in the distribution of these qualities in different areas of the world.

The primary purpose of this paper has been to raise awareness of the need to reduce and ultimately eliminate the presence of low quality engine oils and to similarly increase awareness of the significant greater protection of the engine by selection of higher quality products. Although only five of the many IOM bench tests were chosen for this comparison of the quality of marketed engine oils, it is evident that similar differences could be expected in the other performance properties of engine oils.

It was evident that in each test most of the oils tested were of acceptable quality or pressing the limit. However, it was also evident that some products were very lacking in the particular property even to the level of relatively rapidly causing engine malfunction or failure. Warranty concerns are certainly very reasonable for OEMs producing these automobiles.

For example, the determination of Gelation Index for the European engine oils seemed to predict the likelihood of pumpability failure in 5 to 8 percent of the engine oils collected in 2008-2009 under certain weather conditions. Such low-temperature pumpability failures did occur.

The phosphorous content raises some potential concern for the volatility emissions as well.

These data from the Institute of Materials suggest that such data trends as given in its Engine Oil Database can be critically important to those interested and if used and applied can help improve the presence of acceptable engine oils on the market. As a guide, the data from IOM will be of increasing interest and importance as the use of the automobile grows around the world.

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