The Development of the TEOST Protocol MHT Bench Test of Engine Oil Piston Deposit Tendency

T. W. Selby, Savant, Inc. USA
D. W. Florkowski, DaimlerChrysler, USA

Abstract: Development and application of a bench test called the TEOST® MHT to simulate the oxidation and carbonaceous deposit-forming characteristics of engine oils in the hot zones of modern high-performance engines is the subject of this paper.

Work was initiated because of concerns that ring belt and piston undercrown temperatures of 250°C and higher in modern high performance engines may cause a significant increase in carbonaceous deposits in these areas. In the absence of an engine test and reference oils for such ring-belt deposit evaluation, the TU3MH piston varnish rating test and its four associated reference oils as well as a Matrix of GF-2 and potential GF-3 engine oils were chosen to study correlation.

Two groups of TU3MH engine stands were used to generate data through 1998, one group in Europe and one group in North America. The former, using special pistons, showed fair correlation between the TU3MH and TEOST® MHT-4 protocol ($R^2 = 0.73$) while the latter, using dealer-supplied pistons was somewhat poorer ($R^2 = 0.55$). Analysis of the combined data plus further tests in 1999 using special pistons showed that the total data could be separated into two discrete groups both showing high correlation of varnish with carbonaceous deposits. Similar slopes of the two groups of data suggested a consistent relationship between the varnish and carbonaceous deposits but displaced in varnish severity by some third factor. Further analysis indicated that the third factor was associated with choice of special or common pistons. Importantly, it was indicated that significant carbonaceous ring-belt deposits may still form even when piston varnish levels are very low.

Introduction

Modern Engine Severity and Lubricant Demands

Modern automotive engines have grown increasingly severe in their demands on engine oils as a result of smaller, more powerful engines. Moreover, reduction in the available space under the hood taken up by heat-producing devices such as air-conditioners, transmissions, and turbochargers have added further duress to the engine oil's operating environment.

In comparison to past developments in engine oil formulation, today's (and very near future) needs in resisting oxidation are considerably more demanding of engine oil composition. This is not only true of engine oil additive chemistry but of base stock response.

Modern Base Oils and Additive Response

Over the last score years, successes in hydro-treating and isomerization have resulted in base oils having higher paraffinic content. Such oils, properly additized, have shown the anticipated greater resistance to the formation of sludge and varnish in more severe service.

However, such major changes in base stock character require awareness and understanding of consequent changes in chemical and physical response to additive chemistry. Any assumption that the chemical and physical effects of additives on solvent refined base oils can be fully carried over to such hydro-treated and isomerized, highly paraffinic base oils is open to question.

Specifically, with modern paraffinic base oils using additive technology for solvent-refined base oils, question has been raised as to whether higher levels of paraffinicity can adversely affect the amount and hardness of carbonaceous deposits in the ring belt and under-crown areas. These questions grow more compelling when considering more severe service where antioxidants are more depleted with use.

Need for a High-Temperature Bench Test

As a consequence of such questions and recognizing the cost and variability of long-duration engine tests as a means of evaluating the deposit-forming tendencies of engine oils, another path was selected -- the development of a relatively simple bench test simulating the operating conditions of the engine in the ring belt area.

The TEOST® Bench Tests

Background and Development of TEOST® 33C

Previous development of a very high temperature bench test to simulate turbocharger deposits produced the Thermoxidation Engine Oil Simulation Test or TEOST® Protocol 33C [1,2].

Protocol 33C simulated the cyclic temperatures of 200° to 500+°C experienced in the turbocharger with a 12-cycle test run over a period of two hours and requiring 100+ mL of test oil.

The focus of the test was to obtain the weight of deposit formed on a resistively-heated hollow rod (called the depositor rod) held within a casing as bulk oil flowed by at a rate of 0.45 g/minute. The temperature of the rod was controlled by a thermocouple inserted into the rod as shown in Figure 1.

Using four known performing turbocharger reference engine oils, Protocol 33C was found to rank them in correct order with good discrimination between the better and poorer engine oils. On the basis of a later round-robin, the instrument and technique were standardized by the ASTM as Test Method D 6335 in 1998 [3].

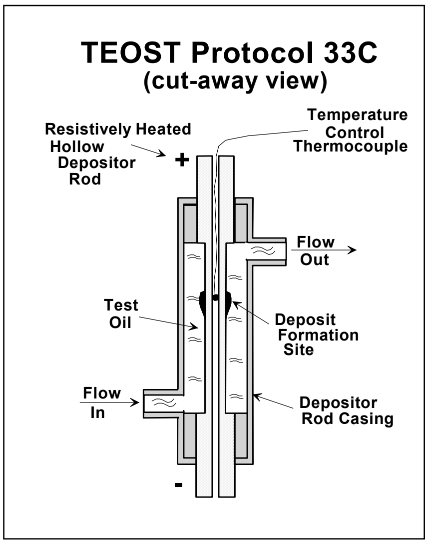

Figure 1 - Deposit Rod zone of the TEOST® 33C turbocharger deposit simulating instrument.

Development of the TEOST® MHT Test Protocols
The need for a bench test simulating high temperature (~250° to 300°C) deposits in the piston ring belt area, led to modification of the TEOST® instrument. This paper presents some of the background and development of the TEOST® MHT test protocols.

Conditions Simulating the Engine Ring Belt
Several parameters were considered either important or necessary for simulating the deposit-forming tendencies of an oil serving under high-temperature engine operating conditions.

***Temperature* -** The first and most important condition was choice of temperature. Temperature studies with a high-performance engine gave the answer that 285°C was a reasonable temperature. It was not necessary to consider temperature cycling as in the turbocharger protocol since a continuous temperature condition was best for generating carbonaceous deposits.

***Thin Film* -** It was considered that the conditions of exposure of the hot oil in the ring belt area of the engine was a thin-film condition and that the oil in the ring groove might stay exposed to the oxidizing conditions for several seconds. In any case, the depositor rod and surrounding depositor-rod casing were entirely revised as shown in Figure 2 although the rod was still resistively heated.

It was necessary to have the oil flow down the rod to obtain the desired thin film. To prevent random flow paths, a forced spiral path was generated by winding a fixed-angle helix of wire around the depositor rod. For further control of oil flow and test repeatability, the iron winding was specially treated to develop an easily oil-wettable surface.

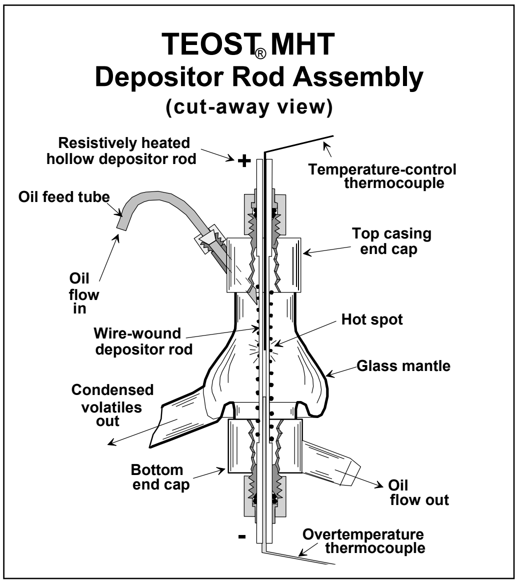

Figure 2 - Redesign of the depositor rod area to create a thin-film oxidation environment.

***Slow Flow Rate* -** As a further effort to form a thin film, the oil flow rate was set at 0.25 g/minute.

***Catalyst* -** Use of a catalyst was important to increase oxidation stress on the test oil and to keep test time within reason. The catalyst selected from a number of experiments was a 3/2/1 ratio of iron, lead, and tin -- all of which are common to, and operative in, the internal engine environment as a results or wear and the development of attack of an oxidized and acidic engine oil. The actual level of catalyst used was 1% of the test sample.

***Sample Size* -** To exert maximum stress on the base oil and its additives, sufficient time is required for each volume element of the test oil to be exposed to the high temperature oxidation conditions existing on the depositor rod surface. At the same time, development of a thin oil film exposure requires relatively low flow rate. Taking both influences into account led to choosing a sample size of 8.5 grams, thus assuring adequate exposure for each volume element of the oil through many repeat exposures to the surface of the hot depositor rod.

***Test Time* -** The second most important factor in stressing the oil was the number of times the oil had to pass over the hot depositor rod. Preferentially, a bench test should compress time to the minimum consistent with repeatable and meaningful results. In the TEOST® MHT-4, the test period found best after considering all of the above variables was 24 hours.

***Air (Oxygen)* -** Air supply was tested at several levels. It was found that if the air flow was too high, volatility of some oils would cause the oil in circulation to run short and abort the test. This occasionally happened at an air supply rate of 15 to 20 mL/minute. However, if the air supply were too low -- e.g. 2 mL/minute -- the rate of oxidation was retarded and the amount of deposits laid down in the test time was significantly reduced. A rate that was found acceptable was 10 mL/minute. Almost all oils could be tested except possibly those of very high volatility and the levels of deposits on the depositor rod ranged from less than 5 mg for a good oil to more than 100 mg for a poor oil.

The present test was identified as TEOST® MHT-4 since three previous test protocols had been tried using different air flow rates.

***Collection of Volatiles* -** In the operation of the automotive engine, volatilization of the engine oil increases the stress on the remaining oil. With less volume, it must circulate more frequently through the hot engine environment. To simulate this aspect of engine operation, the mantle was designed with a skirt/trough to catch any oil which volatilized and ran down the mantle wall.

***Test Protocol* -** A protocol for TEOST® MHT-4 was developed and proven over a period of experimentation. For the interested reader, the protocol is available from the authors.

Selection of Reference and Test Oils
In the area of high temperature ring-belt carbonaceous deposits, no reference oils existed. However, a high temperature piston-varnish-producing engine test called the Peugeot TU3MH had been developed by the CEC as CEC-L-55-T-95. This test provided piston varnish ratings together with several reference oils which had been run multiple times in the TU3MH.

Whether piston varnish ratings would be useful for correlation to ring-belt carbonaceous deposits remained to be determined by the subsequent tests. However, it was thought that reasonable correlation might be found since both forms of deposit are induced at higher temperatures.

In addition to the important reference oils with their multiple runs and statistical solidity, a number of oils from an ASTM GF-3 Matrix study by the ASTM D2 Passenger Car Engine Oil Classification Panel (PCEOCP) were made available by the ASTM Test Monitoring Center.

Table 1 - TU3MH Results Using Special Pistons			
Reference Oils	Number of Round Robin Tests	Average Merit Rating	Standard Deviation
RL 194	18	72.1	8.5
RL 193	7	64.3	11.2
RL 207	4	32.8	12.2
RL 187	5	31.2	6.5

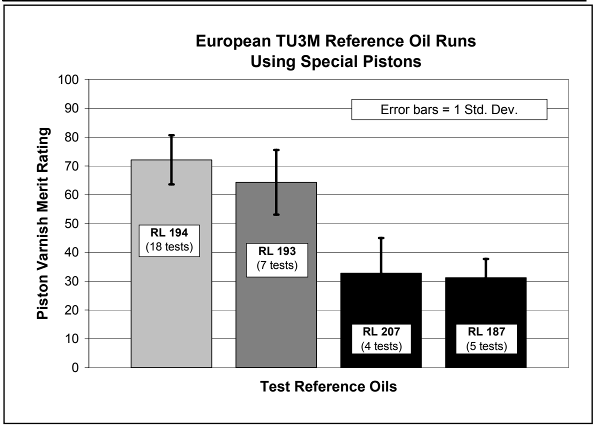

Figure 3 - Results of a large series of TU3MH engine tests using special, controlled ring/ring side-wall tolerance pistons.

Although these oils had no or minimal replication, they still provided opportunity to develop correlation.

European Test Stand Data - Results obtained from multiple tests in European test stands on the four TU3MH reference oils are shown in Table 1.

The older poor-performance reference oil, RL 187, has since been replaced by RL 207 and a minimum merit rating of 60 is required to pass the ACEA A-1 96 requirement.

As noted in Table 1, the TU3MH protocol on these oils required special pistons. Using specially plated pistons having tightly controlled ring/ring-wall tolerances, Table 1 and Figure 3 show that the TU3MH protocol distinguishes clearly among the selected good, borderline, and poor performance oils, RL 194 (good), RL 193 (borderline), RL 207 (poor) and RL 187 (poor), respectively.

With multiple tests for statistical reassurance, data obtained with the special pistons give confidence that the order of improving performance of the four reference oils in the TU3MH test is: RL 194 > RL 193 > RL 207 = RL 187.

North American Test Stand Data - Test stands were also set up in North America, in this case using dealer-supplied common pistons. Calibration results shown in Figure 4 are compared to the European results.

Results on the good reference oil, RL 194, agreed reasonably with the European data. However, results on the borderline reference oil RL 193 gave poor distinction. An explanation was given to the authors by the North American test stand operator* [see footnote]. Consequently, the North American 1998 RL 193 TU3MH test results with common pistons will not be used in the following analyses and discussion.

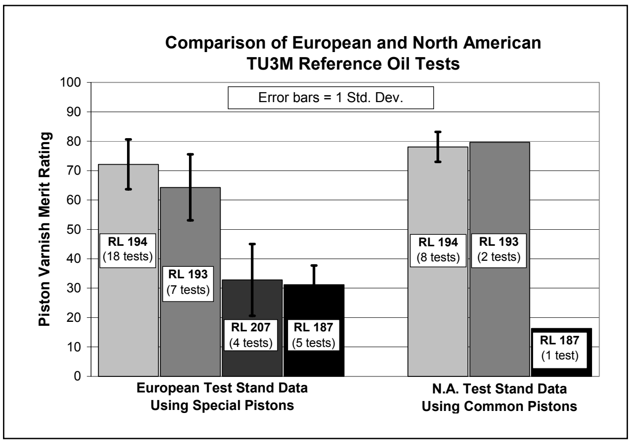

Figure 4 - Comparison of TU3MH engine tests in Europe and North America.

Precision Study of the TEOST® MHT-4 Protocol

Test Oils

Six oils were chosen for a round robin. They included three of the four TU3MH reference oils, RL 193, 194, and 207, plus three other oils.

The latter three oils were composed of a GF-2 reference oil (TMC 1006, considered a borderline reference oil), and two field oils, one of which was a representative of ILSAC GF-2/API SJ oils and the other oil offered as an improvement over the GF-2/API SJ specification (and possibly was a candidate for GF-3 level performance). All three were being run in a taxicab fleet test at the time of their selection for the round robin.

Round Robin Results

A preliminary cooperative round robin was generated using the six oils in three laboratories equipped with a total of six instruments using six operators -- one for each instrument. One analysis of each oil was run by each laboratory to quickly check only the reproducibility of the method. Results are shown in Figure 5.

Reproducibility seems reasonably good for a test characterizing high-temperature oxidation by a method requiring weighing milligram levels of carbonaceous deposit. With greater test familiarity, reproducibility would be expected to improve. Repeatability has also been found quite acceptable in other, as yet unpublished, studies.

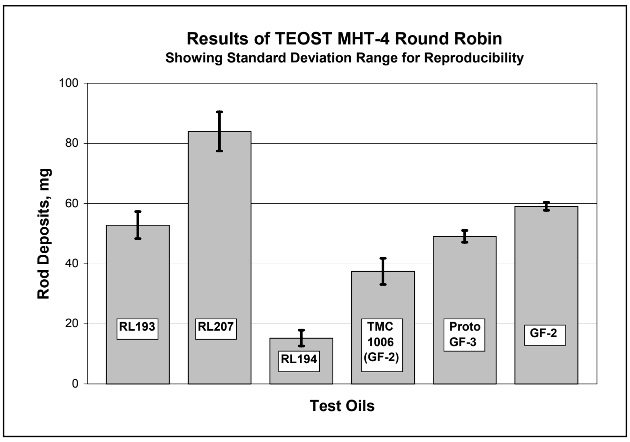

Figure 5 - Reproducibility of the TEOST® MHT-4 in a small six-instrument round robin.

* RL 193 varnish deposits were considered to depend heavily on the amount of ring sticking and thus on the ring/ring side-wall clearance control. The common pistons used in the two 1998 RL 193 tests had no controlled side-wall tolerances. More discriminating 1999 work by the operator using special pistons will be discussed later in the paper.

As shown in Figure 5, the round robin also indicated that the three oils identified as either GF-2 or proto-GF-3 were not greatly different from one another in regard to carbonaceous levels. These results corresponded to the field taxi-cab fleet study where it was later reported by one of the authors that relatively small differences were found in oxidation resistance among the same three oils after these extended taxicab tests [4]. Such findings further emphasized the need to have a deposit bench test corresponding to the field results on GF-2 and proposed GF-3 levels under high performance conditions.

Other Information from the TEOST® MHT-4 **-** In addition to rod deposit information, the MHT-4 test produces 1) oxidized residual oil, 2) volatile products of the oils, as well as 3) varnish deposits on the inside of the mantle -- all of which vary with the formulation and composition of the oil.

Viscosity Increase - In a number of engine tests, the viscosity increase of the oxidized engine oil has been used as a measure of the acceptability of the oil. Taking the residual oil at the end of the MHT-4 analysis, the oils were analyzed in a specially developed cone-plate micro-viscometer that only required 0.5 mL of oil. Results are shown in Figure 6.

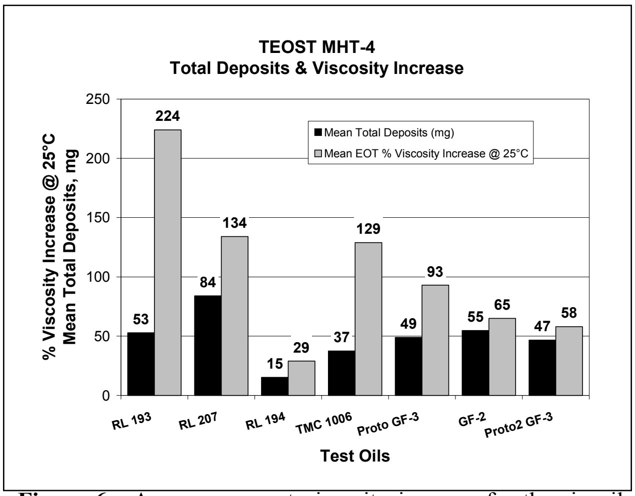

Figure 6 - Average percent viscosity increase for the six oils used in the round-robin plus another GF-3 prototype not included in the round robin for reproducibility.

It is evident that the degree of viscosity change, at least at 25°C, does not correlate with the level of deposits formed. For example, viscosity change in RL 193 is the highest of all the oils tested while that of RL 207 is considerably less. This indicates that viscosity increase is only one measure of acceptance of an engine oil regarding high temperature performance and again affirms the need to develop a high-temperature deposit test.

The results also indicate that different additive chemistries in combination with the base oil can produce widely different responses to oxidation conditions.

Engine Correlation

General

All data collected from European and North American TU3MH test stands through 1998 are shown in Table 2 as well as the data collected from the TEOST® MHT-4 Protocol. It will be noted that there are 10 Matrix oils and four reference oils examined.

Table 2 - Comparison of TEOST MHT and TU3MH Results Obtained Through 1998

	TEOST MHT-4		
1006	38.5	52.6*	
1007	26.7	64.5*	
1008	9.0		80.5*S
425-2	48.2	38.1*	
GF 327	50.8	61.5*	
GF 331	51.7	71.2*	
GF 332	37.7	76.8*	
GF 334	38.7		80.7*S
GF 336	43.6		74.2*S
GF 337	54.7	87.3*?	
RL 193	54.4		64.3AS
RL 194	15.2		72.1AS
RL 194	15.2	78.1A	
RL 207	82.1		32.9AS
RL 187	71.2		31.2AS
RL 187	71.2	16.3*	

* single test; A Average; S Special piston, ? Outlier ?

All of the Matrix oils were run only once in the 1998 series of tests to the authors' knowledge.

Correlation of TEOST® MHT-4 and TU3MH Results

European Test Stand Results **-** Single test results on four ASTM GF-3 Matrix study oils were obtained on the European test stands. These data were combined with results from the four TU3MH reference oils, 187, 193, 194, and 207, to develop correlation with the TEOST® MHT-4 Protocol. Figure 7 shows the results.

The level of correlation shown, $R^2 = 0.73$, is reasonably good and indicates that varnish and carbonaceous deposits are linked to some significant degree. That is, within the repeatability of the two types of tests compared, the data may be interpreted to show that 73% of the variation in the TU3MH piston varnish can be related to the variation in the level of carbonaceous deposits produced by the MHT-4 protocol.

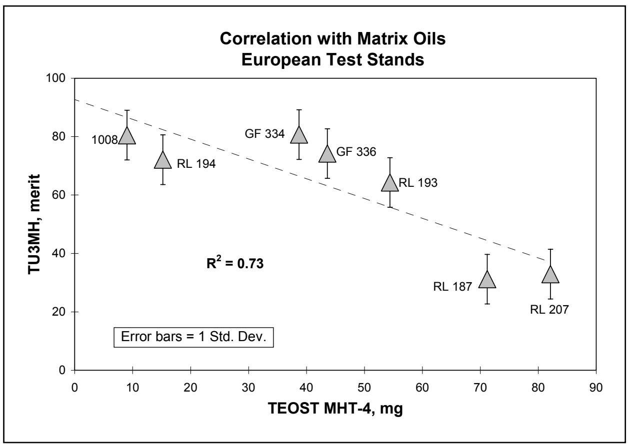

Figure 7 - Correlation of TEOST® MHT-4 results on three TU3MH reference oils plus four GF-3 Matrix study oils.

This reasonably good but not excellent level of correlation suggests that, in addition to varnish effects, other factors such as base stock composition, additive chemistry, and/or piston manufacture might influence the relationship between carbonaceous deposits and varnish. This will be thoroughly discussed subsequently in this paper

North American Stand Results - Another set of available TU3MH data on Matrix oil were obtained on North American engine test stands during 1998 and permitted further comparison with the TEOST® MHT-4.

Figure 8 shows a correlation plot of the TU3MH data obtained on six Matrix oils with the MHT-4 protocol including the reference oils RL 194 (on which multiple runs were made) and RL 187 (on which only one test was made). In comparison with European test stand results, correlation between the TU3MH and MHT-4 tests is somewhat lower with an R^2 value of 0.55.

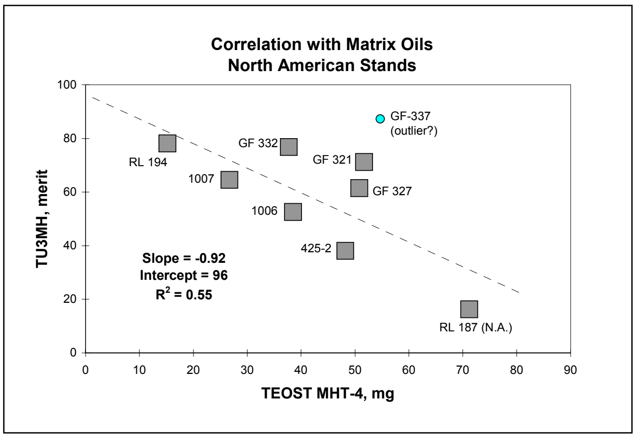

Figure 8 - North American test stand correlation. TU3MH and TEOST® MHT-4 results on two reference oils plus seven oils from GF-3 Matrix study.

The result on one Matrix oil (GF 337) was so different from the other Matrix tests results that it was considered an outlier and would seem to require replicate testing before acceptance.

The disparity between the European and North American data may reflect greater European familiarity with a test developed in Europe. However, as previously mentioned, differences in piston manufacture regarding degree of plating and ring side-wall clearances may be important. This will be discussed in greater detail later in this paper.

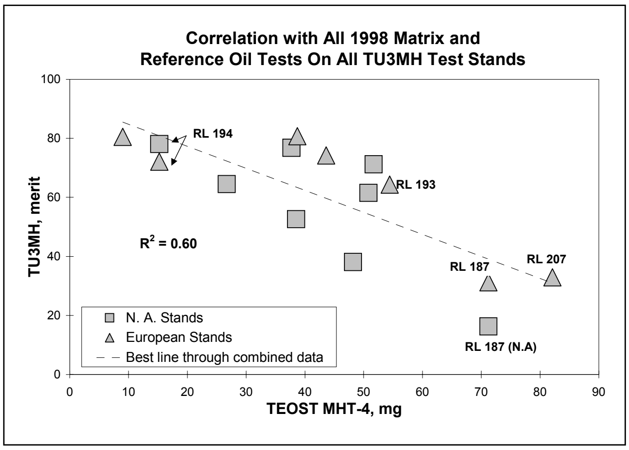

Figure 9 - Overall correlation of TEOST® MHT-4 results with ASTM Matrix test oils in European and North American stands through 1998.

Combined TU3MH Data - The data from all the test stands on which the Matrix oils were run through 1998 are shown in Figure 9. The value of R^2 is 0.60 reflecting the higher correlation value shown in Figure 7 and the lower correlation value shown in Figure 8.

Discussion

Significance of Correlation

Generally, in any comparison of two related but different physical or chemical properties of a material, the question of degree of correlation arises. A high level of correlation is strong evidence that 1) the two properties are tightly interrelated and that 2) the techniques of determining the two properties are individually relatively precise.

A moderately high level of correlation suggests that, 1) other factors are also influential and/or, 2) that one or both of the techniques producing the values may be somewhat imprecise.

In comparison, low correlation raises the questions of either 1) a low level of interrelationship, 2) a low level of precision in one or both of the tests producing the properties being compared, or insufficient data on which to draw conclusions.

In the present case in which two sets of oils are tested with ostensibly the same test protocol, it could be concluded that the better correlation between varnish and carbon deposits (European test stand information) is likely the most correct information.

Alternative Views

However, from Table 2 and Figure 9 closer observations lead to more interesting and informative conjecture:

Test Stand Agreement - It may be observed that none of the 1998 tests on Matrix oils were run in both sets of TU3MH test stands (see Table 2). Thus it is possible and reasonable that the two sets of test stand data are actually in agreement. If so, to the degree that either set is providing consistent data, both sets may be simultaneously defining the influence of another factor or factors.

Support for this alternative viewpoint came in 1999 when further, although limited, work was done. In one study Matrix Oil GF 327, previously run on North American test stands, was tested in Europe and gave similar results.

In another small study, the special pistons used in Europe TU3MH tests were used in North American tests of RL 194 and 193 and gave varnish merit ratings for both reference oils similar to those obtained from European test stands (RL 194 > RL 193). This data was considered highly significant because the use of special pistons brought the two sets of test stands into agreement.

Table 3 - Comparison of New 1999 TU3MH Results with Those Obtained in Earlier Studies

Reference/ Matrix Oils	TEOST mg	TU3MH Merit Rating (1998) N.A.	TU3MH Merit Rating N.A. (1999)	TU3MH Merit Rating Europe
GF 327	50.8	61.5*		<u>64.1</u>*S
RL 193	54.4	79.0, 80.3	<u>68.4</u>*S	64.3AS
RL 194	15.2	78.1A	<u>81.8</u>*S	72.1AS

* single test; Aaverage; S special piston

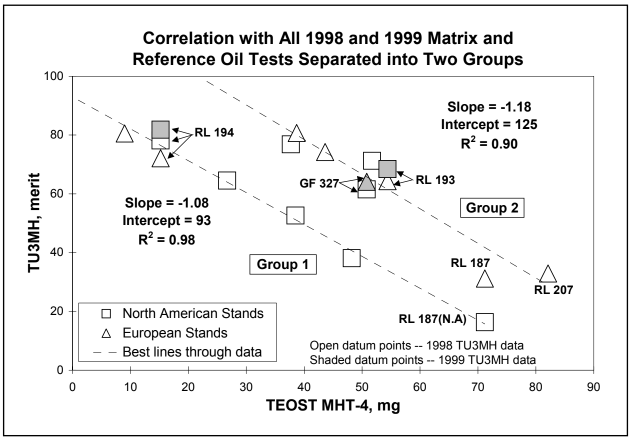

Figure 10 - Comparison of TU3MH results obtained on European and North American engine test stands but separated into two subgroups of data.

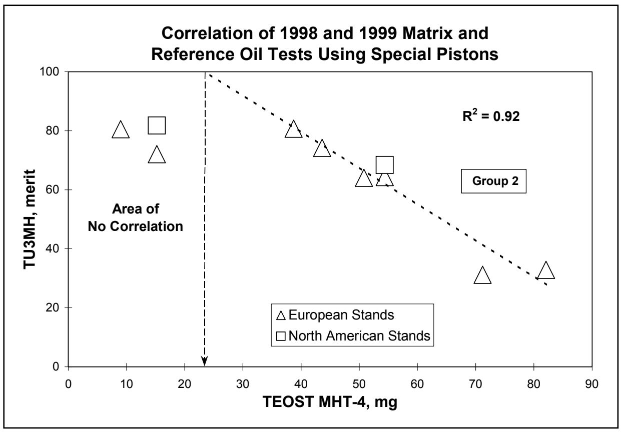

Figure 11 - Comparison of TU3MH and MHT-4 results obtained on European and North American engine test oils using only TU3MH data from special pistons.

These new pieces of TU3MH data are shown underlined in Table 3 and amplify the view that the European and North American data are in agreement -- particularly when data are obtained with the special European pistons.

Two Groups of Data - If then, as seems to be the case, the two groups of engine test stands are in essential agreement -- with a third factor yet to be considered -- the data of Figure 10 (Figure 9 plus 1999 special piston values) seem to fall into two reasonably well-defined groups.

With such separation, the two groups both show individually high correlation between the TU3MH varnish and MHT-4 carbonaceous deposits with R^2 values of 0.98 and 0.90 for Groups 1 and 2, respectively. Interestingly and importantly, the best lines through the groups are essentially parallel (slopes of -1.08 and -1.18, respectively).

Implications - This high correlation of each of two discrete sets of data, if correct, is of considerable interest and significance in understanding the relationship between varnish and carbonaceous deposits.

Level of Correlation - First of all, the apparently high levels of correlation in Groups 1 and 2 individually, indicates that with either, TU3MH varnish is closely related to MHT-4 carbon deposits. The fact that the slopes of both groups are so similar suggests that the same interrelationship between varnish and carbonaceous deposits are operating -- a reasonable expectation.

Variation in Varnish Deposits - Secondly, the existence of two separated but similarly varying groups of deposit data would strongly imply that another factor (or factors) may be causing the separation of such groups of data.

The previously mentioned 1999 studies on North American test stands using the European special pistons with tighter ring/ring-groove side-wall tolerances may give a clue to this factor. That is, the difference in effects between the special and common pistons on varnish level may be that principle factor. Depending on the type of pistons used for the TU3MH tests, such a 'piston factor' would be expected to affect the TU3MH levels of varnish which could only be revealed as two groups when these varnish levels were correlated with another variable such as MHT-4 deposits.

Need for Sufficient Data - Thirdly, two significantly separated groups of individually and strongly, correlated data, can only be found by having sufficient datum values to distinguish the groups to which the data belong. If only a few data points were available and mixed between Groups 1 and 2, they would be likely to produce an erroneously poor and even negative correlation between the variables. Fortunately, sufficient 1998/1999 data were available.

Elimination of Piston Effects; Limits of Correlation - It was possible to test piston effects by using the most reliable TU3MH tests obtained on special pistons, thereby eliminating piston differences. Figure 11 results.

Rationally, correlation between two properties can only be expected when both are systematically varying. Consequently, correlation between TU3MH and MHT-4 deposit levels must end at 100 merit varnish rating.

As shown in Figure 11, replotting the best line through the special piston portion of the Group 2 data and extrapolating to a perfect 100 piston merit value gives a minimum MHT-4 carbonaceous deposit value of 23 mg. below which no correlation with varnish can be expected. Three of the lowest carbon-depositing oils fall in this zone of no correlation* [see footnote].

The Third Factor - Eliminating the three non-correlating special piston data and replotting Group 1 and Group 2 data gives Figure 12.

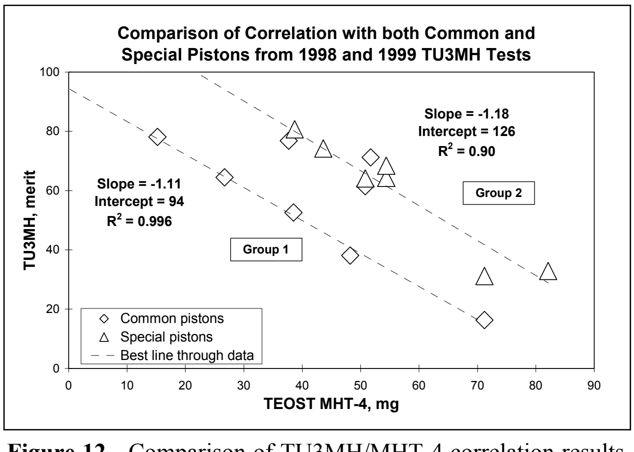

Figure 12 - Comparison of TU3MH/MHT-4 correlation results obtained on random, dealer-supplied pistons and selected ring/ring side-wall dimensioned pistons.

*The fact that light varnish levels are recorded for these three tests suggests that 85 to 90 merit rating may be reasonably be the practical upper limit of repeatable visual discrimination for the TU3MH test. On this basis, correlation between TU3MH varnish and MHT-4 carbonaceous deposits would be expected only when both the varnish merit is below ~85 and the carbonaceous deposits are above ~30 mg.

The special pistons give consistent results whether used in European or North American test stands. Equally evident, the common pistons are completely responsible for the Group 1 correlation even though some of the results obtained on these pistons fall into Group 2 (perhaps reflecting common pistons with closer ring/ring-wall tolerances or oils that are not as responsive to such clearances).

Piston differences thus seem to be the third factor. More particularly, use of common pistons seems the cause of separation of Group 1 from Group 2 data.

Observations/Deductions from Correlation Analysis - The foregoing analysis of the correlation between TU3MH and TEOST® MHT-4 data leads to certain significant observations and projections, as follows:

The Correlation is Varnish Level Dependent - Regarding the TU3MH varnish range,

1. At higher varnish deposit levels, good correlation with carbonaceous deposits would be expected.
2. At very low varnish levels (above ~85 merit), carbonaceous deposits would not be expected to correlate with TU3MH results.
   a. Specifically, TU3MH data obtained with special pistons would not be expected to correlate with MHT-4 deposits below 23 mg -- more probably, ~30 mg.
3. Below a certain low level of repeatable varnish detectability, there is a broad high-temperature carbonaceous deposit range which may require considerable, and perhaps new, engine oil formulation skills.
4. Over the range of correlation between TU3MH varnish (using special pistons) and MHT-4 deposits both sources of data seem dependable and informative.

Overall Consideration - The above observations lead to the consideration that while both piston ring/ring-wall design and oil properties can help control varnish, high-temperature carbonaceous deposits on the piston is likely only controlled by the characteristics of the base oil and additives used. Moreover, given acceptable base oils, the engine oil properties required to control such carbonaceous deposits may at times be significantly different than those required to control varnish as shown by those oils having significant carbonaceous deposits at low varnish levels.

It would be interesting to obtain more data on some of these Matrix and reference oils on both sets of test stands using special pistons with controlled ring/ring-wall dimensions. North American TU3MH tests would be particularly interesting on RL 207 and TMC 1008 as well as European tests on TMC 1006, 1007, and 425-2.

Summary and Conclusions

The TEOST® MHT-4 Protocol

Development of the TEOST® MHT-4 apparatus, protocol, and reproducibility of results have been presented in some detail. The method seems reasonably precise. Essentially the development was a consequence of a need for carbonaceous deposit control in high-performance engines.

Lacking a suitable high-temperature engine piston deposit test with which to compare the MHT-4 bench test, the TU3MH piston varnish rating test was chosen particularly because of the availability of its four reference oils. Results and oils from TU3MH tests on both European and North American test stands on ten ASTM Matrix oils were also available.

Preliminary Data Analysis

Simple regression analysis of the raw TU3MH piston varnish and TEOST® MHT-4 depositor rod carbonaceous deposits on the ten Matrix and four TU3MH reference oils showed reasonable correlation of R^2 = 0.73, 0.55, and 0.60 for the European, North American, and combined data, respectively.

The European test stand data used special chosen pistons for close control of ring/ring-wall clearances whereas the North American test stands used common, dealer-supplied pistons for work through 1998. Such pistons gave little distinction between the known good and borderline reference oils, RL 194 and RL 193, respectively.

New North American Data Using Special TU3MH Pistons - However, more recent work in 1999 with North American test stands using the special, close-tolerance pistons gave results similar to previous European data on RL 194 and RL 193.

Additional Data - The new North American data and a study in Europe were added to the raw information for further analysis.

Further Investigation of the Correlation Data

Two Groups, High Correlation - Appraising the complete data available more carefully, they seemed to fall in two groups with each group individually showing high correlation between the TU3MH and the TEOST® MHT-4. That is, R^2 values of 0.98 and 0.90 were shown for Group 1 and 2 data, respectively.

Presence of a Third Variable - That the data seemed to split into two groups suggested the presence of a third variable and efforts were made to see if the data could be further analyzed to reveal what this variable might be.

Correlation Limits - It was clear that the most reliable TU3MH data were those from tests using the special pistons. Since correlation requires both properties compared to be mutually varying, no correlation could be expected beyond the point at which TU3MH approached its limit of 100 merit rating.

This limit of correlation occurred below the value of ~23 to 30 mg. MHT-4 carbonaceous deposits. That is, below that value, the close correlation found at higher varnish levels was no longer meaningful. Three datum values from low carbonaceous deposit oils fell into this zone of no correlation.

Evaluation of Third Variable; Piston Type - With the elimination of all non-correlative data, remaining Group 1 and Group 2 data were reanalyzed. It became evident that the only data falling in Group 1 were TU3MH data using common pistons. All other data (including some results using random pistons) fell into Group 2.

The third variable was thus strongly indicated to be piston source and choice of either special or common pistons.

Apparent Essential Relationships between Varnish and Carbonaceous Deposits

The studies and analyses of the varnish/carbonaceous deposit relationship in this paper resulted in three basic observations:

1. The seemingly strong varnish/carbonaceous deposit correlation between the TU3MH engine test and the TEOST® MHT-4 bench test is dependent on varnish

levels. Below certain very low levels of varnish, considerable carbonaceous deposits can still occur. Low varnish does not end carbonaceous deposits -- correlation is merely lost since varnish no longer varies while carbonaceous deposits do.

2. Varnish is affected by piston design and manufacture as well as by the formulation of the engine oil -- carbonaceous deposits seem only affected by the formulation of the engine oil.
3. Piston ring/ring-wall design is important in the TU3MH test (and likely other engine tests) when studying varnish and carbonaceous deposit relationships.

Future Work

In view of the need for carbonaceous deposit information from engine tests, a set of extended engine tests on high performance engines is planned. It is expected that this work will also generate a set of reference oils.

The present work strongly suggests further TU3MH tests be run on the oils forming the Group 1 data using special pistons and that further tests be considered for some of the Matrix oils.

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